THE ROLE OF
ABSORBENT BUILDING MATERIALS
IN MODERATING CHANGES OF
RELATIVE HUMIDITY

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Ph.D. thesis
The Technical University of Denmark
Department of Structural Engineering and Materials

October 1998

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Published as a report from the Department of Structural Engineering and Materials,
The Technical University of Denmark. Series R no. 54, 1999
ISBN 87-7740-256-1
ISSN 1396-2167

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THE ROLE OF ABSORBENT MATERIALS IN MODERATING CHANGES OF RELATIVE HUMIDITY

Abstract

An experimental climate chamber controls the water vapour flux, instead of the relative humidity which is the parameter controlled by ordinary climate chambers. This chamber allows measurement of the influence of porous, absorbent materials on the indoor climate.

An assortment of common and unusual building materials has been tested for efficiency in buffering the indoor relative humidity: brick, cellular concrete, wood, earth, lime mortar, gypsum plaster and wool insulation. The best buffer performance among the materials tested is given by wood arranged with the longitudinal direction perpendicular to the exposed surface. The best inorganic material is a specially developed mixture of bentonite, a montmorillonite type clay, with perlite, an expanded volcanic glass.

Such materials, used as walls within buildings, will moderate the indoor relative humidity, over a period which depends on the air exchange rate. This humidity buffering effect is particularly useful in kitchens and bathrooms where intermittent production of steam is effectively absorbed, to be released later. Effective buffering of the daily variation of relative humidity can be achieved.

In buildings with a much lower air exchange rate, such as archives and stores, the buffering by absorbent walls is so effective that it evens out the annual cycle of relative humidity, without needing help from mechanical air conditioning.

In buildings which require both a moderate air exchange rate and a stable relative humidity a symbiotic design, combining mechanical air conditioning with buffering by building material, allows air conditioning of a museum store, for example, using only a small dehumidifier.

Outer walls of buildings which are porous on both sides should theoretically pass water vapour through according to the relative humidity difference across the wall. This means that such a building when warmed in winter will have a higher relative humidity than that calculated from the water content of the outside air, raised to the inside temperature. This is a controversial assertion, which is here supported by indirect evidence from measurements of church climate. This matter is presented as a conjecture that deserves further investigation.

PREFACE

The moderating influence of absorbent materials on the relative humidity in small enclosures has been known, and written about, for ages. The extension of the concept to moderating the relative humidity of large, leaky enclosures like houses has been unaccountably neglected. The influence of the material is diminished by ventilation but a useful contribution remains. In buildings such as museums, where total control of the indoor climate is considered necessary, absorbent materials can be combined with mechanical air conditioning to provide a simpler and more stable control system. Absorbent walls also have the ability, not yet fully explained, to pump water vapour to increase the indoor relative humidity in warmed buildings in winter.

Now we coat all surfaces with almost impermeable paints and even the porous materials we build with are not very water absorbent, or react very slowly. Architects and engineers have divided the task of making a habitable building, so it is not surprising that engineers have concentrated on designing walls as bearing structures and screens against the outdoor climate and have completely failed to see how a wall can contribute to the pleasantness of the indoor climate.

This evolution in building tradition has not only hidden the potential for humidity buffering that lies in common materials, but has also generated an array of condensation problems, not only within buildings but in the structure of walls and roofs.

I became aware of this by chance, when I was called in to investigate a particularly dramatic example of water apparently being spontaneously generated by a building. Later, as happens when one completes one job successfully, other examples of sick buildings came my way. Some of these studies have been published but they are reworked here to form a coherent study of the role of absorbent materials in the regulation of humidity in the indoor air as well as in the structure of walls and roofs.

This thesis is written to satisfy the engineer's demand for solid evidence and justifiable speculation but I hope that it will also be read and in large part understood by architects and by conservators, who mostly have an arts rather than a scientific education. I have tried to avoid jargon and unnecessary use of mathematical symbolism and manipulation.

I have been able to combine old experiences with new experiments through the generosity of the National Museum of Denmark, which gave me study leave for two years and contributed to the experimental expenses. The Danish Ministry of Culture paid my salary for one year. The Technical University of Denmark gave me three months Ph.D. grant. The Danish Ministry of Energy paid for some research which I have used in this thesis. The Copenhagen Conservation School paid for some research equipment.

There are many people I wish to thank. Those who have contributed to what scientific merit there may be in this work are Poul Klenz Larsen, Jesper Stub Johnsen and Poul Jensen, from the Conservation Department of the National Museum, Bent Eshøj from the Copenhagen Conservation School, Conservator Annabel Robinson, David Erhardt of the Smithsonian Institution and my supervisors at The Technical University of Denmark: Anders Nielsen, Kurt Kielsgaard Hansen and Carsten Rode. For technical help in constructing the climate chambers I thank Bent Hansen, Steen Jørgensen, Klaus

Myndal, Anders Brink and Kenneth Strømdahl. Materials were given by Jens Olsen of Dansk Bentonit Miljø A/S, Niels Knudsen of Nordisk Perlite ApS and Jens Ambjerg-Pedersen of Scandan. For photographs and SEM pictures I thank Christian Bramsen, Inger Søndergaard and Ulrich Schnell. I had invaluable help with experiments from several students at The Technical University: Jonas Berthelsen, Mikael Hansen, Mads Hermann, Hans Linde, Jess Sørensen, Henrik Hansen, Tina Larsen, Hannes Köllensperger, Thong Tri Nguyen. Flemming Abrahamsson from Fornyet Energi and Ianto Evans of The Cob Cottage Company taught me the art and science of building in earth.

Tim Padfield

Virum, October 1998

1

INTRODUCTION

Human sensitivity to temperature and indifference to humidity

This thesis is about controlling the relative humidity inside buildings by using the water absorption properties of porous materials.

We put considerable energy, expense and ingenuity into holding a moderate temperature around us but are much less concerned with the humidity of our environment.

This does not mean that the ambient humidity is unimportant to our welfare. There are organisms that thrive at high humidity which provoke allergic reactions, moulds and dust mites for example (1). On the other hand people seem to be able to tolerate the very low relative humidity of warm houses in cold climates (2), so our ideal environment is on the dry side.

Figure 1.1 A cafe scene in Phoenix, Arizona. The air is cooled by evaporation of water sprayed from the edge of the canopy. The air becomes more humid but the customers are more concerned with keeping cool.

Many of the objects with which we share our space are more sensitive to humidity than we are and are affected by both high and low extremes. Pianos and organs go out of tune, wooden furniture warps and its joints loosen, metals corrode (3). The dimensional changes of materials as diverse as hair, paper, and cellulose butyrate are used in commercial humidity sensors. An example of extreme humidity sensitivity is the geranium seed shown in figure 1.2, which twists round on its curly stalk several times as the relative humidity moves from 30% to 90%.

Because of our relative indifference to humidity over a rather large range, houses

Figure 1.2 The seed head of a geranium. The tightly curled, feathered stalks unwind about five turns as the relative humidity changes from 30% to 90%. Photo: John Lee.

and offices do not generally have any humidity control at all. Only museums, art galleries and printers insist on equally close control of both temperature and relative humidity. The building industry is not therefore as experienced in humidity control as in temperature control, a priority that is also reflected in the research papers in building physics.

Alternative, "green", low energy strategies for controlling indoor humidity are much less developed than methods for collecting, storing and controlling heat in buildings, even though there is no difference in principle between using a massive wall to store heat and using a massive wall to store moisture. It just isn't thought to be necessary. The word 'humidity' in the building industry is almost synonymous with condensation and the acute damage that it causes. The architects who design museums do not ever design with a view to providing a natural stability of relative humidity. They design the building as they would for any other purpose and then leave the engineer to provide the necessary air conditioning by mechanical means. The design of one recent archive building hints at a change in attitude, at least for utilitarian buildings whose main role is storage (4).

In this thesis I discuss humidity control from the point of view of a museum conservator, but the arguments apply equally to ordinary houses and offices.

Humidity control in museums

Museum conservators are concerned with relative humidity because all the organic materials of museum objects change size with changing relative humidity, much more than they change size through thermal expansion over the normal temperature range on earth. Laminated materials, such as oil paintings and veneered furniture will therefore distort and suffer shearing stresses with changing relative humidity. At low relative humidity organic materials also become stiff and therefore less tolerant of the shearing stresses between layers. High relative humidity accelerates the very numerous degradation reactions which involve hydrolysis: the addition of water or the hydroxyl group to materials. Corrosion of metals usually accelerates with increasing humidity and finally high humidity encourages living organisms, which are seldom beneficial to museum collections.

The present standards for humidity control in museums derive from an influential book by Garry Thomson (5), though he was by no means the first to emphasise the importance of humidity control.

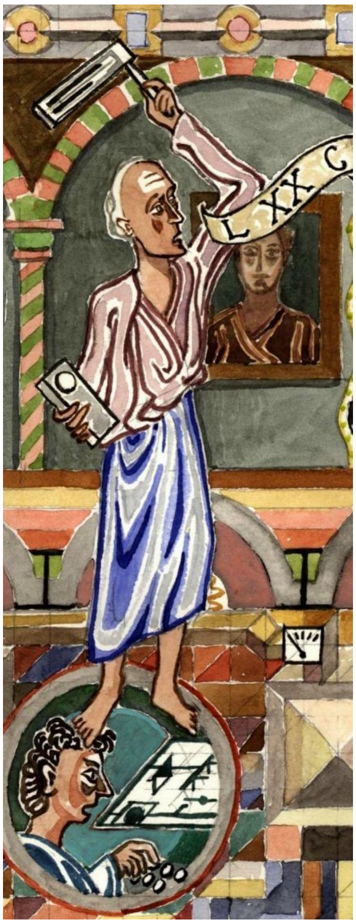


Figure 1.3 Garry Thomson's book "The Museum Environment" became the bible for conservators specifying climatic conditions for museums and art galleries.

Garry Thomson (pictured in figure 1.3, reciting the standard numbers: 50 % RH, 20°C and 100 Lux, while the obedient air conditioning engineer struggles to adjust the machinery) is much more moderate in his views than many conservators, who demand impossibly precise, or at least very expensive climate control, thus shifting responsibility to the air conditioning engineer.

This strict standard for permissible fluctuation in RH has discouraged experiments in passive methods of humidity stabilisation in galleries, because such methods cannot achieve absolute constancy. It is no exaggeration to say that the tight environmental standards have had a pervasive, not necessarily beneficial, influence on museum design.

Humidity control by simple passive methods has been suggested from a very early stage in the development of environmental conservation in museums. In 1934 McIntyre (6) attempted to improve the climate in the orangery at Hampton Court Palace in England by putting lengths of old linen water hose in the ventilation ducts. This was a remarkably ingenious solution at that time, because the response of organic materials to moisture was first accurately measured in the twenties and thirties. He also commented on the usefulness of absorbent buffers in showcases and picture frames.

Since then, development of passive means for stabilising the humidity around art objects has concentrated on refining the performance of the immediate enclosure, the showcase, in museums that are too old, or too poor to enjoy the benefits of modern air conditioning (7). Another popular subject for research has been humidity stabilisation during transport of works of art (8).

Humidity control in showcases and packing cases is rather simple, even trivial, because the air exchanges only slowly with the environment. Almost any absorbent organic material, in rather small quantity, will stabilise the climate in a confined space for a short time. The only difference between a showcase and a packing case is that the temperature is likely to vary more during transport. The effect of temperature change on humidity control in a confined space is described in reference (9).

Humidity control in ventilated spaces

Humidity control in storerooms is a little more complicated than in showcases or packages because the ventilation rate is enough to stress the ability of absorbent materials to absorb and release water vapour fast enough to compensate for the air change. The ventilation rate in store rooms can be low, because there are no people permanently resident in the room, but it is desirable to maintain a slight over-pressure within the room to stop dust and pollutants from entering. The possibilities for low energy control are summarised in chapter 6.

Figure 1.4 Humans, from the point of view of building physics, are merely sources of water.

Humidity stabilisation in a well ventilated space such as a museum gallery, or the living room of a house, is much more difficult. Moisture exchange through ventilation competes with the moisture released or absorbed by the stabiliser. An important complication is the presence of people, who, from the point of view of building physics, mainly function as sources of water.

The factors that must be considered when attempting to increase the scope of humidity stabilisation from the small container to the inhabited area are therefore the rate of transfer of water vapour through the surfaces of the room, the water capacity of the material, the generation of water vapour by people and the loss (usually) of water vapour through ventilation.

The porous wall

Stabilising the humidity in a ventilated space cannot be done by discretely distributing canisters of silica gel. The walls and ceiling of the room must be brought into action as stabilisers.

The original practical work reported in this thesis is mainly directed towards evaluating the performance of porous, water-absorbent walls as moisture buffers for rooms that have the typical ventilation rate for inhabited spaces: about half an air change per hour.

Porous, absorbent walls are almost extinct as a building element in the western world, but they have a history stretching back through millenia. Such walls are generally simple in structure and made of readily available and cheap materials such as earth, wood and plant fibres. One of their valuable assets is an ability to moderate the indoor relative humidity during periods when large quantities of water are released by cooking and bathing.

Walls with a porous surface towards the room are now limited to basements, stables and churches, where the tradition for limewashing survives. Everywhere else a smooth, washable surface is considered more desirable and plastic emulsion paint is the nearly universal interior finish in the western world.

I describe in chapter 6 an example of good humidity buffering in a church with porous walls, and a contrasting example from a nearby church with non-porous interior finishes.

Porous outer walls are particularly distrusted by modern architects and engineers. Their argument is that air from inside the house, where the water vapour concentration is nearly always greater than that outdoors, will move into the wall. In a cold climate the water vapour in the wall will sometimes condense. The liquid water can then cause damage by supporting rot, by freezing and by dissolving and transporting salts which corrode metal parts and crumble the wall through crystallisation. Architects therefore specify an impermeable barrier in the form of paint or a plastic foil close to the interior surface to prevent the inside air from penetrating the wall faster than it can evaporate to the outside.

Condensation damage is, however, not unknown in modern buildings with vapour barriers and more or less non-absorbent materials in the walls (10). The reason for this is that any hole in the barrier will allow air to flow into parts of the wall which have no ability to delay condensation by absorbing water vapour. After condensation has occured, the nearly impermeable wall hinders the evaporation of water out of the wall. Absorbent walls, on the other hand, can be expected to survive a degree of leakage, because the materials will absorb water vapour for a considerable time. The absorbed water will later be released when the outside weather is warmer, or it will be released by diffusion into the relatively dry air outside.

Figure 1.5 In modern buildings an impermeable barrier is often placed just behind the interior finish.

Condensation in nearly impermeable structures is a particular threat to museums. Museums are humidified in winter to about 50% RH. Water is liable to condense at any point in the wall that is below about 9°C, which is the dewpoint of air at 50% RH and

20°C. Nevertheless, museums in old buildings, typically of massive brick construction, seem to survive whereas some purpose built museums with complicated precautions against condensation in the walls drip copiously from the facade in cold weather.

Figure 1.6 The National Museum of American History, in Washington D.C. On a bright spring morning the marble facade is stained by meltwater from ice that has condensed from the inside air.

There is another good reason for evaluating the absorbent wall as particularly suitable for museums. Museums have people in them for about eight hours a day. An absorbent structure will moderate the indoor relative humidity during the relatively brief opening hours. A rather small air conditioning system can then re-establish the correct climate during the long period when there is nobody in the building, and therefore no need for ventilation to the outside. The saving in energy and noise are two advantages, another is the smaller space occupied by the distribution ducts.

Indoor air quality

In the home and in the office, porous, absorbent walls are equally beneficial. The "Sick Building Syndrome" has become a cliché, used to berate designers for all manner of defects which cause psychological or physiological harm to the occupants. The extraordinary number of synthetic chemicals which outgas from modern interiors cannot be blamed on impermeability, but the mould growth that adds natural irritants such as spores to the air can certainly be reduced by permeable walls. Impermeable walls are much more prone to transient episodes of condensation caused by cooking and washing, or simply by the breathing of a large gathering. Insects also thrive where liquid water is available (11).

Dust mites, whose excrement is a potent allergen, thrive only above about 50% relative humidity. A bedroom with windows closed against the night cold will rise considerably in RH during the night, from moisture from the breath and bodies of the sleepers. A porous wall will absorb this moisture and release it when the room is aired during the day, giving a lower average RH. This will reduce the operating time of a dehumidifier, or make it unnecessary.

This brief description of the need for humidity buffering and the unused buffering potential, and other advantages, of porous walls has introduced the main themes of this thesis. The next sections of this chapter introduce those aspects of the physics of water vapour in air that underlie the arguments, and the experimental methods, that will be treated in detail in later chapters.

Aspects of the physics of water vapour that are relevant to experimental and theoretical studies of porous walls

Porous walls exchange water vapour with the room and with the outside air. The thread that runs through this work is the dynamics of the exchange of water between the liquid state, the vapour state and water bound in hygroscopic materials. The discussion of these equilibria is complicated by the contrast between the behaviour of water in air and the behaviour of water in all other materials: the maximum water vapour content of air rises steeply with increasing temperature while the water content of materials depends mainly on the relative humidity (defined below) and is nearly unaffected by temperature. When the temperature changes uniformly in a closed system containing both air and absorbent materials there is a transfer of water between them. When a temperature *gradient* is established across an absorbent material the distribution of water between air and material is difficult to predict.

The equilibrium between water and water vapour

The fundamental measure of water vapour concentration is the pressure it exerts on the walls of its container (in the absence of air). If the container also contains some liquid water the vapour pressure is called the saturation vapour pressure.

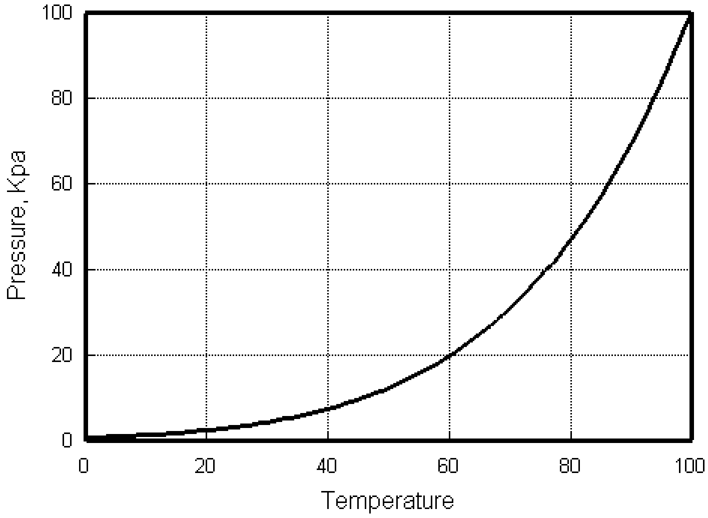


Figure 1.7 The saturation vapour pressure of water.

The saturation water vapour pressure increases steeply with temperature, as shown in figure 1.7.

It would be strictly accurate to write about the equilibrium of water between space and liquid, because the water vapour pressure, and the corresponding water content expressed as kg per cubic metre, are hardly affected by the presence of air, according to Dalton's law of partial pressures. It is, however, customary to talk about the water content of air and the relative humidity of air when discussing microclimate, because air is the carrier gas for both water vapour and heat.

Engineers also express water vapour concentration in units of kg per kg of dry air. This is useful when calculating the heat that needs to be added, or removed, in air conditioning systems, but it is confusing when dealing with moisture equilibria between materials and the surrounding space, where the air plays no role at all.

The formula for the vapour pressure of water and the set of equations linking the various units for expressing water vapour concentration in air are listed in an appendix.

The measure of atmospheric moisture most frequently used in this thesis is the relative humidity (RH). This is the ratio of the actual water vapour concentration to the maximum possible (saturation) water vapour concentration. The water vapour concentrations can be expressed in any units, because the result is just a ratio. The reverse calculation of water vapour concentration from the RH requires that the temperature be known.

Relative humidity is a materials scientist's or chemist's concept, because it is the same as the thermodynamic activity of water. Materials which react reversibly with water, such as cellulose, absorb water according to the relative humidity, with only a slight temperature dependence.

Engineers prefer vapour pressure, as a more direct measure of concentration than RH. There is no doubt that the units one customarily uses colour the way one thinks about a subject. Vapour pressure is actually a rather strange unit to use in daily calculations, and can cause confusion. The water vapour pressure difference across an outside wall can easily reach 1500 Pa (the total air pressure is about 100,000 Pa). This gives the impression of a considerable potential driving water vapour through the wall. However, the total atmospheric pressure difference across a wall is just a few Pascal, because the water vapour displaces air from the mixture so that the difference in total pressure across a wall is only that caused by wind, by ventilators and by small density differences caused by temperature and humidity variations.

In reality it is the slow mass flow of air caused by this tiny difference in total pressure that is often the effective mover of water vapour through a wall. The diffusive movement of water molecules caused by the vapour pressure difference is generally a minor contributor, given more importance than it warrants because it can be calculated by computer programs.

There is even some doubt that the vapour pressure is the driving force for diffusion through walls when there is no air pressure difference. In the building literature it is often assumed, as though there could be no possible doubt, that vapour pressure is the defining variable when discussing water movement in walls, but there is evidence that it is the relative humidity difference that drives diffusion through absorbent materials (12). The distinction is important, because, if relative humidity difference is a driving force for water movement, a porous wall will actually humidify a warmed building in a cold climate: pumping water in against the vapour pressure gradient.

Moisture content of materials

The basic diagram describing the interaction of materials with water vapour in the surrounding space is the sorption curve, often called the isotherm.

The curves shown in figure 1.8 are for cotton at three different temperatures (13). The shape is typical for most materials. Brick, for example, has a much lower absorption but the shape is similar if the vertical axis is expanded.

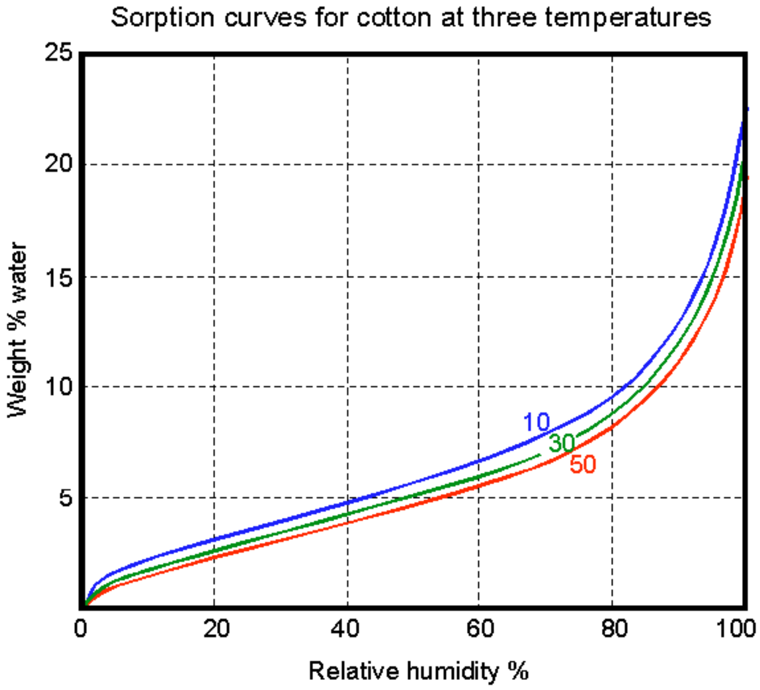


Figure 1.8 The absorption isotherm of cotton at three temperatures

Notice that the atmospheric moisture is defined as RH. Vapour pressure could be used to draw the diagram but the curves for different temperatures would then be spread far apart, concealing the virtual insignificance of the temperature in defining the water content of porous materials.

The curves shown were measured by slowly increasing the ambient RH and weighing the material at each step. The curve obtained by first wetting the material and then drying it out would lie somewhat higher. This phenomenon is known as hysteresis. It looks dramatic when plotted from 0% to 100% RH but the actual behaviour of materials exposed to smaller cycles of RH follows a narrower cycle. Generally, materials settle to an only approximately predictable water content when they are subjected to randomly varying steps of ambient RH.

The small temperature dependence is only significant in unusual circumstances, which will be described in a later chapter. For most purposes the sorption curve can be considered independent of temperature when atmospheric moisture is defined in RH units.

How materials buffer the ambient RH against the effect of temperature change

The RH of air falls as the temperature increases, while the moisture content of cotton, at a given RH, hardly changes. The RH decrease caused by raising the temperature of a small volume of air is therefore at least partially compensated by the automatic release of water from an enclosed mass of absorbent material.

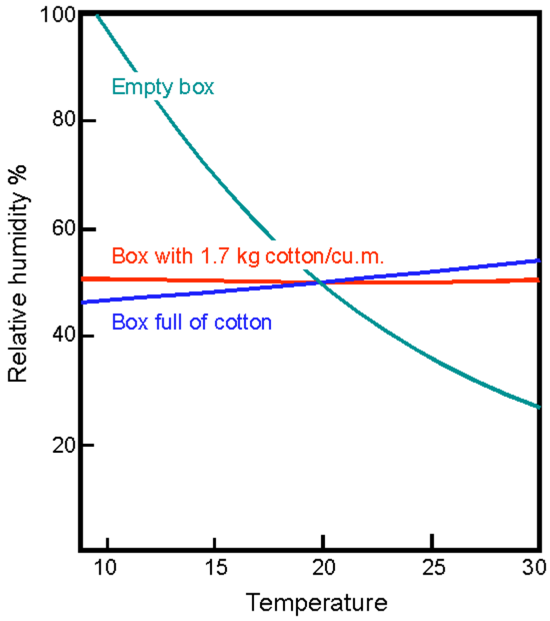


Figure 1.9 The change of relative humidity with temperature in a box with and without cotton as a humidity buffer.

Figure 1.9 shows how materials stabilise relative humidity change provoked by temperature change. Imagine a box with a volume of one cubic metre which contains 8.5 g of water vapour. This will have a RH of 50% at 20°C. An increase of temperature will cause the relative humidity of the air in the box to fall (the steeply descending curve). This is because the vapour pressure exerted by the fixed number of water molecules increases just a little, in proportion to the absolute temperature, whereas the saturation vapour pressure of water increases very steeply, exponentially with temperature. So the ratio of the actual vapour pressure divided by the saturation vapour pressure, which is the RH, falls.

If the box is now filled with, for example, 10 kg of cotton already equilibrated to 50% RH at 20°C, the RH actually rises slightly when the temperature is increased. This is because the exchangeable water in the cotton, about 600 g, is vastly greater than the original 8.5 g in the box. The sorption curve of cotton entirely controls the climate in the box. As the temperature rises, the cotton, with its nearly constant 6% water content, forces the surrounding RH to a value slightly higher than 50%, as can be seen by drawing a finger horizontally (for constant water content) to the right (for rising temperature) in the absorption diagram for cotton, figure 1.8. The cotton therefore releases a very small amount of water, negligible in proportion to its reserve of 600g, to raise the RH slightly to the new equilibrium value.

If the box contains just 1.7 kg of cotton the water supplied by the cotton exactly compensates the tendency for the RH of the air to fall as the temperature rises (the nearly horizontal line).

1.7 kg of cotton is just about the weight of one rather long-winded Ph.D. thesis. The diagram demonstrates that in confined spaces, with no air exchange, the ambient RH is controlled by the materials in the space, in striking contrast to the outside world, where materials have no choice but to come to equilibrium with the totally uncontrollable RH of the vast mass of air wafted past them by the wind.

How materials buffer the ambient air against RH change caused by injection or loss of water

The previous diagram described a closed system with constant total water content. Figure 1.10 shows how absorbent materials will also reduce a RH increase caused by adding water vapour to the air, at constant temperature.

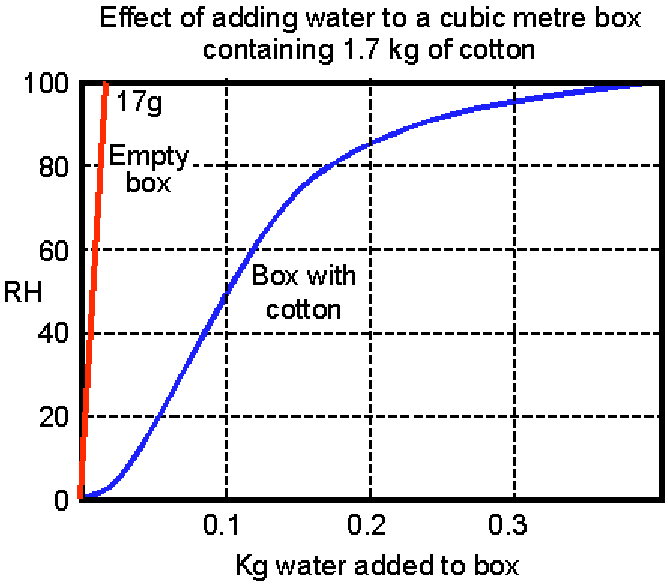


Figure 1.10 Buffering the relative humidity of a box against the effect of adding water: 17 g of water added to the dry empty box will raise the RH to nearly 100%. If there is 1.7 kg of cotton in the box over 200 g of water must be added to give the same RH increase

Consider the same empty box. One need only add 8 g. of water to bring the RH from 50% to over 90%, at a constant 20°C. If the box contains 1.7 kg of cotton one must add 150 g of water to the cotton at 50% RH to drive the RH above 90%.

Buffering of interior spaces by water absorbent materials

These two diagrams show clearly the remarkable ability of relatively small quantities of absorbent materials to stabilise the relative humidity of confined spaces against the effects of changing temperature and changing water content, due usually to air leakage. The water exchange capacity of cotton is in about the middle of the range for absorbent materials. Wood, regenerated cellulose and wool are more effective, mineral products like clay and cement are somewhat less effective. The least absorbent porous materials are synthetic fabrics such as polyester and polypropylene and glassy materials such as brick and mineral wool.

The dynamics of water exchange

The description of the humidity buffering process given above takes no account of the rate of the processes involved. The diagrams illustrate the state of the system when it has come to equilibrium. This is adequate to calculate the buffer capacity necessary for a transport case or a showcase, where the air exchange is much slower than the movement of water vapour between the air and the materials within the case, but it is not adequate for designing humidity buffering for more open spaces, such as store rooms or museum galleries.

The biggest hindrance to the confident use of the basic data described in the preceding sections is insufficient knowledge of the dynamics of the process: how well does buffering work when there is continuous air exchange diluting the effect of the buffers and exhausting their reserves of moisture? How can we overcome the limitation of the slow passage of water vapour through surfaces, so that a greater depth of material can exchange water with the room air? These are the questions that I set out to answer in this thesis.

Diffusion of water through materials is generally assumed to follow Fick's law. This states that the rate of diffusion is equal to the water potential gradient multiplied by a constant. If the process takes place at constant temperature, any unit of potential gradient will do: RH difference per metre or vapour pressure difference per metre will give the same result, as long as the constant matches the unit. However, at least one common absorbent material, wood, does not obey Fick's law (14). Furthermore, the "constant" depends on the water content of the material.

There are at least two published computer programs (15,16) that allow calculation of the rate of movement of water vapour through the components of a wall. Both programs take the indoor relative humidity as a controlling parameter, rather than as a parameter that is dependent on the interaction of the wall with the room air. A reiterative calculation is therefore necessary to estimate the effect on the room climate of water transfer through the surface of the wall.

There is some published research on the buffering of room climate by furnishings (17) but there seems not to be much interest in taking this research to its logical conclusion: to design walls that give the optimum buffering of the daily variation in human activities and, more ambitiously, to design buildings that buffer the seasonal change in RH caused by winter warming.

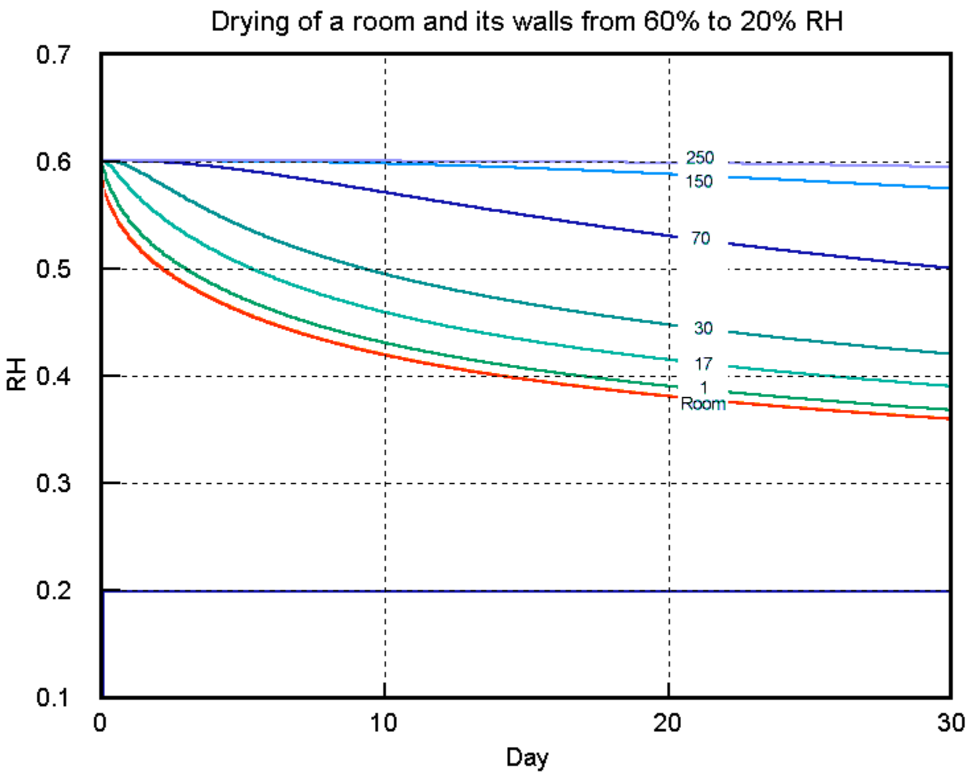


Figure 1.11 Fick's law applied to the drying of a room bounded by porous, absorbent walls, all initially at equilibrium with 60% RH. The room has half an air change per hour. The outside air is at 20% RH and at the same 20 degree temperature as the room.

The RH is calculated for the room and for various depths, in mm, from the surface of the wall, which is 300 mm thick and sealed on the far side.

The wall area is numerically equal to the room volume, which is typical for an ordinary house. The wall has approximately the moisture sorption and permeability of mud brick.

Figure 1.11 is a theoretical calculation, described in detail in chapter 3, which shows how the limited permeability of the material of a wall reduces its effectiveness as a humidity buffer in a ventilated room. In this example there is half an air change per hour to the outside air, which is at the same temperature but at 20% RH. The room RH drops rapidly from its original 60% but steadies at about 40% because a sufficient RH gradient is established between room air and wall to drag moisture ever more reluctantly out of the wall. The nearly unaltered RH deep within the wall (the flat curves at the top of the diagram) demonstrates that there is no lack of water during this period of a month but that it cannot reach the room.

There is some doubt about how accurately Fick's law describes moisture movement through walls. Furthermore, currently available programs do not deal with convective processes in perforated walls. It is just such a wall that one would envisage as a humidity buffer: air channels within a massive absorbent wall which take in room air and let it out again after convective streaming up or down within the wall. The thermal analogy is the north European tiled stove, which has a labyrinth of brick passages to suck heat from the smoke as it travels towards the chimney.

A climate chamber for simulating water vapour flux

The unsuitability of existing theoretical models for calculating interior relative humidity is matched by a lack of experimental facilities for investigating moisture buffering in ventilated spaces. Climate chambers invariably impose an interior relative humidity, to which the material under test must react. There are no experimental facilities for investigating how the material under test influences the relative humidity of its surroundings.

A rather unusual climate chamber is required to conduct an investigation into how porous walls stabilise the relative humidity in a room. The chamber should not impose a particular relative humidity on the enclosed air but should instead generate a *flux* of water vapour that simulates the water produced by human activity and the water lost (usually) by ventilation to the outside.

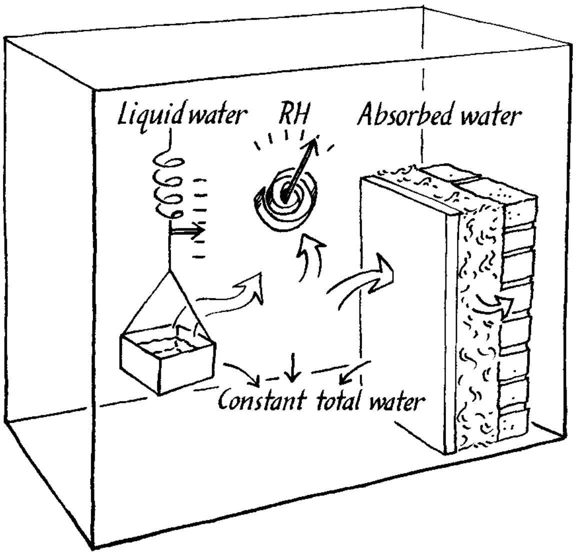


Figure 1.12 Principle of operation of the water vapour flux chamber. The airtight chamber contains a fixed quantity of water which is distributed between three components: a water tank, which is weighed, the air in the chamber, whose RH is measured and the experimental wall, whose change in water content must be the remainder.

The water vapour flux, which is a quantity, is more relevant to such an investigation than the relative humidity, which is a potential. The difference can be illustrated by letting a kettle boil unattended in the kitchen. The relative humidity of the kitchen air will soon rise to 100% and remain there. But the kettle will continue to release water vapour, which will condense on the walls and influence the room climate for hours after the water vapour source is removed. A chamber which just applies 100% RH has no way of knowing how much condensation is occurring.

The climate chamber needed for humidity buffering investigations must therefore control the flux and measure the RH, which is more or less exactly the opposite to the usual climate chamber and requires a fundamentally different design.

To conform with the scientific tradition for validating experimental results with theoretical calculation, or the other way around, this climate chamber has its theoretical doppelganger: a computer model that works in exactly the same way. The experimental chamber and the matching program are described in the next two chapters.

The different roles of the inner and the outer wall in humidity buffering

The inner walls of a building can be designed to function as a humidity buffer with a reasonably predictable performance. The daily buffering of the room climate involves only a thin surface layer of the wall, typically 10 mm., as shown in figure 1.11. A better performance can be obtained by perforating the wall to give a larger surface for diffusion.

The inner surface of an outer wall performs the same buffer function as an internal wall, but elaborate perforation of an outer wall will reduce its thermal insulation and increase the risk of condensation. The experimental investigation of an outside wall requires a double climate chamber, beyond the resources of this investigation. The theoretical study is also complicated. The outer wall of a building experiences both a temperature and a humidity gradient. Heat transfer caused by the temperature gradient is easy to calculate but the calculation of moisture transport caused by the humidity gradient is a more controversial matter. The gradient can be described in two units (at least), vapour pressure and relative humidity, which often have opposite gradients and therefore cause opposite flows of water.

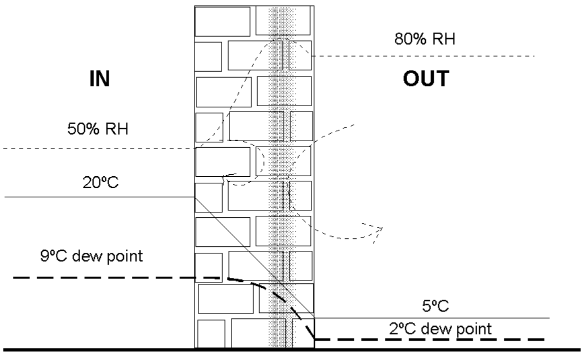
If the vapour pressure gradient is the effective influence, the outside wall will function as a slow dehydrater of the indoor climate, because the inside water vapour concentration is generally higher than that outside, so there will be a slow diffusion of water vapour outwards. The importance of this process, in comparison to dehydration by leakage, depends on the permeability of the wall and the leakage rate through definite gaps in the building. If, on the other hand, the potential driving the water movement is the relative humidity rather than the absolute humidity, there will generally be an inward drift of moisture. The magnitude will again be slight and difficult to measure without a specially built experimental arrangement. Hints that the process may be important come from studies of the climate in two churches, which are reported in chapter 6.

In any practical situation the effectiveness of drying, or wetting, by diffusion through the outer wall is tiny, unless the air change is rather small, as in a storeroom or a large church with small windows. The usefulness of porous walls lies more in their ability to buffer the indoor climate against sudden crises, such as leaving the kettle boiling, or as a moderator of the effects of the daily routine of a family's cooking and bathing. In an ordinary building one could envisage installing a vapour barrier in the outer wall at a depth from the inner surface that the room cannot "see" on this daily cycle. This would allow a complete decoupling of the requirement for buffering the indoor climate and the need to protect the wall itself against damage by condensation.

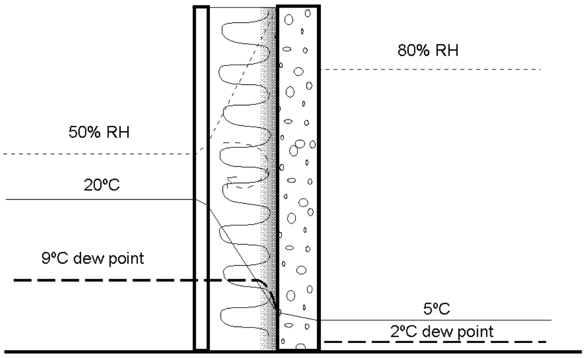
The doubtful practical value of vapour barriers, particularly in non-absorbent walls

All walls leak to some extent, whether they are officially designated as porous or not. Since the inside air is more humid than that outside there is a possibility that it has a dewpoint above the outside temperature. If this happens water will condense at some point within the wall, as the inside air diffuses through it.

Condensation in the structure of humidified buildings



A porous brick wall allows diffusion of water vapour into the outer air
Absorption of water vapour into the brick inhibits condensation



An internally insulated concrete wall suffers condensation close to the outer wall
Condensed water is not absorbed and drips down the inside surface of the wall

Figure 1.13 A porous wall (top) will absorb water vapour from air diffusing through from the inside. A non-porous wall (bottom) will not absorb water vapour and so the dew point of the air will remain constant until the air cools below the dew point and begins to deposit dew within the insulation and on the back of the concrete facade. Notice that the RH within the wall rises to 100% at the inner surface of the concrete. The RH within the concrete is undefined, because water diffuses so slowly through it.

A postulated advantage of porous walls is that they will absorb moisture from the air as it flows through the wall, so that the dewpoint falls as the air cools on its passage through the wall. The dew point at any given point will always be below the temperature at that point. The process is illustrated in figure 1.13 (top). The absorptive capacity of the wall is limited, so the added water must be lost in some way. Evaporation to the outside is one possibility, redistribution within the wall and evaporation to both sides will occur when the weather warms up. The balance between the processes which increase the water content of the wall and those which reduce the water content is subtle and opinion on the merits of the computer programs designed to calculate this balance is not unanimous.

The programs are certainly bad at predicting the effects of building faults, such as holes in the vapour barrier and cracks in absorbent materials. Holes in vapour barriers in a non absorbent wall can be expected to channel air into concentrated streams which will cause abundant condensation in particular places. Cracks in absorbent materials will also channel the air but the porous surface of the cracks can be expected to absorb and redistribute the moisture from the air. There is surely a case for introducing "fuzzy logic" into the presently available computer programs, as a polite way of accepting the inevitability of construction faults.

The role of absorbent insulation in outer walls and in roofs

Water absorbent insulation has very little buffer capacity, because there is so little of it, when the quantity is expressed as weight per unit area of wall. The actual material is only there to fix in place the air, which is the real insulator. Even this limited buffer capacity is useful in limiting brief periods of water release into the spaces within the wall. This usually occurs when sunlight warms the roof of a building.

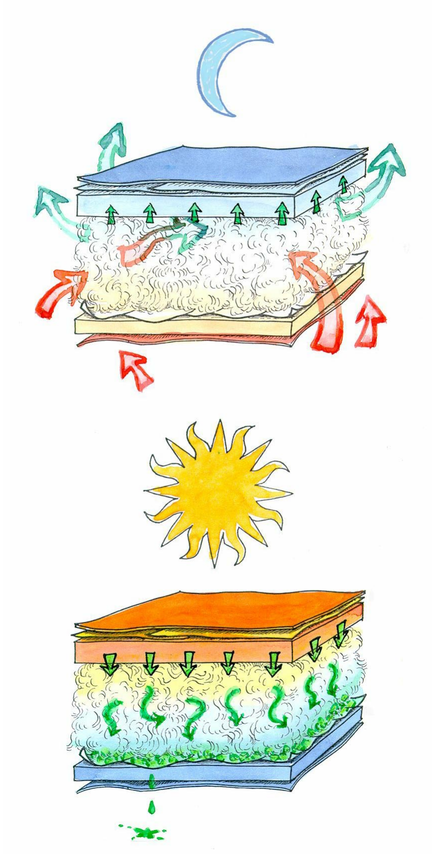


Figure 1.14 Distillation of water from a roof deck moistened by water condensed during the winter (top). On a sunny spring day (bottom diagram) the water will be distilled over to the relatively cool ceiling. The process can be reduced by absorbent insulation, or by impermeable insulation.

The process is illustrated in figure 1.14. During a cold night, and at intervals all through a long winter (top), water condenses from warm inside air drifting upwards through the roof. A roof deck of absorbent plywood will absorb this water without obvious symptoms. In the spring when the sun warms the roof (bottom) the water will be distilled rapidly from the plywood and diffuse through the insulation to condense on the cooler surface of the ceiling below. Absorbent insulation will absorb this moisture on its journey and thus reduce the amount of liquid water that forms on the lower surface, or prevent condensation completely, depending on the amount of water involved. This buffer action can only cope with a small quantity of water but that is all that can be released from a wooden roof deck in a short period.

Two products have been developed as alternatives to the standard air barrier to minimise damage by this kind of process. The "Hygrodiode" (18) is a porous membrane covered on each side with strips of impermeable material offset so that water can creep diagonally through the membrane. The other is a plastic membrane (19) whose permeability varies strongly with relative humidity so that it is quite permeable to water at high RH. Both of these products will transmit water condensed on the ceiling by this distillation process and allow it to evaporate to the interior. However, the same effect could possibly be obtained by using an absorbent ceiling material as well as absorbent insulation.

Neglect of humidity buffering by the building industry

It is astonishing that the ability of common materials such as paper, wood, textiles, even clay, to moderate the relative humidity indoors and within walls and roofs has not been exploited by the building industry.

In this thesis I present some systematic laboratory research into the microclimate around absorbent materials, together with case histories about real buildings which show the influence of absorbent building materials in moderating the indoor climate and preventing condensation damage.

The next three chapters describe the laboratory investigations into the absorptive and buffering properties of selected building materials. After that there is a chapter about moisture buffering in real buildings, describing examples of passive buffering and mechanically assisted buffering.

2

A CLIMATE CHAMBER THAT CONTROLS WATER VAPOUR FLUX

General design considerations

The climate chamber for testing the moisture absorbent properties of porous walls must be able to imitate the interior climate as it is influenced by the test wall. The chamber must be able to generate water vapour regardless of the prevailing relative humidity. This is what happens when we cook or take a shower. A few minutes inattention to the cooking can fill the kitchen with steam. An absorbent wall will mop up the water and moderate the relative humidity, which an impermeable wall cannot do: dew will form as drips on the surface. A climate chamber that defines the relative humidity cannot imitate this situation.

If we remember, we can switch on an extractor fan or open a window to reduce the high indoor water vapour concentration. The climate chamber must also be able to imitate this negative flux.

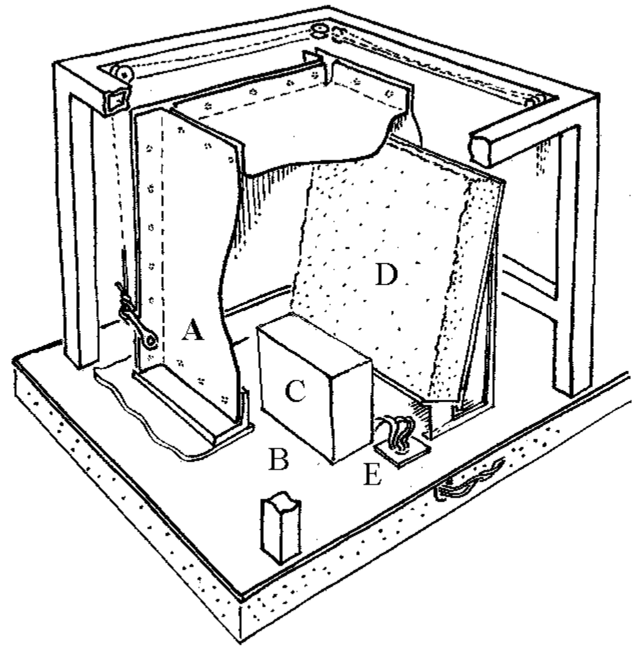


Figure 2.1 A cut away diagram of the experimental chamber. The scale is distorted to emphasise the main features. It is a stainless steel box ***A*** *without a base, that sits on a stainless steel plate* ***B****. Electrical and other services* ***E*** *are sealed through the base. The experimental wall* ***D*** *is tilted back on a support so that it can be constructed of loose blocks. The air conditioning equipment* ***C*** *is within the box.*

An orthodox climate chamber controls a potential: the relative humidity. A leak doesn't matter; the control system will notice a fall in RH and react to restore the set value by adding water, without caring what happened to the lost water. The climate chamber described in this chapter controls the quantity of water emitted into, or absorbed from the air. Leaks will destroy the accuracy of the accounting. The chamber must therefore be airtight.

A chamber that is intended to investigate convective processes within a test wall should be able to accommodate a slab of wall about one metre square. The wall might be up to 300 mm thick. The control apparatus should be within the chamber, to avoid problems with condensation caused by the different temperature outside the insulated, thermostatically controlled chamber. The air speed over the test wall should be adjustable, so there must be a reasonable space for air braking grids between the air conditioner and the test wall.

All these considerations lead to a design with a chamber volume of at least a half cubic metre.

A chamber that lifts off a heavy baseplate that extends well beyond the chamber will allow heavy, loosely piled up experimental walls to be prepared outside the chamber, then moved into place easily. The seal will extend all round the foot of the chamber, so the construction must be precise.

The chamber must also be built from non-absorbent materials so that the water is only absorbed into the experimental wall. If these conditions are fulfilled it is not necessary to weigh the wall itself. This is a great advantage, because the various test walls will be of very variable water absorption, weight and thickness, making it difficult exactly to measure relatively small variations in weight.

The chamber construction

Figure 2.1 shows the climate chamber with the design features emphasised. It is a stainless steel box without a base, that sits on a stainless steel plate which in turn rests on 100 mm of firm insulation ("Oasis"). Electrical and other services are sealed through the base. The experimental wall is tilted back on a support so that it can be constructed of loose blocks. The air conditioning equipment is within the box.

The sides are 1 mm thick, bent and spot welded to each other and to a L-section flange that forms the base. The seams are sealed with silicone. The seal with the base is a silicone skirt, 1 mm thick and about 60 mm broad. It flops down onto the baseplate under its own weight, giving a seal that is diffusion resistant but will not withstand a pressure difference. The seal is reinforced by pressing the skirt down with flexible tubes made from bicycle inner tubes filled with steel shot.

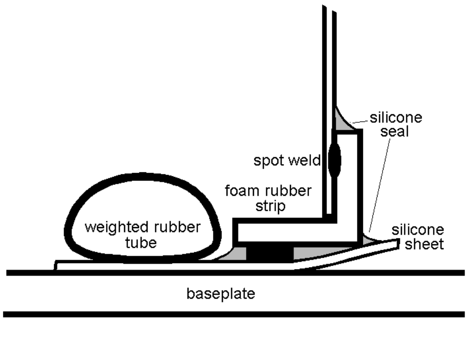


Figure 2.2 Detail of the seal. The flange around the base of the box has a foam rubber strip stuck underneath it. A wide silicone rubber strip is fixed to the flange with silicone sealant. The foam rubber gives space for the sealant and tilts the silicone so that it tends to press against the base plate. The seal is reinforced by weighted cycle inner tubes laid around the wide skirt which extends over the base plate.

The box can be lifted up within a frame of square aluminium tubes by cords attached near the base flange and brought over a system of pulleys to one point. Here the cords are attached to a tackle with a 4 times advantage.

Leakage tests, described in detail later, gave an exchange rate for water vapour corresponding to about one air change every ten days. The chamber cannot resist differential air pressure, so the natural atmospheric pressure variation will pump air in and out of the chamber. To reduce this leakage the box was given a pressure buffer system (figure 2.3). This was a double skinned polyethylene bag, about 300 x 200 mm in area, suspended over, and sealed to, a brass tube 300 mm long x 8 mm diameter, that extended from the top of the case. The bag deforms easily to take up volume changes caused by pressure or temperature variation.

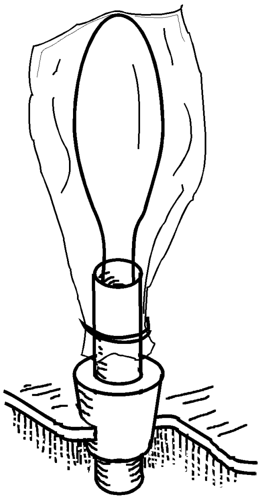


Figure 2.3 The air bag on top of the chamber which buffers pressure change

Air pumping caused by thermal expansion and contraction and leakage due to buoyancy of warm air is further reduced by placing the chamber in a room which controls its temperature with a precision of 0.2 degrees. The chamber itself is precisely controlled to about two degrees above ambient. The slight over temperature is necessary to ensure accurate control against the variable heat output of the air conditioning package within the chamber.

The empty chamber with its control apparatus has a certain water absorption. Tests on the empty chamber are described later. The error is very small for experimental walls of absorbent materials which are tested at around 45% to 65% RH, because the influence of the box absorption in this RH range is very small. Generally the RH variation was kept small, by using a large area of experimental wall, because the RH can be measured with greater precision than the other variables.

The water flux that must be provided

The environment of indoor structures will be nearly isothermal, between 15 and 25 degrees. The amount of water needed to change the RH of the chamber air from zero to 100% will be about 20 g/m^3. The amount of water that may be exchanged with the test wall is much larger. To get an order of magnitude, consider a wooden wall, 50 mm thick and half a square meter in area. This weighs about 12 kg and will exchange about 1 kg of water when the RH changes from 30% to 80%. The process is however very slow for this thickness of massive wood. Useful information about the behaviour of the wooden wall can be obtained with a smaller exchange: about 100 g of water.

The flux generator therefore needs to be able to control about 200 g of water. It should be able to release and absorb this water from air with an RH between 100% and 20% RH. The lower limit is set by the instrument used to measure RH in the chamber.

The flux should be able to imitate the release of water in a house. The worst case that I could measure is cooking a large pan of spaghetti, which releases a flux of about 20 g/(m^3.hr) into a small kitchen. The only source of negative flux is air exchange to the outside. A house at 20°C and 60% RH contains about 10 g/m^3 of water. Outside air at 5°C and 90% RH, a dreary winter day, contains about 6 g/m^3. So one air change per hour will move 4 g/m^3 out of the house.

Assuming a climate chamber of one half cubic metre, the flux generator should ideally be able to evaporate about 10 g/hr and condense about 6 g/hr.

The principle of operation of the flux generator

The design of the flux generator evolved at the same time as experiments were being performed. Only the final design is described here. Faults in the early designs caused some of the strange characteristics of graphs shown in chapter 4.

The principle of operation is that an open tank of water within the chamber is held at a temperature that causes water vapour to evaporate from, or condense into, the water surface.

The tank is weighed. The difference from the weight at the beginning of the experiment is water that has been gained or lost to the air in the chamber, which in turn equilibrates with the wall under test.

Design considerations

The most important concern is that all water added to, or removed from the air must pass through the surface of the water in the weighed tank. Condensation on, or evaporation from unweighed surfaces will ruin the performance. This means that the coldest part of the entire system must be the water surface.

The design should also look ahead to the development of chambers that can function at a variable temperature.

This can be achieved by having a large radiator within the chamber that can be warmed or cooled but must never be below the dew point of the air. On, or beside this radiator is mounted the weighed water tank. This tank normally operates at a lower temperature than the radiator.

The engineering challenge is to both cool and weigh the water tank.

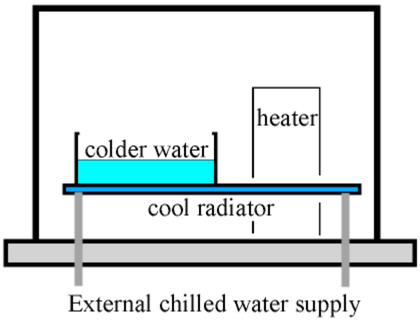


Figure 2.4 The two temperature principle in flux control: The horizontal radiator controls the air temperature, in competition with the heater. The cooler water tank condenses or evaporates water into the chamber.

More detailed design considerations

The water temperature in the tank must be controlled between about ten degrees above ambient, for rapid evaporation at high RH, to twenty five degrees below ambient, for absorbing water at low RH. It is possible to absorb water on an ice surface but the transfer of heat through ice is slow, because convection is impossible. It is better to use a solution of a hygroscopic salt, glycerol or sugar: materials that function as antifreeze but are scarcely volatile.

The addition of an antifreeze chemical has the additional advantage that it evens out the need for heating and cooling. This is best explained by pointing out that a sugar solution at ambient temperature is at equilibrium with less than 100% RH. This means that heating is necessary to achieve 100% RH and that less cooling is necessary to achieve a low RH than when pure water is in the tank. The disadvantage is that these solutions are viscous and therefore worse at conducting heat from the cooling source to the surface.

The water reservoir is weighed, so the cooling and heating must be applied without disturbing the weighing. There are two ways of doing this. One is to immerse a fixed cooling coil in the water (or solution). If the entry into the water is slim there will not be much interference with the weight through surface tension. The insulation must, however, extend below the water surface, or water drops will still accumulate on unweighed surfaces.

The other cooling method, which was the one adopted, is thermoelectric cooling of the bottom of the tank. A thermoelectric cooler (TEC), also called a Peltier cooler, is a device that uses the Peltier effect: the release of heat at the far junction between two dissimilar conductors when a voltage is applied to the near ends. The Peltier effect is the reverse of the Seebeck effect, which is the generation of a voltage between the ends of a pair of dissimilar wires joined at one end and exposed to a temperature gradient. This is the effect used in thermocouple thermometry.

Practical thermoelectric devices are made with semiconducting alloys of bismuth, antimony and other semimetallic elements. Many alternations of the two materials are arranged in series with all the cold junctions fastened to one thin ceramic plate and the hot junctions arranged on an opposite ceramic plate. A typical assembly is 40 mm square by 4 mm thick. If the hot side is held at room temperature by a heat sink and the cold side is insulated it can reach about minus 40 degrees. At this point the heat transfer backwards through the device, combined with ordinary resistive heating, prevent further cooling.

In practice it is feasible to cool a water tank thirty degrees below ambient, which gives a theoretical lower limit for absorption of water from air at 10 % RH. Since dewpoint sensors use exactly the same technology this limit matches the measurement technique used in the chamber.

Electric power must be brought to the TEC: 5 A at 12V at maximum cooling. This requires robust conductors but they must not interfere with weighing the tank.

The final design is shown in figure 2.5.

Construction of the flux generator

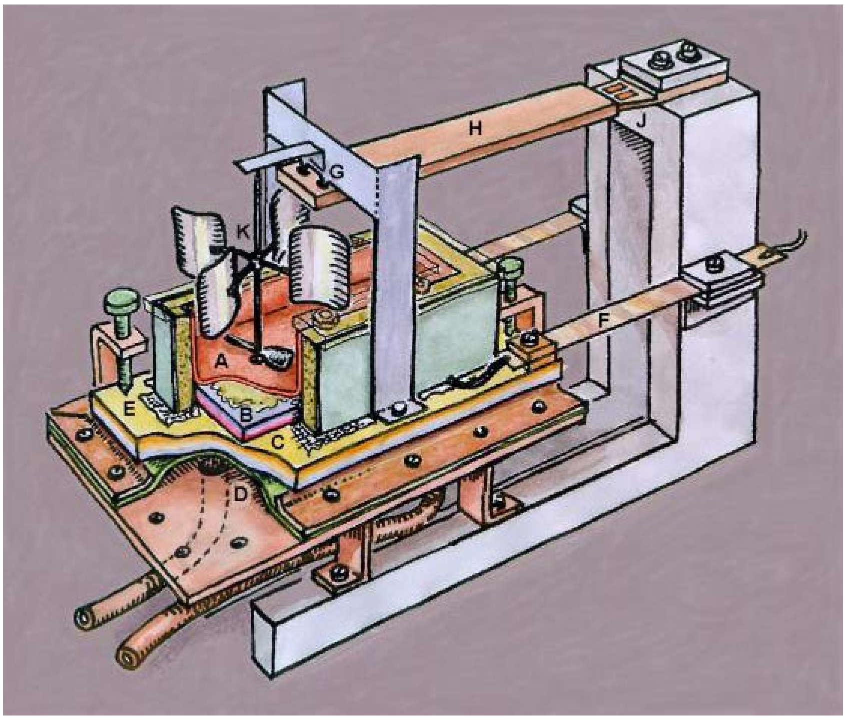


Figure 2.5 The flux generator. The device is 350 mm long. The cold water tank ***A*** *is made of copper and is clamped down over two thermoelectric coolers* ***B****. The heat sink for the coolers is the aluminium plate* ***C****. This is cooled by water circulating in the flat heat exchanger* ***D****. The top of the heat exchanger is a flexible silicone membrane which is pressed up against the heat sink by water pressure. The vertical displacement of the heat sink is limited by three screws* ***E****.*

Electric power is brought to the thermoelectric cooler through thin strips of springy stainless steel ***F****, which are clamped, through insulators, to the heat sink.*

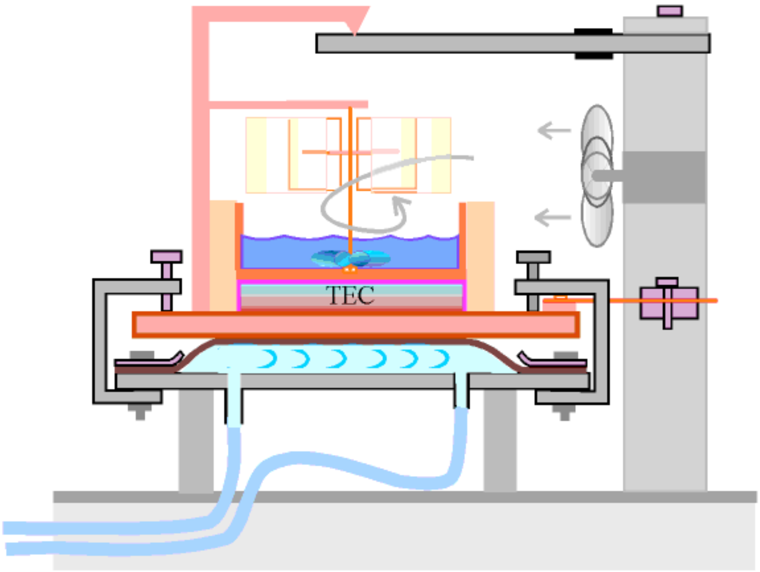
The entire assembly of heat sink, cooler and tank is weighed by suspension from a cantilever spring of hard aluminium alloy ***H****, whose deflection is measured by a strain gauge bridge* ***J****. The cooling water pressure is reduced during weighing so that the tank hangs free on the beam. It is constrained to vertical motion by the parallel motion system of the beam and the two steel springs, which are held in slight tension by the tendency of the tank to swing away from them.*

The wind driven stirrer ***K*** *circulates the water, which would otherwise achieve a stable stratification with the hotter water at the top, reducing the efficiency of condensation. The wind spilled from the stirrer blades brings air to the cold water surface.*

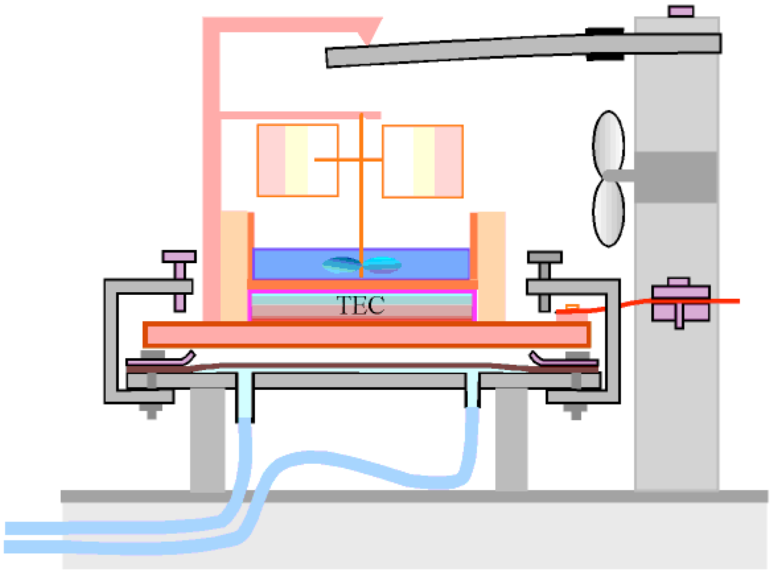
The weighing process

Once a minute the water pump and the air circulating fan are stopped. The membrane collapses clear of the heat sink, so that the entire weight of the reservoir assembly rests on the weighing beam. The process is shown in the diagram below.

Two stage water cooler
for controlling water vapour flux into a climate chamber



In normal operation the water pressure forces the membrane up against the heat sink of the thermoelectric cooler



When the water flow stops the membrane collapses and the reservoir hangs from the weighing beam

Figure 2.6 The weighing process. In normal operation (top) the pressure of the circulating cooling water presses a silicone membrane up against the TEC heat sink. When the water is to be weighed (bottom) the cooling water pump is stopped and the membrane collapses clear of the heat sink.

The point of contact between tank assembly and beam is exactly defined. The stirrup has two sharp points of stainless steel that point downwards and rest on the floors of two holes drilled 2 mm into the beam, which is 6 mm thick. Contact is maintained all the time. The springiness of the beam is an advantage here. Normally, one would use a stiffer load cell for measuring weights of about 1 kg.

The beam is 25 mm wide and has an unsupported length of 160 mm. The beam is thinned near the clamped end to 3.5 mm. The width tapers so that the sides at this point would, if extended, meet at the tip of the beam. This arrangement gives a uniform strain over the area covered by the strain gauges.

The strain gauges each have a resistance of 350 ohms. They are arranged as a full bridge, with two above and two below the beam. They are attached with epoxy glue and protected from water vapour by a thin layer of microcrystalline wax which is melted over the gauges and the fine wires that connect them. This wax gives perfect protection. The gauges show no change in signal with constant load and varying RH.

The gauges are however sensitive to temperature. In principle the bridge arrangement should compensate automatically for temperature effects but this is only exact if the bridge is without strain under the typical load. The gauges were mounted on the unstressed beam, so the approximately 800 g load of the reservoir and heat sink unbalances it enough for the temperature effect to be quite large. However, the chamber temperature is sufficiently constant for this not to be a problem.

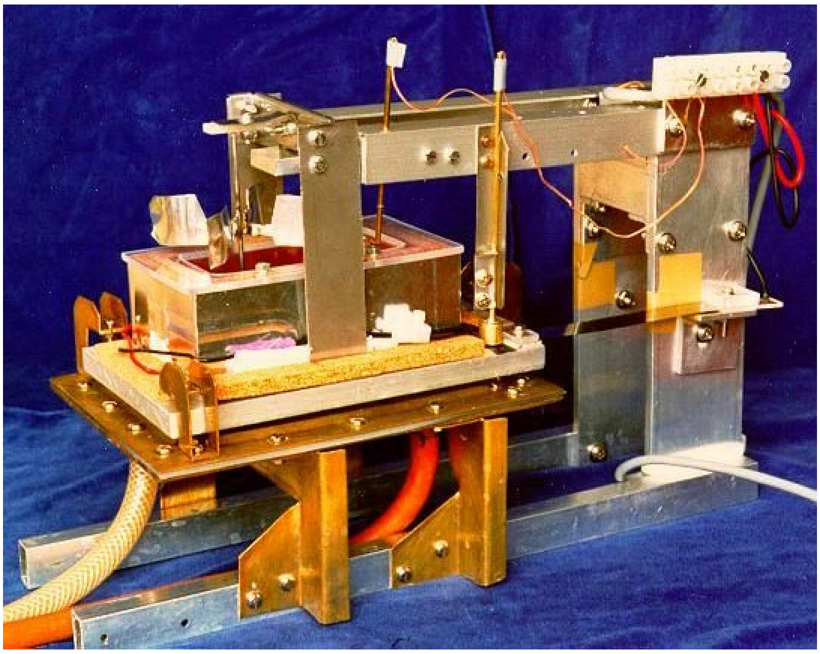


Figure 2.7 The complete flux generator. In addition to features already described, this photograph shows two rods descending from the top frame member that protects the weighing beam, whose tip only is visible. These rods hold thermocouples which measure the water temperature and the temperature of the heat sink. The heat sink thermocouple does not touch the surface but receives radiant heat focussed by a brass reflector onto its blackened surface. Its signal is used to check for failure of the primary cooling system, which would cause the thermoelectric coolers to overheat.

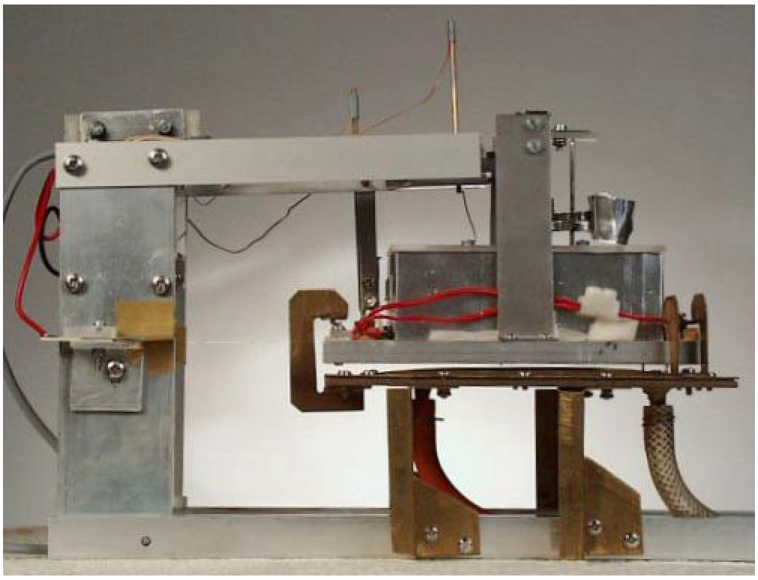


Figure 2.8 A side view of the apparatus with the cooling water stopped and the membrane collapsed, so that the water tank and heat sink hang free on the weighing beam. Notice the brackets with adjustable screws that restrain the upward movement of the heat sink when the membrane is expanded. These screws are adjusted so that the pins in the stirrup rise just clear of the beam, relieving it of stress and reducing creep. Photo: Christian Bramsen.

Measured drawings are in the appendix.

The primary cooling circuit

The cooling water serves two purposes. It cools the TEC heat sink as low as possible without causing condensation. Its pressure also holds the tank assembly firmly fixed in its frame until a few seconds before it needs to be weighed.

The cooling water, like the water in the tank, has a variable temperature. It is always controlled at one degree over the dew point in the chamber (the exact difference can be set by the operator) so that condensation cannot occur on the exposed parts of the primary cooling system.

The cooling water is held in an insulated reservoir outside the flux chamber. When its temperature rises more than the set difference over the chamber dew point temperature a valve opens to allow chilled water, at 6°C, to circulate through a coil of copper tube immersed in the reservoir.

Theoretically, it should be necessary to heat the reservoir water when the flux generator is heating the weighed water tank to evaporate water into a high RH in the chamber. The heat sink will then be cooling the circulating water. In practice enough heat is generated by the pump and by friction and heat gain from the room to ensure that the water temperature never falls below the chamber dew point.

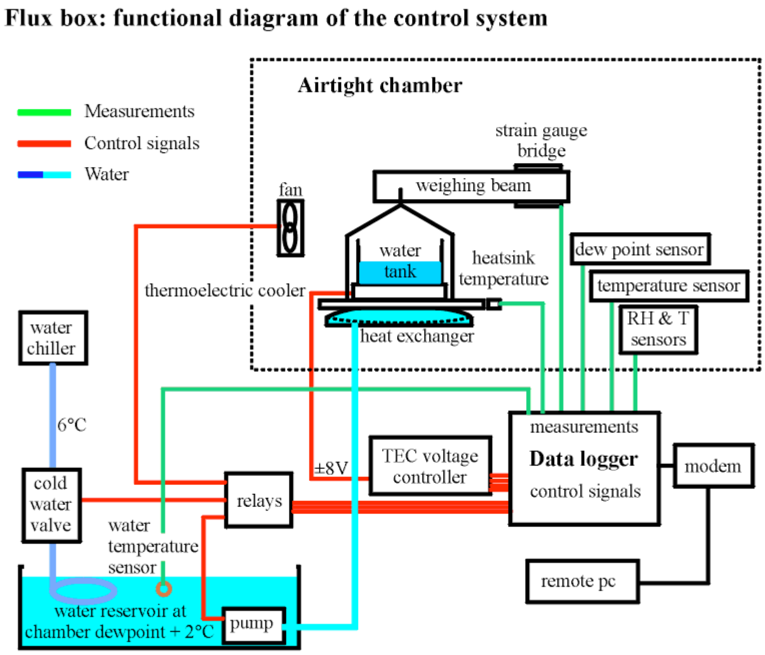


Figure 2.9 The control system for the flux generator. Sensors report the cooling water temperature in the reservoir and the dewpoint in the chamber. The datalogger controls a valve which lets even colder water cool the reservoir. The cooling water that runs through the experimental chamber is always above the dewpoint of the air in the chamber.

The diagram, figure 2.9, shows the control system. The reservoir is a standard laboratory water bath of about 7 litre capacity. The pump of the bath is used both to mix the water and to circulate it through the experimental chamber. The cooling coil is about 3 m of 10 mm diameter soft copper tube. It is connected to the house chilled water supply through a solenoid operated valve. The data logger operates the valve to keep the cooling water temperature a set number of degrees above the dewpoint in the chamber.

Controlling the temperature of the water tank in the chamber

The datalogger has preprogrammed instructions to calculate the intended weight of the water tank at any moment. The datalogger looks at the actual weight, compares it with the intended weight and calculates a voltage to apply to the thermoelectric device to cause evaporation or condensation to correct the weight. These control algorithms are described later.

Thermoelectric devices cannot be controlled by simply switching them on and off in a cycle, as is done with most control systems. The thermal cycling will fatigue the semiconductor device and shorten its life considerably. The TEC has to be fed a gently changing voltage. The data logger works out a suitable voltage, which is sent out as serial bits through an optical isolation stage. A shift register assembles the pulses into a parallel digital representation of the voltage. This is converted into a voltage by the digital to analog converter. A buffer amplifier adjusts the amplitude and level to suit the power control stage (1.2 to 10V).

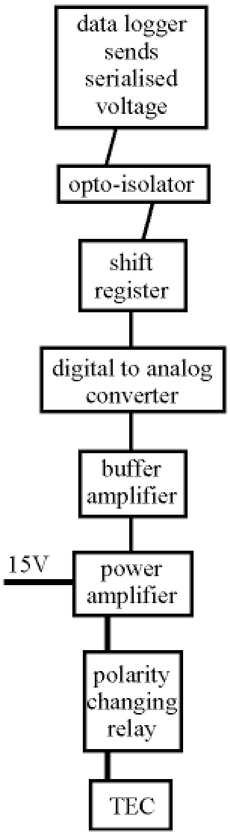


Figure 2.10. Block diagram of the train of instructions from the data logger to the thermoelectric cooler. The TEC takes a high current from a separate power supply, so the data logger control signal is sent first through an optical isolator to guard against electrical interference.

The data logger can only send out a digital signal. This is decoded and turned into a voltage. A buffer amplifier adjusts this voltage to match the characteristics of the power amplifier which controls the current through the TEC.

The final stage is a power MOSFET, which follows the input voltage with a constant difference. It provides the high current, at 0 - 8V required by the TEC. A separate signal from the data logger sets the polarity of the voltage: to make the TEC cool or warm the water tank.

The electronic circuits are described in an appendix. The data logger program is described later in this chapter.

Summmary of the flux control system

The water vapour flux into the chamber is controlled by the surface temperature of a ventilated water surface in a small tank within the chamber. This temperature is controlled by a two stage cooling process. The first stage uses an external supply of cold water which is held always just above the dewpoint of the inside air. This cold water supply cools the hot side of a thermoelectric cooler which pushes the temperature of the internal water container below the dewpoint, if condensation is required. If evaporation is required the thermoelectric cooler is operated with a reversed voltage, so that it heats the water tank (and cools the cooling water, which has such large heat sources in its circuit that it doesn't matter).

All parts of the instrument that can be below the dewpoint are weighed, so the amount of liquid water in the system is always known, and is always in the tank. The water in the original filling that has left the tank must be either in the air, where the amount can be calculated from the measured dewpoint and the known volume, or in the experimental wall. In this way the water content of the wall is known, indirectly, so that its performance as a buffer of humidity can be described quantitatively.

Temperature measurement and control within the chamber

All the experiments were made at constant temperature. Very good temperature constancy is important because a one degree rise in air temperature would cause the RH in the empty chamber to fall by about 3%. The RH within the test walls, however, increases slightly with temperature, because here the RH is controlled by the material. The relative progress of RH in the chamber and within the test wall will be difficult to interpret if the temperature is allowed to wander more than a few tenths of a degree.

The heat released into the chamber is rather variable. The primary cooling circuit, operating just above the dew point, tends to cool the chamber more as the RH decreases. The cooling effect of the water in the weighed tank reinforces this cooling effect. On the other hand the heat given off by the heat sink just under the TEC will tend to warm the chamber, depending on how hard the TEC is working. When the flux generator is evaporating water strongly at high RH the heat output to the chamber is large.

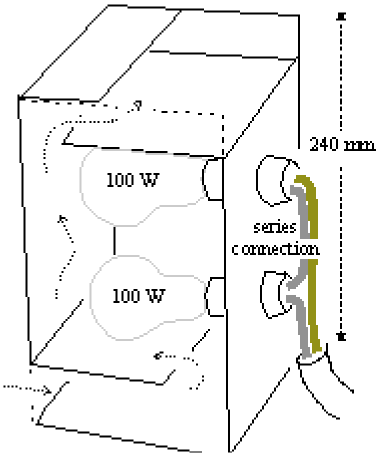


Figure 2.11 The chamber heater, cut away to show two light bulbs, wired in series to reduce their operating temperature and to increase their lifetime in a regime of constant switching. The case is designed to give good ventilation while allowing little light and radiation to escape.

The chamber temperature is controlled by a heater which holds the interior at 22.7 degrees, which is 2.5 degrees over the room temperature. Heat loss through the 1 mm stainless steel walls is enough to ensure accurate temperature control by heating alone.

The heater consists of a pair of 100 W bulbs wired in series so that they give much more heat than light. They are mounted in a stainless steel labyrinth designed to allow good air circulation with little light or radiant energy emission. Radiation towards the test wall is further reduced by a second screen of crumpled aluminium foil.

Air is forced through the heater by a fan mounted in a square metal tube. The 240 V supply to the lamps is controlled by a standard PID controller. This is a type of controller which adjusts the 'on' time during a cycle of, typically, one minute. This gives much more accurate control than a thermostat which only switches on when the temperature falls below a certain value and switches off again when the temperature exceeds a higher temperature, so that the temperature cycles within a "dead band".

The temperature is not under computer control, because it does not ever need to be adjusted. A copper constantan thermocouple within the chamber is connected directly to the controller. The chamber temperature is measured independently by a thermistor placed inside a copper block in the air stream entering the heater.

The dew point temperature within the chamber is measured by a thermoelectric sensor (General Eastern). This has a small mirror with a precious metal alloy surface which reflects the light from a light emitting diode (LED). The mirror is cooled by a small thermoelectric cooler. When the temperature reaches the dew point the water droplets on the mirror reduce the specular reflection of the LED into a light sensitive transistor. The power to the TEC is then automatically reduced until a steady state is reached with the mirror lightly misted and at the dewpoint. A platinum resistance temperature sensor just beneath the mirror is measured by the data logger. The dew point sensor is placed in the flow of air entering the heater. A loose cap over the sensor reduces the air velocity and functions as a radiation shield.

Other temperatures are measured within the chamber and outside. These are the water temperature in the tank and in the reservoir of the primary cooling water. The temperature of the heat sink under the water tank is measured as a safety precaution. In some experiments the psychrometric wet temperature was measured. All these measurements were made with type K (chromel-alumel) thermocouples. This type was chosen, rather than the more traditional type T (copper-constantan), because the metals are relatively poor thermal conductors, so that the temperature of the junction dipping into the water tank, for example, is not made inaccurate by heat conduction from the air above the water surface. The wires are also quite strong, so that very fine wire can be used, with a further reduction in heat flow.

All the thermocouples are connected to copper wires close to the copper block containing the thermistor which measures the air temperature in the chamber. The copper conductors connect to the data logger through a sealed hole in the base of the chamber. The data logger uses the temperature derived from the thermistor resistance as the reference temperature for the thermocouples, which only measure temperature difference.

The control software

The experiments are all conducted at constant temperature so the temperature is set by hand. All other activity in the chamber and its associated supplies is controlled by a Campbell Scientific data logger (Type CR10X). This data logger can be programmed in a rather primitive language which has standard instructions for processing most standard sensor measurements. It can also control other devices through a set of eight ports which can be set to 0 or +5V (TTL logic levels). The data logger can be programmed and milked for collected data either directly from a nearby computer or by telephone via a modem. This is rather useful because most of the experiments last about a week, need little attention after setting up and can therefore conveniently be checked remotely.

Various safety tests are programmed into the logger so that the most likely faults, such as failure of one of the cooling systems, can be prevented from damaging the apparatus.

The processing of the signals from the various sensors is quite standard, except for the RH measurements within the test wall, which will be described later.

The essential measurements and control settings

The measurements that the data logger needs in order to control the system are the weight of the water reservoir, the temperature and dewpoint in the chamber, the circulating water temperature, and, for safety checking, the heatsink temperature.

The user-defined data that the logger needs are the weight cycle for the reservoir. This is defined as a cycle time in hours, a half amplitude in grams and a waveform: triangular or sine.

There are several other parameters that the user must define: the offset between dewpoint and cooling water temperature, the smoothing constants for the reservoir temperature control (discussed in detail below) and a correction factor for weight calibration.

The logger ensures that the weight of the reservoir follows the defined cycle. It does this by noting the time, and working out the target weight of the reservoir. It then looks at the actual weight and adjusts the voltage applied to the TEC to compensate for the error, by cooling or warming the water. The details of this process are described later.

Finally, the logger checks for overheating of the TEC, to which it responds by setting the TEC voltage permanently to zero and setting an alarm flag for the operator to notice.

A typical experiment

The graph in figure 2.12 shows the course of a typical experiment. The chamber temperature and relative humidity are shown in the two upper curves. The other curves show the various control values: the water temperature, the cooling water temperature, the heat sink temperature, the voltage applied to the TEC and the intended and measured weights.

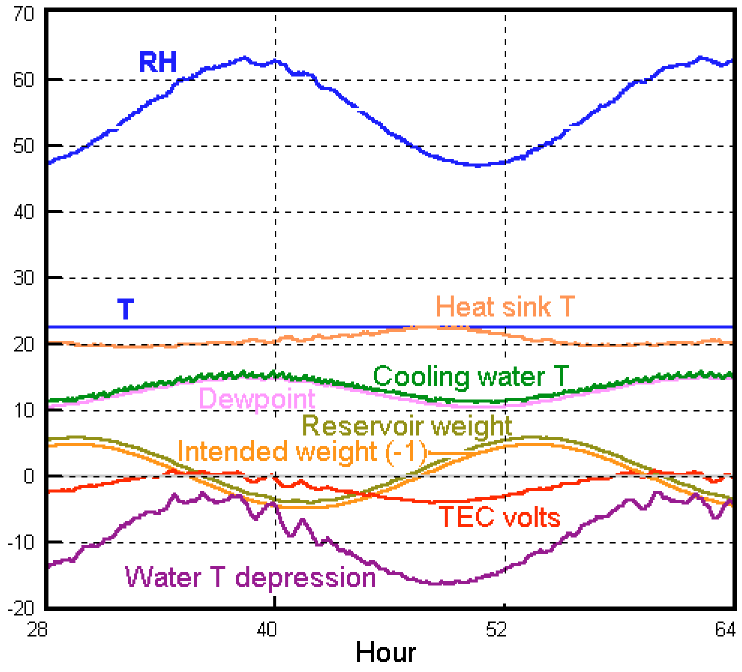


Figure 2.12 Graph of the control signals. The values of variables used to control the chamber are shown for a typical experiment. The intended weight and the reservoir (tank) weight are separated by one unit for clarity. The water tank temperature is expressed as the depression below the ambient temperature.

The actual weight follows the intended path so closely that the curves are artificially separated on the diagram.

The oscillation in the RH curve shows up the limitations of the control algorithm at cycle times of one day or less. The controller has to cope with considerable inertia in the temperature of the water, an ever changing set value, and an unpredictable RH, which is controlled by the absorptive power of the experimental wall, which the controller can know nothing about in advance.

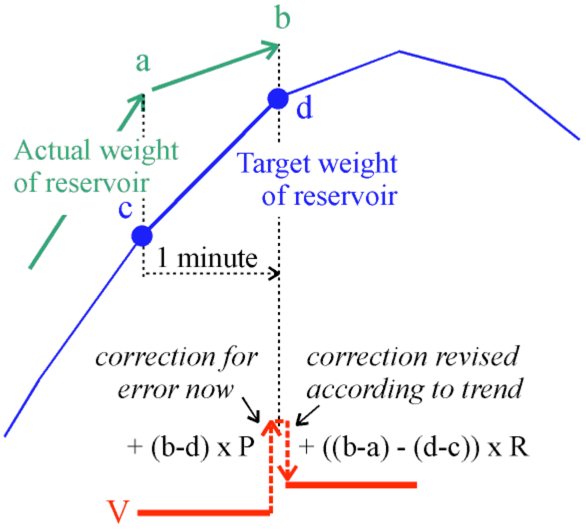


Figure 2.13 A diagrammatic explanation of the control algorithm for the thermoelectric cooler. Time is moving from left to right. A portion of a sinusoidal curve of intended water weight is shown with two solid circles indicating two successive control calculations, one minute apart. Below the curve, the expression on the left is the correction for the instantaneous error. This gives a large rise in voltage (more cooling). However, the error is less than the previous error a minute before. The expression on the right is the correction for the rate of approach to the correct weight. This reduces the correction suggested by the immediate error. The result of these two calculations is sent out as a serial signal to the voltage controller described earlier.

The control algorithm for the thermoelectric cooling is shown in figure 2.13. In the first calculation the absolute difference between actual and intended weight is used to raise the existing voltage, in this example, because the reservoir is too heavy, so water must be evaporated away. This can be regarded as a combination of proportional control with a measure of integration, because the existing voltage is the result of previous calculations.

This correction alone would cause oscillations about the correct value. A damping signal is added by calculating that the weight, in this example, is converging towards the correct value. The first correction is therefore partly reversed to anticipate, and delay, the crossing of the curves.

Each of these two corrections includes a user-set multiplier. These can be adjusted by experience as the run proceeds, to give a relatively smooth graph.

This is clearly a task that needs an intelligent program which learns about the performance of the wall as the run proceeds! Such a program is beyond the capacity of the data logger to store and maybe beyond the capacity of the author to write. The oscillations seen in figure 2.12 have no significant influence on the scientific results.

The control sequence

The controller is activated once a minute. The data logger stops the fans and the water pump. It waits eight seconds for the air to become calm and for the rubber membrane to collapse clear of the suspended water tank. It then measures the strain on the beam and calculates the weight. The error is computed and the new TEC voltage is calculated as described above. This voltage is sent to a controller as described earlier. The fans and the water pump are then re-started and the data logger sleeps for the rest of the minute. Once every five minutes the data logger records in its permanent memory the average values for several calculated and measured parameters. An annotated example of the control and measurement program is included in an appendix on the CD-ROM.

The performance of the chamber

The limitations to the accuracy of experiments conducted in the chamber are set by air leakage to the room and by water absorption on the interior surfaces. Imprecisions in measurement and calibration of the various sensors are minor problems in comparison with these fundamental limitations.

Residual absorption is shown in figure 2.14. The measured RH swings much less than that predicted from the actual weight of water in the tank and the standard properties of moist air. Notice that the actual RH leads the theoretical value. This confirms that there is some residual absorption which causes the RH to bounce back quicker than expected as the flux is reversed.

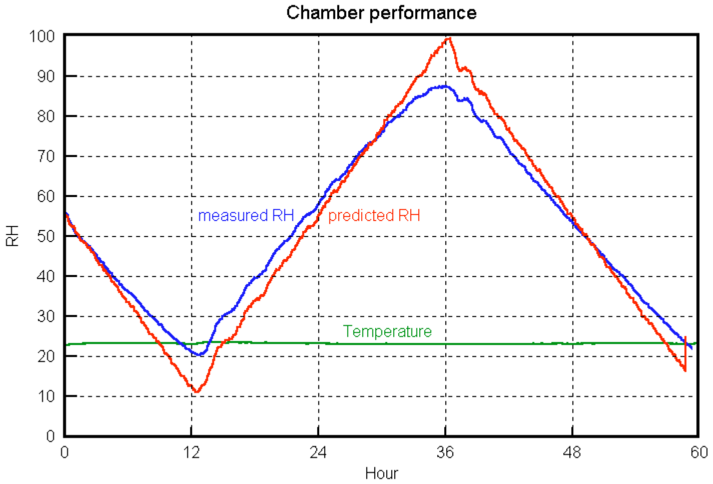


Figure 2.14 The measured RH in the chamber, compared with the RH expected for an inert chamber.

This graph demonstrates that RH buffering is a universal phenomenon! The surface area of materials in the chamber is quite large because of the intricacy of the equipment. Some parts are slightly water absorbent. There are aluminium parts for heat sinks and beams and also for some components which would be difficult to form in stainless steel.

The materials of the bought components, such as the dew point sensor, cannot be chosen for low water absorption. Further reduction of the water absorption would require considerable extra effort.

Above 85% RH the measured RH curve flattens out, giving a very rounded peak. 80% RH is the practical limit for experiments in the chamber. The rounding at the lower end of the RH range further limits the linear range to 30% - 80% RH.

The leak rate of the chamber

The leak rate is shown in figure 2.15. The actual RH is the wavy line. The smooth curve is an exponential best fit, assuming an end point at the 59% RH ambient condition. The air exchange rate is once per 12 days. The RH comes more steeply up to the exponential curve at the beginning of the test. This is certainly due to buffering of the RH by interior surfaces. The fit to an exponential curve becomes closer as time passes. There is still some buffering, so the real air exchange rate is somewhat faster, maybe around ten days. More accurate data could be obtained by using fluorinated trace gases but this is unnecessarily elaborate for the experiments that were performed in the chamber, which involved much more effective RH buffers and short cycle times.

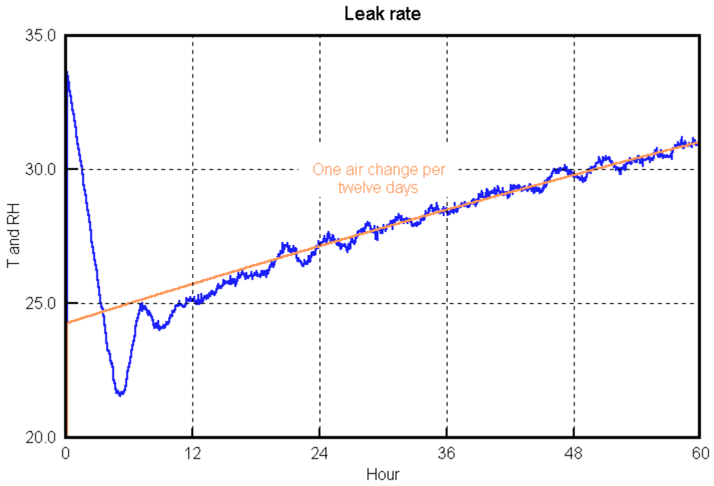


Figure 2.15 The drift of RH caused by air leaking between the case and the 59% RH in the room. The wobbly curve is the measured RH. The smooth curve is the exponential fit with a half time of 12 days. The dip in measured RH at the beginning is caused by instability of the control system when the forced downward trend of RH is suddenly stopped.

The accuracy of flux control can be judged from the deviations from a straight line shown by the 'predicted RH' curve in figure 2.14. The instability is worst when the flux is suddenly reversed. The measured RH line in figure 2.15 also shows a regular cycling. These errors are due to imperfect tuning of the proportional control. The response to the instantaneous error and the error trend is adjusted by the operator, who has two constants to play with. These two settings depend on the load, that is on the buffering by the test wall. In practice one setting was arrived at by trial and error on a moderately absorbent wall and then used for all experiments. The instability is insignificant when the test wall is present to buffer the RH in the chamber. Improvement would require two fundamental changes in the apparatus. The correction algorithm could be refined, which would require replacing the data logger with full computer control. The programming language of the data logger is too primitive and the number of instructions that it can hold is too small to allow subtle manipulations. The strain gauge weighing system would also need to be changed to a professionally made load cell, as used in balances. The beam system weighs to 0.1 gram precision. An improved control algorithm could use 0.01 g precision to get a more reliable indication of the trend of the error.

The measurement of RH within the test walls

Many of the experiments described in later chapters report values of RH in small cavities hollowed out within the experimental wall. Some of the values are a long way from theoretical predictions, so it is important to know the performance of the sensors with considerable accuracy.

There is not much choice of sensor for this job. The sensor must be small and it must not absorb water in amounts that compete with the processes it is measuring. There are two types of small RH sensor, apart from exotic experimental devices. The resistive sensor is a wafer of polymer with a surface coating that absorbs water according to the RH and becomes more, or less electrically conductive. Capacitive sensors detect the presence of absorbed water through its influence on the capacitance between two porous electrodes plated on the surface.

Figure 2.16 The General Eastern RH sensor. It is about 10 mm high. The base is coated with a thin layer of a water absorbent polymer. The resistance between the two gold electrodes is measured.

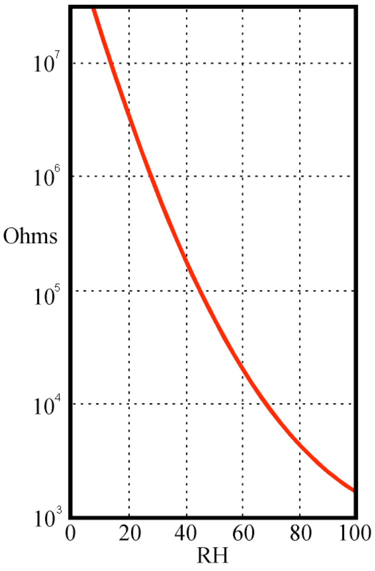


Figure 2.17 Characteristic curve of the General Eastern RH sensor. The resistance varies nearly as the logarithm of the logarithm of the RH.

The capacitive sensor can be obtained with on-chip electronics but resistive sensors are cheaper and have some advantage in precision over a small RH range.

For this job a resistive sensor from General Eastern was chosen. It is shown in figure 2.16.

The variation of resistance with RH is very large. It is shown in figure 2.17. The data logger provides a pulsed voltage to the sensor. Constant current will cause electrolytic processes in the sensor and destroy it very fast. The resistance is measured by a simple bridge circuit.

It is linearised over the RH range of the various experiments by using a resistor network as shown in figure 2.18.

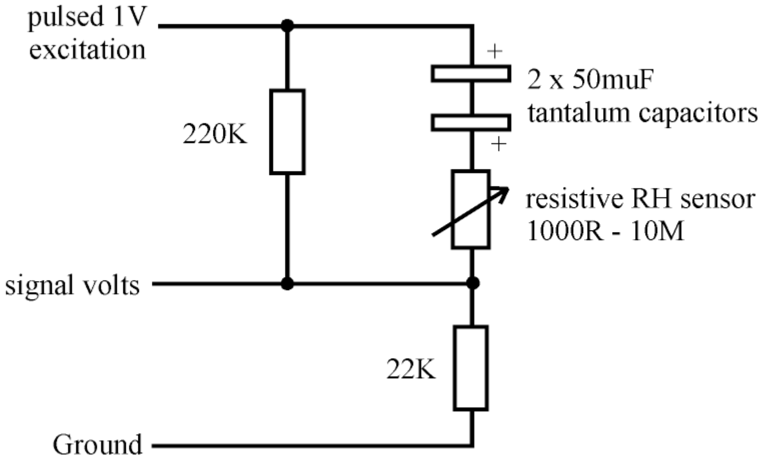


Figure 2.18 The circuit which linearises the voltage - RH curve of the sensor. The two capacitors are to block direct current, which will destroy the sensor.

A team of four sensors is permanently installed ready to probe various parts of the test wall. The sensors are individually calibrated in the display software by applying a multiplier and offset to the raw results from the data logger bridge circuit. The calibration is shown in figure 2.19. Between 40% and 65% RH the sensors and the dew point meter give identical readings. Beyond these limits the sensors can still be used but require extra manipulation of the signal in a spreadsheet program. Most of the experimental runs lie within the limits of linearity of the circuit.

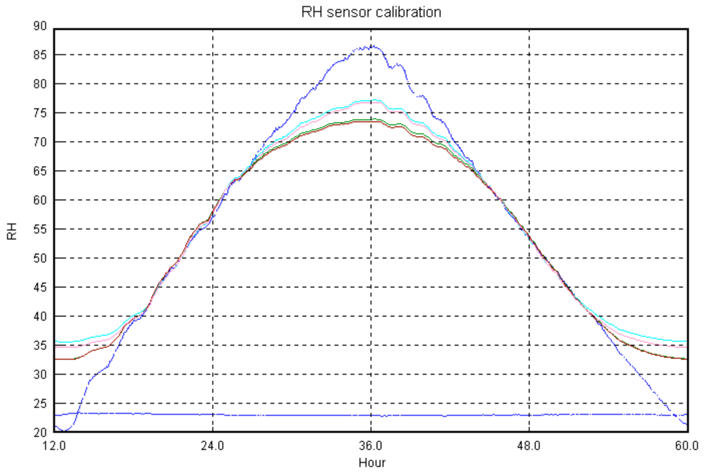


Figure 2.19 A comparison of the RH indicated by the dew point meter (the curve with the greatest amplitude) with the RH given by four polymer resistance sensors. The values all agree closely between 40% and 65% RH

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Notice that there is negligible hysteresis; the agreement between the RH from the sensors and the RH from the dewpoint is the same going up as coming down. The sensors are very precise, because they give a very large signal and are therefore very suitable for showing the tiny variation in RH deep within a water absorbent test wall. The response time of the sensors is very fast compared with the rate of change of the RH within the specimens, even though they were sometimes wrapped in permeable plastic to protect them from powdery materials.

The air flow over the test wall

The air in the chamber is moved around by the fan which blows air over the flux generator. The air stream is directed downwards to optimise several processes. The water stirrer is pushed round by the spiral air flow at the edge of the airstream. The main air stream scours the inside surfaces of the water tank. It also plays on the heat sink, providing a little extra cooling, particularly when the TEC is working hard. The stirrer blades and the tank impede the flow and disperse the air so that the air flow at the test wall beyond is quite uniform, though turbulent, with an average speed of 0.2 m/s. This is at the high end of the acceptable indoor air speed. More would be regarded as a draught. This air speed is about right for this experiment, where the surface resistance is a hindrance to accurate measurement of the properties of the absorbent wall. On the other hand the air speed is not unrealistically fast.

The air speed was measured with the chamber in normal operation. A slim hot wire anemometer on a long rod was inserted through the hole normally occupied by the neck of the pressure buffering balloon. The air speed was measured in a grid at about 50 mm from the wall surface. The variation from place to place was 0.3 m/s opposite the fan to 0.2 m/s at the farthest edge of the wall. These values were measured with a 6 second time constant. The instantaneous measurements showed turbulent conditions with the air speed varying from 0.04 to 0.4 m/s.

The complete chamber for controlling water vapour flux

Figure 2.20 shows the complete chamber open, with a test wall of mud bricks

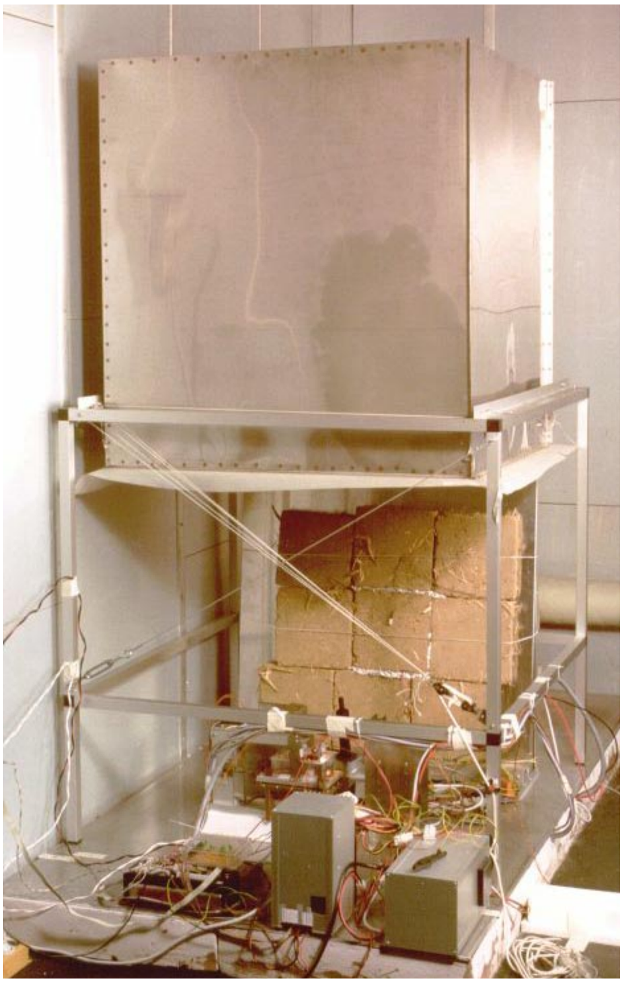

Figure 2.20 The flux controlling chamber with a wall of stacked mud tiles. The middle tile contains buried sensors. The flux generator and the heater are in the middle distance. In the foreground from left to right: the data logger, the voltage controller for the TEC and the temperature controller. The white object on the right is the insulated water supply to the heat exchanger.

The usefulness of the flux chamber in materials research

The reader may by this point be wondering if the flux chamber was worth the trouble. It is much more complicated than an orthodox RH chamber. What can it do beyond what a RH chamber can?

The purpose of the exercise was to investigate what happens when various sources force water vapour into a room with abundant absorbent materials. The water will absorb into the walls according to the RH gradient between the room air and the boundary layer next to the wall surface. However, in this enclosed environment the RH gradient is itself defined through this absorption process. The flux chamber is therefore the only direct way to investigate the processes influencing indoor climate.

A double flux chamber, with the experimental wall sandwiched between the chambers, would be even more useful, providing fresh information that cannot be obtained by conventional means. The flux through a wall subjected to a difference of both temperature and humidity can only be investigated by a system that measures the quantity of water transmitted, and the quantity received on the other side. Such a chamber does not appear in this thesis. I do however present data which hint at the need for such a chamber.

It seems therefore worthwhile to review the qualities and faults of this prototype and suggest how the performance could be improved in later versions.

A review of the performance of the chamber

The chamber has proved very reliable, needing no repairs over its year of operation in its final form. The principle of using thermoelectric cooling backed up by water cooling to near the dew point works well and solves the main disadvantage of the TEC: its inefficiency, with consequent overheating of the chamber. The principle could be used to give up to ten times the flux rate of this chamber without requiring substantial change in design. The chilled water could also be driven through a large cooling radiator, controlled by an independent valve, to allow operation below ambient temperature. This is an important consideration in a double chamber designed to imitate the outer wall of a house.

One serious miscalculation was the construction of the chamber. It should be really airtight, not just resistant to diffusion without pressure difference. The chamber was made by spot welding thin stainless steel plates to each other and to a more substantial L section frame at the bottom. The heat of welding distorted the structure so that the base of the frame was not plane. At one corner there was a gap of 2 mm between the box and the baseplate that it rests on. This gap was filled by the silicone elastomer used to provide the seal, but the variable thickness of elastomer gave uneven pressure on the baseplate and thus allowed flow of air under very low differential pressure. In retrospect the box should have been bolted together or glued with epoxy. The seal at the base should also have been a proper O ring seal with closely spaced screws holding the box to the base plate.

The other weak link in the design is the weighing beam. The strain gauge bridge is working at the very limit of attainable precision. The electrical interference, unavoidable in a research institution with masses of electrical machines, limits the weighing precision to 0.1 g., even with repeated weighing at each measuring interval. This very moderate precision does not affect the interpretation of the experimental runs but it spoils the accuracy of the flux control, because the datalogger/controller needs to have good information on the rate of approach to the set value. A professionally constructed load cell would give much more accurate information for the control calculation and allow use of control algorithms that would more quickly suppress oscillations of the water vapour flux.

The condensing power of the water tank could be improved. It turns out that most condensation occurs on the copper sides. A high water level markedly reduces the condensing efficiency, in spite of vigorous stirring. It may be that copper fins should stick up through the water surface to ensure uniform performance as the tank fills.

The heat exchanger is too small. The silicone membrane blows up to touch only an area of the heat sink that is about equal to the area of the TEC. The heat sink reaches 40°C when the TEC is working hard. The area of contact with the water chilled membrane needs to be several times as big.

Other uses for the flux chamber

The flux chamber can be used as an orthodox RH chamber. The temperature of the water tank is adjusted to maintain a constant dew point reading from the sensor. The sorption isotherm of materials can then be found by stepping the RH and measuring the water absorbed or lost by the water tank at each step. Similarly the water vapour permeability can be measured by mounting the test material over a tray of saturated salt solution and running the chamber at a fixed, different RH. The rate of change of the tank weight at constant RH would then give the permeability of the material. The chamber could in fact have been used to measure all the hygroscopic material properties used in this thesis but the flux experiments used all the available time so these static properties were measured in more orthodox instruments, as described below.

Other instrumental techniques used in this research

The sorption curves of some of the experimental materials were measured by weighing them after equilibration with the atmosphere over various saturated salt solutions. The full isotherm was not determined because nearly all experiments were confined between 70% and 40% RH. Most of the sorption data were determined in a RH chamber in which a dry and a saturated air stream were mixed. The streams were switched by a proportional controller which took its signal from an electronic RH sensor which was in turn calibrated against a dew point sensor. The weight of the specimens was determined by hanging them from a balance which was mounted above the chamber. At the moment of weighing a clear passage was briefly opened for the thin connector between specimen and balance.

Water vapour permeability was measured by the "cup" method. The experimental material forms the lid of a container which is filled to 15 mm from the underside of the test material with a drying agent, water or a saturated salt solution, according to the RH region for which the permeability is to be measured. The upper surface is ventilated by a constant velocity air flow at 50 % RH, measured by a chilled mirror dew point sensor and a platinum resistance temperature sensor. The cup is weighed at intervals. The permeability is calculated from the rate of change of weight when the system has reached a steady state.

The methods described above measure the equilibrium value for absorption and the steady state value for permeability. The results from the flux chamber are in principle able to give both the absorption curve and the permeability from dynamic tests at different frequencies. However, data from the flux experiments gave very different values for the permeability, and lesser differences for the sorption. This matter is discussed in detail later.

3

MODELLING MOISTURE MOVEMENT

The reason for modelling

Computer models of moisture movement are used in three different contexts in this thesis. A simple isothermal model is used as a companion to the chamber experiments, allowing testing of theory against measurement, and extrapolation of short experiments to longer times. A more complicated model, which includes heat transfer, is used to predict the performance of alternative air conditioning systems that co-operate with climate buffering materials. This model is also used to explain the idea that moisture movement through outer walls is driven mainly by the relative humidity gradient.

There are several published programs for modelling heat and moisture movement through walls. Inexplicably, none of them include the indoor climate in the calculation. The person running the program sets the indoor temperature and RH as boundary conditions for what happens in the wall. Since my purpose is to investigate how walls influence the indoor climate I had to write the programs myself.

Another reason for modelling as well as measuring is that there is some doubt about the correctness of predicting rapidly changing conditions using absorption and permeability properties of materials obtained under equilibrium or steady state measurements. The results from a computer model which is fed the static properties of the materials can be compared with the dynamic experimental results. Alternatively, the dynamic material properties can be obtained by optimising the fit between theory and experiment.

The description of the programs begins with the isothermal model and then explains the extensions needed to cope with a temperature gradient.

Basic concepts

The computer simulation uses the general method known as Finite Element Analysis. The experimental system: weather, room, and wall, is divided into slices. Each slice is regarded as homogeneous. Water is transferred between the slices according to set rules for a brief time. After each cycle of transfers the state of each slice is updated and then the process is repeated. The division into slices is made so fine grained that the step in water content from one slice to the next is small compared with the total variation over all the slices. The time interval between iterations must also be small, to ensure that the slice which is subjected to the greatest change in water content is not forced to an extreme water content where the rules of exchange between slices are no longer valid.

The exchange of water between slices is based on Fick's first law: that the flux of moisture through a porous material is proportional to the concentration gradient. As the moisture penetrates the pores under this driving force it is absorbed into the surrounding material according to the equilibrium described by the sorption curve.

In this simple version of the model, the equilibration of water with the material is assumed to be instantaneous in each slice, so the dispersion of water into the heart of the material is limited by the resistance to diffusion. There is some evidence that this is a naive assumption. Wood, in particular, is thought to absorb water rather slowly from the vapour diffusing through the cell cavities (14).

The model includes the inside climate as an active participant in the game. The inside climate can generate a moisture flux but not a relative humidity. That is forbidden because the porous wall contributes to the moisture content of the room, so the RH cannot be a quantity defined by the person running the program. In this way the model follows the design of the climate chamber described in the previous chapter.

The published descriptions of models that have been used as inspiration and guidance for this, much simplified version, are listed in references (15,16,20).

The choice of language and programming style

The computer model is intended to provide insight into the physical processes at work and to allow "what if ..." calculations with different material constants, as well as speculative changes to the algorithms to see if one can achieve a better fit to the chamber results. It is not meant to be a tool for designing walls, in competition with established heavyweight programs such as MATCH and WUFI.

It is important that such a program should be designed from the start to be naturally immune to side effects whereby an alteration to one action has unintended, and maybe never discovered, effects on other calculations. One way of improving the resistance to side effects is to use simple algorithms, as close to the underlying physics as possible. Another technique for achieving natural immunity to side effects is object oriented programming. This is a concept which will not be discussed in more detail here, except to explain that the underlying idea is to encapsulate the processes and data for each layer in the model wall within an object which cannot directly be altered from other parts of the program. Objects can only influence each other by sending messages through the filter of an interface. There is no single array of data values which can be freely updated by various procedures scattered around in the code.

These considerations led to the choice of Java as the programming language.

The program is kept simple and easy to change as ideas develop. This means that there is no elegant mathematics to speed up the calculations, and no convergence tests. The process plods along at the simplest possible level, made possible by the speed of modern computers. The check against wild values forming transiently in a slice because of too long a time between iterations or too thin a slice is left to the person running the program: the slice dimensions and iteration time are varied and the results are checked for consistency over a range of values.

This means making many trial runs. For this reason, and also because of the many graphs of experimental runs, a graphing program was written specially for this project.

The basic physics of the model

The numerical ingredients in the model are the diffusion coefficient used in Fick's first law and some approximation to the slope of the sorption curve, for calculating the water absorbed at each point through the material. Both of these constants are known to vary with water content. However, the main purpose of this program is to model the interior walls of houses, which are usually operating in the middle of the RH range. I have therefore assumed constant coefficients.

The question of what really is the potential which drives moisture diffusion is ducked by making the whole process isothermal, so any unit will do.

Finally, one more constant is necessary. This controls the rate of entry of water vapour into the wall. The diffusion rate through the wall surface is calculated from a fixed surface resistance.

A systematic description of the program

The wall

The wall is divided into slices parallel to the surface. The movement of water between the slices is controlled by the concentration difference (the vapour pressure difference is the quantity actually used) between adjacent slices operating against the resistance to diffusion of the material. This movement is summed over a short time, just a few seconds. Water enters the first slice from the room at a rate determined by the surface diffusion constant. At the same time some water is being lost to the next slice, according to the concentration difference between the two slices. The action then moves down through the layers to the back of the wall. Then the state of each slice is updated by taking the net gain of water, adding it to the water already present and equilibrating this water with the material, according to the water capacity. This generates a new equilibrium RH which, together with the temperature, defines a new water vapour concentration which is used in the next iteration.

That is all there is to the physics. The program structure is also simple. Each slice is an object which contains its own constants (diffusion and sorption coefficients, density) and state (water content) in variables which, once the starting state has been constructed, can only be changed by that object's own functions.

There are just two important functions belonging to each slice. One looks at the state of the adjacent slice 'upstream' (towards the room) and the state of its own slice and calculates how much water will move across the boundary between them during the specified time interval. It then sends back to the adjacent slice a message stating the amount of water it has taken. The other function receives this message from the next slice downstream and then updates its own slice's state.

The transport of water between the slices is repeatedly calculated, using only two constants: the diffusion constant through the material and the water capacity of the material (which is just the absorption isotherm simplified to a straight line).

The wall is divided into as many slices as are needed to give a stable calculation. The calculation always goes through the wall from the inside towards the outside.

The weather outside and the climate in the room

The weather and the room are represented by specialised slices. Two further constants are needed here: the leak rate of outside air into the room and the surface resistance between room and wall. The surface wall slice notices that the upstream slice is the room and uses the surface resistance, which is a property of the room, to calculate the water flow, rather than its own material diffusion constant. It is merely a container for water diffusing in through the surface resistance. The function that updates the state of the wall slice does, however, use the static properties of the wall material, such as its water capacity. This anomalous surface slice is made thin, so that the distribution of water with depth is hardly distorted by the odd behaviour of the surface slice. The diffusion coefficient of the wall material is first used when moving water from the surface slice to the next slice.

The order of the calculations

In this cascade of calculations each object looks 'upstream' at the previous object to decide how much water will stream into itself. Alternatively, each object could look downstream at the next object and decide how much water to pump out into its neighbour. The two treatments are, I think, equivalent. I have chosen the first because the message about how much water is received by each object is sent back after the focus has passed from the upstream object. It can then update itself without risk that the result can affect this round of the calculation.

The cascade starts again with the room leaking in some weather. The weather then updates itself by looking at the time and deciding where it is in its endless cycle. It could also easily be programmed to look up its values in a file, such as a test reference year.

The room has an extra function which allows it to add water to itself, or take some away, according to a user set cycle time and amplitude, precisely as in the experimental chamber.

The program controller and the starting data

The controlling object calls on each slice in turn to activate its diffusion calculation (described mathematically later). The last action of this diffusion function is to send back to the previous slice the amount of water taken, thus causing the previous slice to update itself. The program controller takes care of the return to the top of the cascade. It knows the calculation time interval, when to write intermediate results to a file and when to stop.

The user loads the material data into the wall slices and instructs the calculation controlling object how frequently to run. This is achieved through a user interface which is also programmed in Java, using a RAD (Rapid Application Development) program called JBuilder (Inprise corp., formerly Borland). This part of the program manages a database of starting data which is loaded into the objects before the controller is let loose on them. It is a complicated and uninteresting part of the program which is not described here.

The advantage of this way of programming is that one can make a new type of object called wood, for example, which appears to its neighbours just like the wall slices described above but has a completely different way of updating itself.

The program in more detail

This section deals with the next level of detail in the programming: the class definitions and the calculation algorithms. The program code is listed in an appendix. The scientifically important code, which is very brief, is marked by bold type. A narrative explanation of these short code sections is given below. The formulæ are written out without use of symbols. This is partly because the expressions are not manipulated further, so there is no real need for symbols. Furthermore, the program code uses names rather than single character symbols, so the equations listed here are easily identified in the program code.

The class *Slice* defines variables common to all types of slice: weather, room and wall. This class also declares, but does not define, the two calculating functions, called *diffuse* and *update*. *Slice* is an abstract class which cannot be used directly but can only serve as the base for deriving more specialised classes. The various classes derived from *Slice* are described later.

The starting states of the slices of the model building are constructed from a file of starting data. The program then calls the *update* function for the weather. Then it calls the *diffuse* function of each slice in turn, passing as parameters the address of the previous slice and the time interval. The *diffuse* function works out the water movement into the slice from the previous slice. When it has finished it calls the *update* function of the previous slice, informing it how much water it has taken in.

After the last slice the program starts again with the room slice and cascades down through the wall slices. The weather is included at the end, in the case of an outside wall. This cycling continues for the preset number of hours. The state of the slices is written to a file at an adjustable interval, typically every hour.

The calculations

The description starts with the behaviour of a typical wall slice and then describes the special behaviour of the weather and room classes.

Diffuse, for a wall slice, calculates the flux streaming in from the previous slice. To do this it takes the vapour pressure of the previous slice and its own vapour pressure, thickness and diffusion coefficient. These values are inserted into Fick's first law to derive the flux into this slice. Flux into the wall from the chamber is regarded as positive.

flux = time × diffusion coefficient ×
(vapour pressure of previous slice - vapour pressure in this slice) / thickness

Diffuse finally calls the previous slice's *update* function with the flux as parameter.

The *update* function for this slice, which is called by the next slice downstream, adds to the pre-existing water content the flux which the slice received from its previous slice and subtracts the flux lost to the slice downstream, which it has just been told about. The slice then recalculates its RH, using the water capacity:

New RH = water content/(water capacity × density × thickness).

The water capacity is in units of kg/kg/(100%RH).

The new vapour pressure, and other climatic variables, are calculated from the RH by standard climate calculations, available as static functions in the class *Cmath*. (A static function can be regarded as a utility, available to any other function in the program) and listed in normal mathematical symbols in an appendix.

This calculation set: -{ flux into this slice, update previous slice }- , cascades down from slice to slice.

This is the basic pattern. The object oriented approach ensures that the physical state of each slice can only be altered by that slice's own *update* function. Its current vapour pressure is only *shown* to the next slice and the amount of water taken from it is *reported* in a message from the next slice.

The driving force in this model is vapour pressure difference. This is not controversial because the model is isothermal. It makes no difference how the water content is expressed, because all forms: vapour pressure, concentration, relative humidity, are equivalent.

The specialised derived classes

There are different *diffuse* and *update* functions for the various sub-classes. These are explained below.

The weather slice (class *Weather*) is the start of the cascade. Its *update* function calculates the weather according to a pre-set cycle. It ignores the flux returned as the parameter. Its *diffuse* function is similar to that of the wall slice, with the surface resistance instead of the material resistance.

The room slice (class *Room*) has a *diffuse* function that calculates a constant leak rate of air from the previous slice, which is usually the weather.

water in = leakrate × iteration time × volume ×
vapour pressure recalculated to kg per cubic metre

'Water out' is calculated similarly, using the room vapour pressure. Finally:

flux = water in - water out

A further peculiarity of the room's *diffuse* function is that the room itself is equipped to generate a water vapour flux, independent of the outside weather, to imitate man-made water sources. This can be a constant or cyclic flux and is calculated much like the weather.

The wall slice (class *Wall*) has a *diffuse* function that first enquires about the type of the upstream slice. If it is of type *Room* it uses this calculation:

flux = time × vapour pressure difference × room diffusion coefficient

Notice that the path length is not used in this formula. It is built into the room slice's 'diffusion coefficient'. This flux is therefore the water passing just into the surface of the first wall slice, taking no account of slice thickness. The wall's *update* function does however use the thickness and so the water is correctly 'distributed' through the slice. (This treatment of the surface is a bit clumsy. Maybe there should be a separate *Surface* class characterised by zero water capacity, but this complicates the programming considerably and breaks the uniformity of the present structure).

The next wall slice notices that its upstream neighbour is of its own type and uses the standard calculation in the *diffuse* function:

flux = time × vapour pressure difference × diffusion coefficient / thickness

The first wall slice should be thin, because it does not contribute to the resistance of the wall.

A rapid iteration time, typically ten to thirty seconds, is needed to prevent the thin surface wall slice from acquiring too large a change of RH in one iteration. The program does not check that each movement of water is infinitesimal, so each construction must be checked for stability by running it with different time intervals. The simplicity of the program is compensated by the speed of modern computers.

The program that models combined heat and moisture transport

A computer model that includes heat flow is used in chapter 6 to predict the performance of a museum storeroom. Heat moves through the wall in an exactly analagous way to moisture. Heat moves at a rate equal to the temperature gradient multiplied by a diffusion coefficient, called the thermal conductivity. After the heat has moved into a slice it reacts with the material according to the heat capacity, to cause a rise in temperature. This is programmed in a very similar way to that described earlier for moisture movement.

There is a link between heat and moisture movement. This is illustrated in figure 3.1.

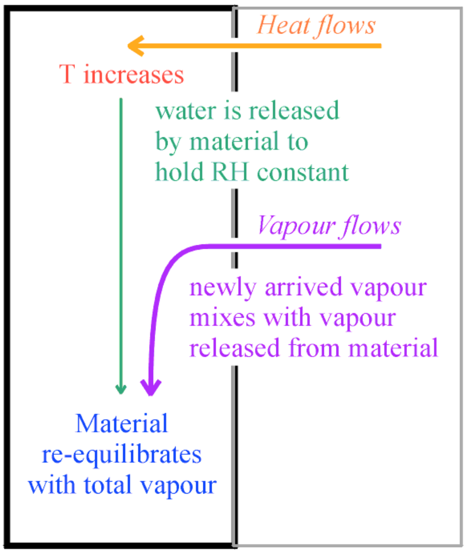

Figure 3.1 One slice of the wall, showing both heat and water vapour moving into the slice from the slice to the right. After the heat flow has raised the temperature the material releases water, to maintain a constant RH (because the RH equilibrium of absorbent materials is nearly independent of temperature, depending only on the water content). Water also moves into the slice by diffusion from the right. These two sources of water are added together and then re-equilibrated with the material to give a new value for the water content of the material, and a new value for the vapour pressure in the pores.

The explanation given here is strictly formal. There is no attempt to give a microscopic description of what is happening. The space available for mixing the vapour is the whole volume of the slice, which is also occupied by the material. This is unrealistic but makes no significant quantitative difference with absorbent materials. As explained in chapter 1, the water content of the material entirely dominates the space around it and asserts almost the same equilibrium RH over a large range of ratio of pore space to solid. This trick eliminates the need to know about the pore volume and has the programming advantage that the large mixing space reduces the chance of the RH going to extreme values.

The situation within mineral insulation, such as glass fibre, can also be modelled safely using this assumption. The ratio of absorbent material to surrounding space is now much smaller but the model is closer to the physical reality.

This model is also different from the isothermal model in other ways. It is used to simulate buildings in the landscape, so the outer surface of the wall reaches close to 100% RH. The constant water capacity has to be replaced by a proper sorption curve. The diffusion coefficient is also strongly affected by the RH at the high end. The diffusion through the surface is affected by wind speed, though this can be averaged. These complications led to restriction of the program to working with wood, with the isotherm and moisture coefficient derived from functions hard coded into the program. It was not therefore possible to use the program for the varied materials and laminates investigated in the climate chamber. It was in fact written several years ago, using a core of methods developed by Poul Jensen (21) for investigating the drying of timber. His model had been tested against the measured drying of wood so I have re-used it, only adding routine functions for calculating the effects of leakage and of mechanical air conditioning processes.

Capillary movement of water

The two commercial programs mentioned earlier, MATCH and WUFI, include capillary movement of liquid water as a transport mechanism which dominates at high RH. The program just described does not treat capillary movement separately. It includes the measured variation with RH of the water vapour permeability in wood as an alternative way of treating the matter.

My general approach has been to use measured parameters, without enquiring at all deeply into their physical meaning. The model programs are not the main subject in this thesis. I have used them to extrapolate experimental results and to test alternative interpretations of measurements in buildings. The programs are just intended as an aid to designing further experiments and as a guide for developing measurement strategies in real buildings.

4

EXPERIMENTS IN THE FLUX CHAMBER

Introduction

The flux chamber was used to measure the ability of materials, and combinations of materials, to buffer the relative humidity of an enclosure against the effect of a varying flux of water vapour.

The usual procedure was to evaporate about ten grams of water into the chamber air and then withdraw it again in a sinusoidal cycle of, typically, one day's duration. If the chamber were empty, this flux would cause the relative humidity to cycle between about ten and 90%. An absorbent material within the chamber will diminish the amplitude of the relative humidity cycle because there will be a redistribution of the water between the air space and the material. A material with a steep sorption curve, that is with a rapidly increasing water content with rising RH, will absorb much of the water released into the air and thus prevent the RH from varying much.

The other factor that influences the chamber RH is the permeability of the material: if it is very permeable it will be more effective in buffering the RH as water is injected into the air, because the storage capacity of a greater thickness of material will be available to buffer the RH.

A relatively minor influence on the chamber RH is the resistance to water vapour transfer of the boundary layer of air right at the surface of the wall.

The cyclic variation in RH measured in the chamber during the flux cycle is an expression of the combined porosity and absorptive power of the material, or assembly of materials, in the test wall. These two independent factors can be separated, in principle, by running the experiment with different cycle times, because the absorption curve is independent of time.

A complicating factor is the RH dependence of both the absorption and the permeability. This can in principle be studied by increasing the amplitude of the applied flux cycle or, more simply, by running several successive flux cycles of small amplitude, starting from a higher or lower average RH value.

A further complication is that there is some evidence that the permeability is time dependent when the flux is varying.

There are experimental limitations to the cycle time, the flux amplitude or the mean chamber RH. The flux generator has a limited ability to withdraw water vapour from the chamber. The chamber has a small leak rate to the room which limits the cycle time to about five days. The dew point detector has a 15% RH lower limit and the RH sensors that were embedded in the test walls are imprecise below about 25% RH. Finally, at high RH the surfaces of the walls and equipment in the chamber begin to compete with the absorption by the test wall. These practical limitations are discussed in detail in chapter 2.

Construction of the test wall

Figure 4.1 The interior of the chamber. The air conditioning assembly is on the right. On the left is the material under test: in this example it is wool insulation faced with vapour retarding paper and backed by aluminium foil and polyethylene film. The wires leading to RH sensors within the wool can be seen entering the far edge of the experimental wall. One of the small resistive sensors is seen dangling in front of the face of the assembly.

All the test materials are put into the chamber as walls, tilted slightly back to allow safe stacking of the individual pieces without any binder.

The ratio of surface area to chamber volume was chosen with care. A vast area of very absorbent material will absorb a large flux without the RH of the chamber changing by an amount that can be measured with precision. A small area of poorly absorbent material, on the other hand, will allow the same water flux to swing the RH to such extreme values that the results will be spoiled by the water absorption of the materials that the chamber itself is built of. A standard flux and exposed area of material would allow rapid visual comparison of the performance of the various materials. Finally the chamber should imitate a plausible combination of material area, air volume and water production in a dwelling, so that the graphs would show instantly if the material were of any significance as a moisture buffer.

The compromise wall area used for nearly all the experiments was about one third of a square metre of exposed surface in the 0.5 cubic metre chamber volume. The ratio was not defined exactly because some test constructions occupy more volume than others.

The back of the wall was sealed by aluminium foil and by thick polyethylene sheet. The experimental setup imitates the performance of the materials when used as interior walls of buildings, in double the quoted thickness. The performance of the outer walls, with their varying temperature gradient, requires much more elaborate equipment. In this dissertation the humidity buffering processes occuring in outer walls are illustrated by case histories from real buildings rather than by laboratory experiments. Some insulating materials were, however, included in the laboratory tests.

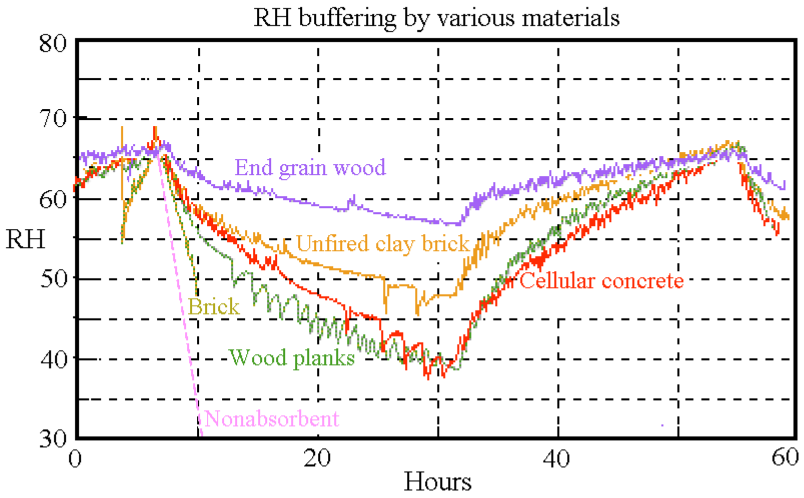

Figure 4.2 A comparison of several building materials, built as walls 0.5 m^2 by 30 mm thick, sealed on the back. The jagged curves are due to intermittent release of water from a condenser to the weighed water tank in an early version of the flux generator. This fault was corrected in later experiments. The curves are extracted and assembled from a series of experiments in which each material in turn was exposed to repeated cycles in which water was withdrawn at a steady rate for 24 hours and then returned to the air in the chamber at the same rate. The RH change is buffered by desorption and then by re-absorption of water by the materials.

The choice of materials for testing

The first experiments in the chamber were designed to find the order of magnitude of the buffer performance of a range of building materials. Figure 4.2 combines data from five materials, each tested separately. The materials were built as walls, 0.5 m^2, 30 mm thick and sealed at the back. The starting equilibrium RH for all materials was between 58% and 68%. In the graph the separate experimental curves have been superimposed so that they all start at about 65% RH, for easier comparison.

Water vapour was withdrawn from the chamber at a steady rate that would bring the empty chamber from 100% to 0% RH in twelve hours. The theoretical curve for the empty chamber is shown as the steep dotted line descending at the left. Brick is not much better at giving out moisture to buffer the fall in RH than a totally nonabsorbent material. Brick is quite porous and becomes quite absorbent at high RH but at these moderate values it has hardly any water absorption. Wooden planks are surprisingly bad at buffering the RH. This is because they have a very low permeability to water, though the water capacity is high. Cellular concrete has a moderate buffer capacity. Its permeability is high but its capacity is not great: notice how the curve is straightening out as it crosses the curve for wood towards the end of each leg of the cycle, indicating that its capacity is becoming exhausted, while wood still has a water reserve available which is being drawn out by the high RH gradient at the surface. Unfired clay brick is much superior to burnt brick as a humidity buffer but the best buffer of all is wood cut across the grain so that the high permeability in this direction can release the high water capacity of the wood.

Other materials and combinations were tested in later experiments but the set described above covers the range of observed buffering by massive materials. One absorbent insulator, wool, was also tested. It has a high permeability and high water capacity per kilo but the density of wool insulation is so low that it has a limited buffer capacity in practice.

In real life the surfaces of these materials exposed to an inhabited room would be decorated and protected against becoming dirty unreasonably quickly. These finishes increase the surface resistance to moisture movement and suppress expression of the behaviour of the material behind. The use of moisture barriers or retarders in outer walls also prevents absorbent materials from influencing the indoor climate. The performance of lime and gypsum plaster and vapour retarding paper was studied but paint was not included in this study.

Reporting the results

The experimental settings changed according to the material. In particular the position of RH sensors within the material varied from wall to wall, according to thickness and layer structure. For this reason I have abandoned the traditional separation of experimental results from discussion of their significance. The structure, behaviour and performance of each material or assemblage is discussed in turn, in a qualitative way, at the point where the experimental curves are shown. Then there is a page summarising the test results for all the single materials, exposed to a daily cycle. In the next chapter selected data from this catalogue of buffer materials are discussed in more detail. Exact values of sorption and diffusion coefficients are given. Finally the experimental results are compared with results from computer models.

The typical flux cycle

The left half of the graphs in figure 4.2 shows the course of the climate within the chamber during a linear withdrawal of water vapour into the water tank, while the second half shows a corresponding return of water vapour to the chamber air. Most of the graphs reported in this chapter were, however, obtained with a sinusoidal variation in flux.

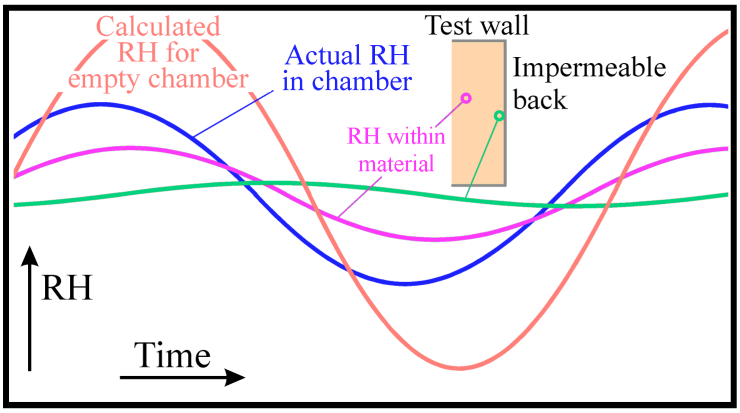

Figure 4.3 An explanation of the typical appearance of the graphs in this chapter. The widest cycle is the RH calculated from the flux acting in the empty chamber. The next curve is the measured RH. The shallower curves show the RH in cavities hollowed out in the experimental wall.

This provides data that can be studied by models based on an electrical analogy. On a more mundane level, it is much easier to control a sinusoidal variation in flux than the sharp change of flux at the points of a triangular waveform.

The flux cycle imposed on the chamber was usually chosen to give a nearly 100% RH swing over one day in the empty chamber. This basic daily cycle imitates the daily rhythm of both climate and human activity, but runs were also made with longer and shorter cycles to provide data for the computer simulations designed to separate the influences of absorption and diffusion. In these runs the flux was usually adjusted so that the maximum rate was the same, regardless of cycle time.

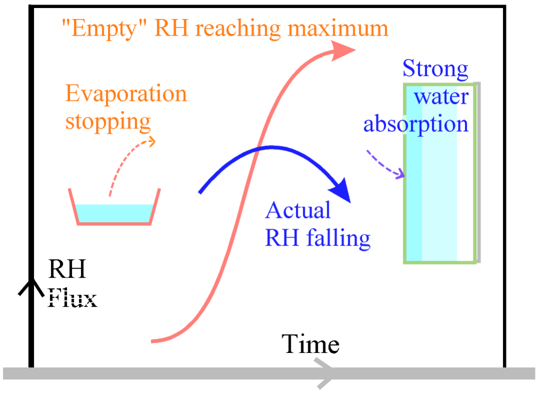

Figure 4.4 An explanation of why the buffered chamber RH cycles up and down in advance of the RH calculated for the empty chamber. In the diagram the cycle of the chamber climate has been frozen just as the weight of the water reservoir reaches its mimimum. This, in the empty chamber, would coincide with the maximum RH. However, the flux has been slackening for some time before the peak RH is reached, while the absorption of water vapour into the test wall is still strong, because of the still relatively high, though diminishing, RH in the chamber. The absorption rate into the material exceeds the slackening flux well before the top of the "empty" RH curve, so the buffered RH is already on the way down before the calculated "empty" RH reaches its peak.

The RH measured within the material lags behind the chamber RH, as expected, because of the relatively slow diffusion of water into the depths of the wall.

In nearly all the graphs in this chapter the imposed flux cycle is presented in the form of the expected RH in the empty chamber. It is always the most extreme fluctuation. The observed, buffered RH in the chamber is the next in amplitude. A comparison of these two curves gives an immediate visual impression of the ability of materials to moderate relative humidity. The RH at various depths within the test wall is often shown in other, shallower, curves. Without exception the deepest RH shows the smallest amplitude.

Most of the graphs show just one daily cycle, after the system has settled to a steady rhythm. Sometimes, however, the approach to the steady cycle reveals interesting details of the process, in which case more cycles are shown. Usually the hours elapsed from the beginning of the experiment are shown on the horizontal axis, even though only one day's data is shown.

The daily cycle is the most relevant. Passive humidity buffering by wall materials in ventilated buildings cannot overcome the influence of the outside climate in the long run, which means about a week. The response of materials to two and four day cycles is, however, displayed in some graphs in this chapter, because it shows up the different performance of materials according to whether they have a high water capacity or a high permeability.

Accuracy and precision of the measurements

Contrary to received wisdom, the dew point sensor that measured the chamber RH was less reliable than the resistive RH sensors embedded in the materials under test. Wood products, in particular, release easily condensable vapours that deposit on the cold, damp mirror of the dew point sensor. The indicated RH could rise by 4 percent over the two or three weeks required to make a test in the sealed chamber. The mirror was cleaned and the calibration checked each time the chamber was opened. Even so, a detailed comparison of the chamber RH with the RH within the material is not really possible. This experimental problem points to a fundamental problem with the use of building materials to moderate indoor relative humidity: the slow ventilation rate that is necessary for them to function increases the concentration of pollutants outgassed from the materials. This is a serious problem in museums as well as in climate chambers, because the water soluble materials that cause a high indicated dew point on the chilled mirror are precisely the chemicals that absorb water and facilitate the corrosion of metals.

Fortunately, the resistive RH sensors used within the test material, and sometimes as a check on the dew point drift, proved very robust and extremely sensitive to small changes in RH, which is all that ever happens inside good moisture buffers. The combination of the accuracy of the clean mirror dew point measurement with the reliability and sensitivity of the resistive sensors ensures the overall good accuracy of the data.

The sensors buried within the wall occupy a space about 10 x 15 x 5 mm deep. The cavities enhance the diffusion of water vapour while the sensors obstruct it. The sealing in of the sensors also leaves cracks and inhomogeneities that are not typical of the material as a whole. The signals from these sensors cannot therefore be assigned to a precisely defined depth in the specimen.

The assumption of constant temperature is not quite true. Rapid changes of flux cause warming, or cooling, of the experimental materials through the heat of vaporisation of water. Temperature changes of up to half a degree were measured in some experiments deliberately run with high flux. These small, temporary temperature differences account for some anomalies in the fine structure of the observed RH within specimens, but the assumption of constant temperature does not introduce significant errors in interpretation.

The buffer performance of wood cut across the grain

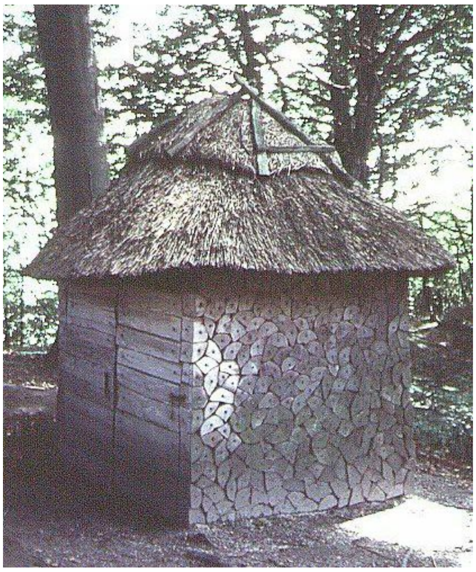

Figure 4.5 A small shed in the eighteenth century pleasure garden at Liselund on the Danish island of Møn. Sadly, the end-grain wooden wall is a sham: thin slices are nailed onto planks.

The catalogue begins with tests on wood used in an unusual way, emphasising the unused potential in common materials.

A panel was made of many blocks sawn from a plank of Norway Spruce, *Picea abies*. These were stacked with the cross section facing into the chamber. The exposed area was 0.33 m^2 and the depth was 30 mm.

Figure 4.6 A block of end grain wood with a thin slice removed so that a small RH sensor could be placed in a cavity in the wood.

One block had a 3 mm slice sawn off it. Under this a hole was bored to take a small RH sensor. The slice was replaced over the sensor and the block was then glued in a group of seven blocks, one of which had a similar hole bored in the back. In this way the RH was measured at approximately 3 mm below the surface and at the back, about 20 mm behind the surface. The blocks rested against a plate of aluminium.

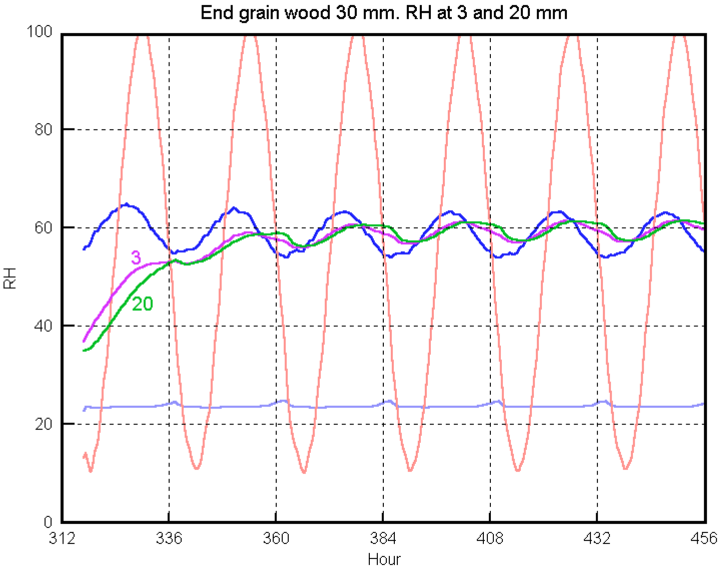

Figure 4.7 The approach to equilibrium of end grain wood blocks, 30 mm thick. The RH at 3 mm below the surface and at 20 mm rises steeply from the initial wood equilibrium at about 38% RH. The chamber RH is correspondingly dragged down a little as it loses water to the wood.

Figure 4.7 shows the first six daily cycles for the panel. The good stabilisation of the relative humidity is immediately noticeable. The 90% RH swing of the empty chamber is reduced to 10%. The curves for 3 and 20 mm behind the surface are delayed and of lower amplitude but are close to each other. This pattern cannot be exactly reproduced by a model based on Fick's law, however much one varies the three parameters: sorption, diffusion and surface resistance. The matter is taken up in the next chapter.

Note that the chamber RH is the result of the interaction of wood and air. The RH cycle shows a descending tendency because the wood withdraws water until the two phases, wood and air, are in equilibrium, averaged over several cycles. This is the important difference between the flux chamber and the usual environmental chamber which controls the RH. It is important to bear in mind that the RH cycle is not controlling the moisture absorption of the wood: the chamber space and the wood are exchanging water in an attempt to come to equilibrium with each other. The flux cycle forces a continual disturbance of this equilibrium by supplying water to the air, or by withdrawing water.

The curves for the RH within the wood are not truly sinusoidal. This is because of the disturbance in the temperature at times when the flux generator was working hard at condensing water from the air. The heat generated during this process overcame the temperature controller. This fault was corrected in later experiments.

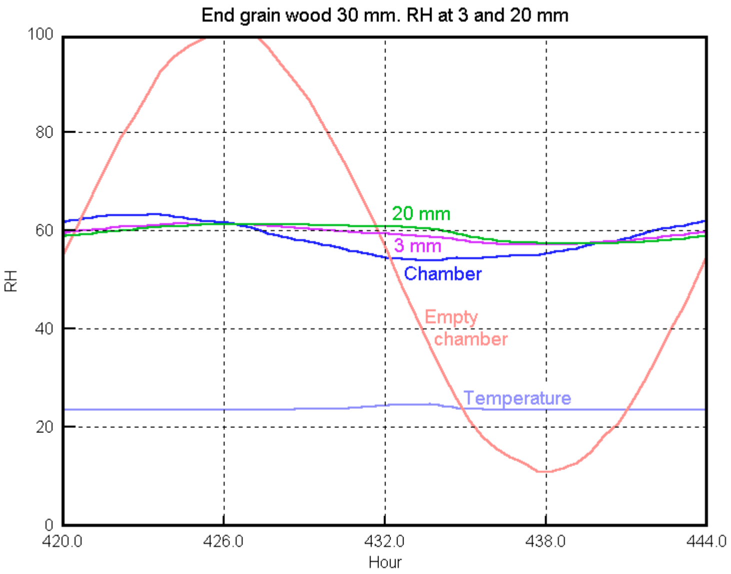

Figure 4.8 A single day cycle for end grain wood.

Figure 4.8 shows a close up of one cycle from fig.4.7. Notice the very good stabilisation of the chamber RH. The wood is exchanging water throughout its entire thickness, as shown by the green curve for the 20 mm RH following closely after the curve for RH at 3 mm. This indicates very fast diffusion of air through the wood. It also hints that absorption of water into the wood substance must be rather slow.

The entire thickness of the wood is in play. The 30 mm thickness of this wooden panel is therefore usefully employed in buffering the daily cycle of humidity in a house. A thicker layer would be even more effective. A ceiling made from tiles of wood cut across the grain would form an excellent humidity buffer. End grain wood is used for flooring but it rapidly clogs with dirt. End grain wood behind a permeable protective coating would also be quite effective.

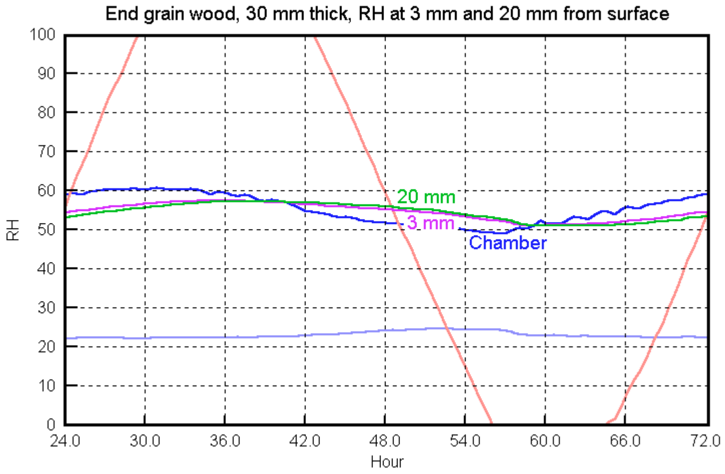

Figure 4.9 A two day cycle with double the flux amplitude. This flux would cause condensation in the empty box but the wood buffers the RH very effectively.

A longer cycle with double the flux amplitude would cause the RH in the empty chamber to reach 100%, followed by condensation on the walls. The wood entirely prevents this. Notice that the RH within the wood is uniform from 3 to 20 mm and the amplitude is close to that of the RH in the chamber. The phase delay is about 0.2 cycles. At this cycle time a greater thickness of wood would give better performance. The flux is "seeing through" the wood.

End grain wood is the most effective buffer for relative humidity among the materials tested. It is not, however, without defects. End grain wood panels are physically weak and expand and contract as they exchange water vapour with the air. The wood outgasses numerous organic chemicals. One of the most abundant, acetic acid, is corrosive to the base metals, lead and zinc. The cocktail of chemicals within the wood does, however, make it resistant to fungal growth, so end grain wood would work well in a bathroom to absorb the intermittent flux of steam from the shower. The brief period of raised, but still moderate water content as the wood first absorbs and then releases water vapour will not cause fungal growth, whereas intermittent condensation on non-porous surfaces will eventually result in mould growth.

Wooden planks

A wood surface cut parallel with the cell direction reacts to the water vapour flux much more slowly than does end grain wood. Diffusion across the cell direction is about ten times slower than diffusion along the cell direction. The buffer performance of the wood is now limited by the diffusion rate. Only a thin surface layer is effective in buffering the daily cycle.

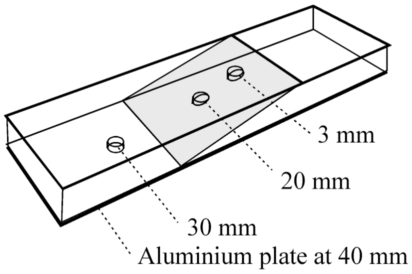

Figure 4.10 The RH sensors within the wooden planks were installed in shallow holes drilled into a very oblique section. The thin wires were led parallel to the surface to the edge of the plank, to minimise movement of air bypassing the hard route through the solid wood.

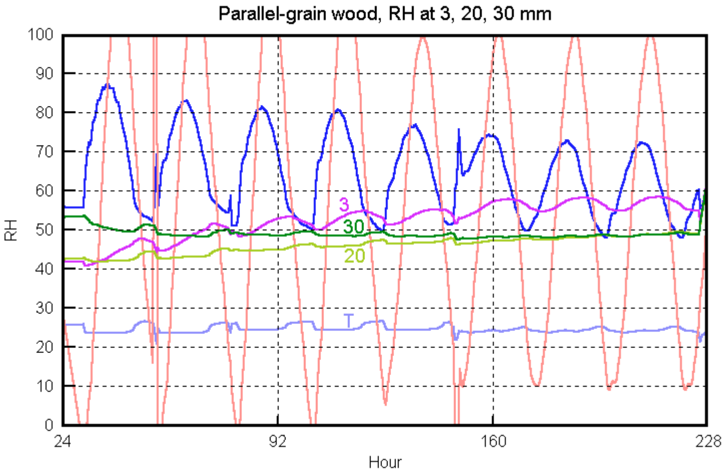

Figure 4.11 The initial cycles for wooden planks. The flux amplitude was changed at the fourth cycle.

The messy start to this graph is quite informative. It shows how slowly the inside of the plank reaches equilibrium The sensors inside the plank were installed in a room at about 40% RH. The sensor at the back of the plank, however, was installed at the last minute in the more humid room containing the experimental wall. At the beginning of the run the back sensor slowly fell in RH as it came to equilibrium with the low RH of the middle of the plank. Meanwhile the middle of the plank was slowly absorbing water from the front, exposed to the relatively humid chamber. The sensor at 3 mm took about 8 days to come to equilibrium with the chamber. During this time the chamber RH showed a steady fall in its mean value as it lost moisture to the wood. After 8 days the interior of the wood was still far from equilibrium with the chamber RH.

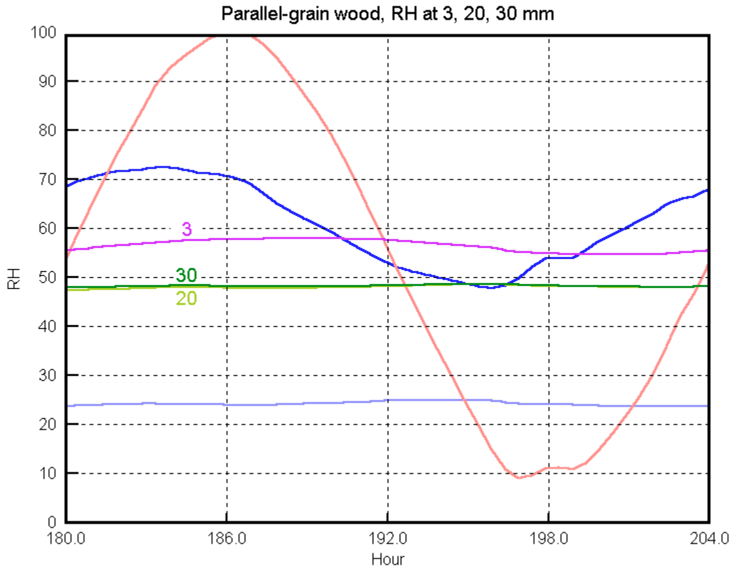

Figure 4.12 A single day extracted from figure 4.10. The interior of the wood is far from equilibrium and not at all affected by the daily flux cycle in the chamber

The contrast with the behaviour of end grain wood is very striking. The buffer capacity is very moderate. The sorption curve is of course exactly the same as that of end grain wood but the diffusion is so slow that only the outer few millimetres are engaged in reacting to the daily flux cycle. The slow diffusion of water vapour through wood means that it actually behaves as a vapour barrier to the daily flux cycle, while allowing the yearly cycle to reach right through it.

Clay tiles

Figure 4.13 Panoramic view of Shibam in Yemen. Unbaked earth bricks are used to build up to eight storeys. Photo: Pia Olsen

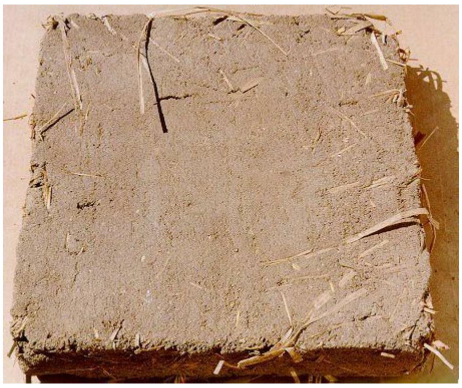

Figure 4.14 Unbaked clay tile made from moraine clay, glacial sand and straw. The clay was pressed into a mould 200 x 200 x 40 mm. The dry tile is approximately 190 mm square.

Sand bound with clay is still the world's commonest building material, but it is not the subject of very much academic research. The tiles made for this experiment were a typical earthy mixture of moraine clay, sharp sand and rounded sand, from Stenlille in Zealand. The clay sand mixture was adjusted to the right consistency for building according to the stickiness as measured by a naked foot stamping the plastic mixture. Straw was added until the mixture became too stiff to mix. It was then pressed into a wooden mould, 200 x 200 x 40 mm (the only precision measurement in the exercise) and turned out to dry in the open for two days before a further maturing period of four weeks indoors. The tiles are a lean mix, coherent enough for building but with less clay than the mixture could hold without excessive shrinkage.

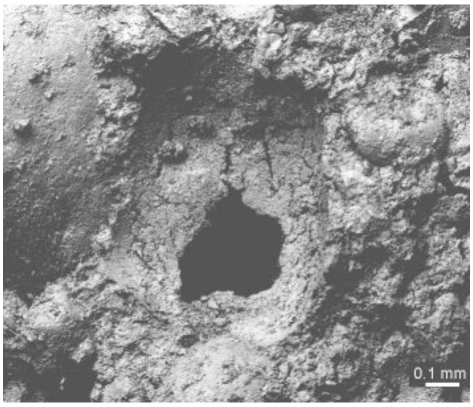

Figure 4.15 SEM picture of a broken surface of a mud brick. In the centre is the smooth depression where a sand grain has pulled out, leaving a thin wedge of clay and a void behind. The shrinkage cracks in the clay give the porosity that allows good humidity buffering. The close contact between sand grains gives good resistance to shrinkage. This is a good building quality but less than ideal as a moisture buffer. Photo: Ulrich Schnell.

Holes were dug in one of the tiles, from the back. RH sensors were inserted and sealed with plugs of nearly dry clay set in a wet clay mortar. This is why the start of the experiment shows very high RH for the enclosed sensors. It takes over a week for these sensors to come to equilibrium, although a minimum of water was used to dampen the tile so that the mortar would seal the cavities well. This hints at a buffer performance limited by the permeability of the material. The shallowest sensor is at 15 mm. This is because the coarse structure of the clay would give very untypical results if the sensor were placed at the 3 mm depth used in the experiments on wood.

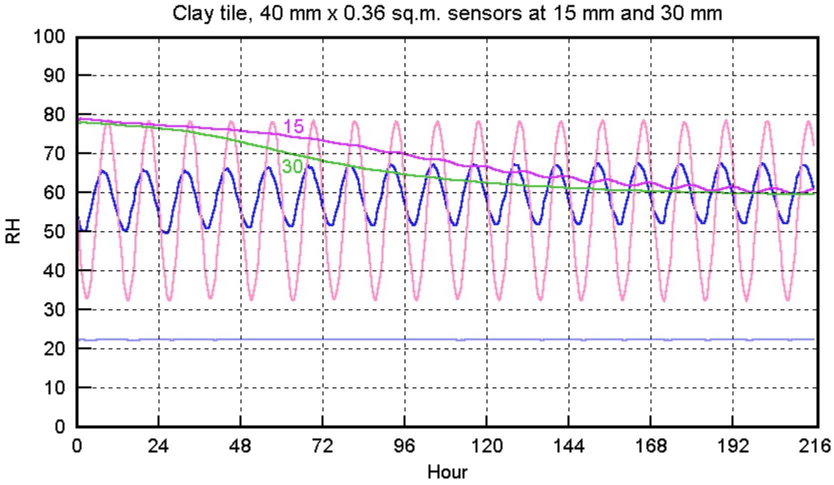

Figure 4.16 The first cycles for clay tile. The cycle time is 12 hours. The built in sensors start at a high RH because a wet creamy clay mortar was used to seal the cavities containing the sensors. The deep sensor comes more quickly to equilibrium because less water was used to install it. Notice how the average chamber RH rises as the clay dries

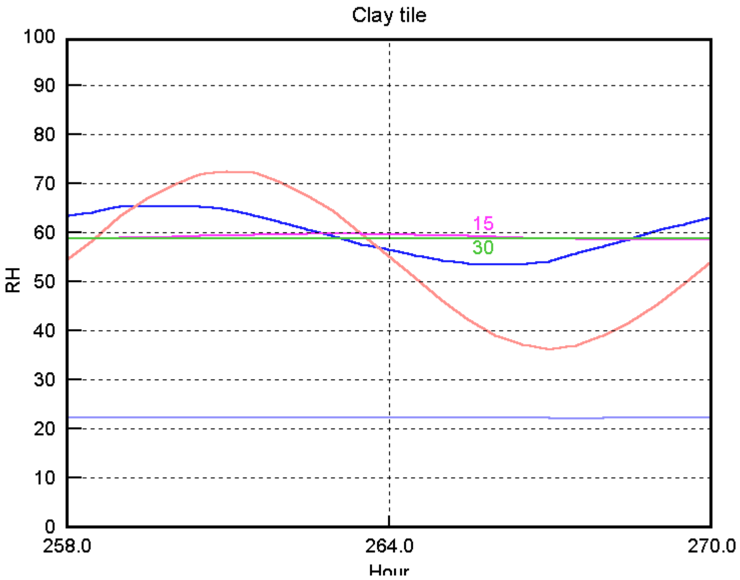

Figure 4.17 A single 12 hour cycle from later in the experimental run whose start is shown in figure 4.16. The buffering is moderate, even though the sensor at 15 mm is scarcely reacting.

The diagram for the single cycle shows that the buffering is moderately good but is only engaging the outer layer of the tile. The sensor at 15 mm is hardly reacting at all to the twelve hour cycle. The efficiency of the buffering at this short cycle time is limited by the resistance of the boundary layer.

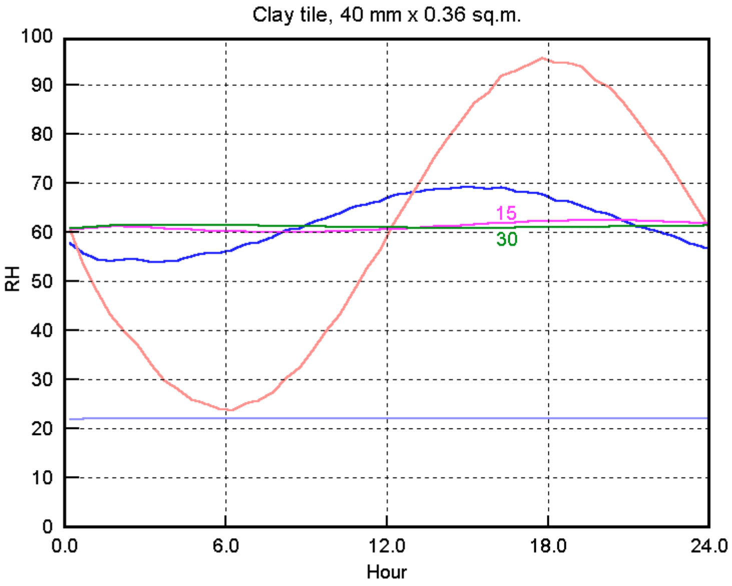

Figure 4.18 The daily cycle for clay tile. The buffering is good, in spite of the very slight engagement of the material in depth.

The daily cycle also hardly stirs the deeper layers, although the buffering is good. The clay performance resembles that of the wood planks: the water reserve is there but it is not readily available to moderate the daily cycle.

The next diagram shows a two day cycle.

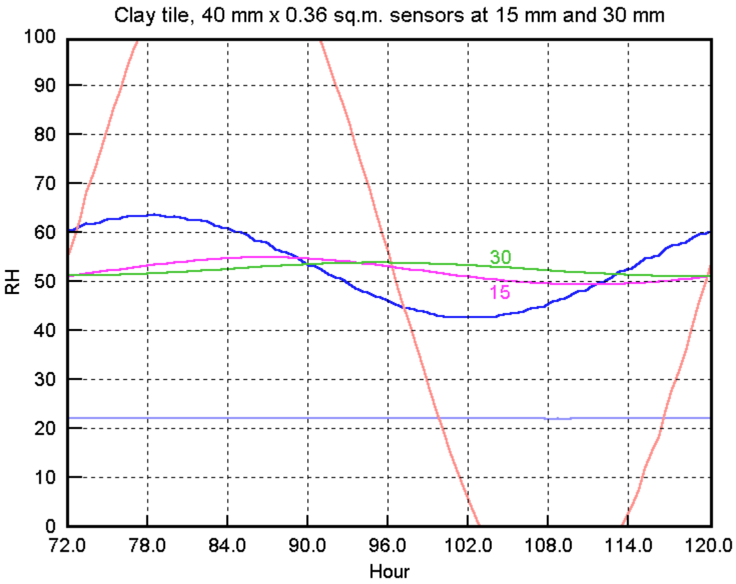

Figure 4.19 A two day cycle does reach down to the back of the clay tile.

The two day flux cycle does stir the deepest layer of the clay tile. The optimum thickness for effective buffering of the daily cycle is about 20 mm. This amount of clay can certainly be used as a plaster over a brick wall, as a substitute for gypsum or lime plaster, which have very little buffer effect, as later graphs will show. The clay tiles used in this experiment were friable and not immediately useful as an interior finish but a combination of clay tile with a thin porous covering of gypsum or lime, maybe in the form of a fresco painting, would be an interesting and practical interior finish.

A clay tile made specially to function as a humidity buffer

The clay tile investigated in the previous section was just a typical clay brick mixture. Mud brick is always a local product. The moraine clay was not analysed, because an exact description of that particular clay would be no help to anyone building anywhere else. Its buffering action was quite good, so it seemed worth investigating the possibility for developing a well defined clay mixture with superior humidity buffering. A 20 mm layer of such a clay could be used as an interior wall finish instead of gypsum or lime plaster, which have very poor buffering properties, as will be shown later in this chapter.

Figure 4.20 Bentonite clay (left) and Perlite grains of up to 2 mm diameter. The bentonite is 80% montmorillonite clay in very finely divided but compact form and is very impermeable indeed. The admixture of perlite opens the structure and makes the resulting tiles dimensionally stable and porous.

A search of the literature suggested that the clay with the best water absorption properties is sodium montmorillonite, in the finely divided form known as bentonite. This is a marine clay formed by the weathering of volcanic rock. Denmark has vast supplies of this clay in a homogeneous deposit extending from Lolland to Fyn.

If one takes the trouble to develop a specialised product as a substitute for an extremely common material it makes sense to look at the other ingredients as well. The requirements for a thin vertical surface layer are rather different from the requirements for a brick. The filler and dimensional stabiliser in mud brick is sand, usually quartz. This is heavy, has no moisture absorption and little thermal resistance. A replacement filler should be light and water absorbent. It should add high porosity to the mixture. One use of bentonite is to waterproof toxic waste dumps and ornamental fountains, so in its pure state it is no good at all for buffering humidity. An effective opening of the structure is essential to change it from a moisture blocker to a moisture buffer. Bentonite also swells enormously when wetted, so the filler should ideally lock its particles together better than sand to withstand the movement of the bentonite.

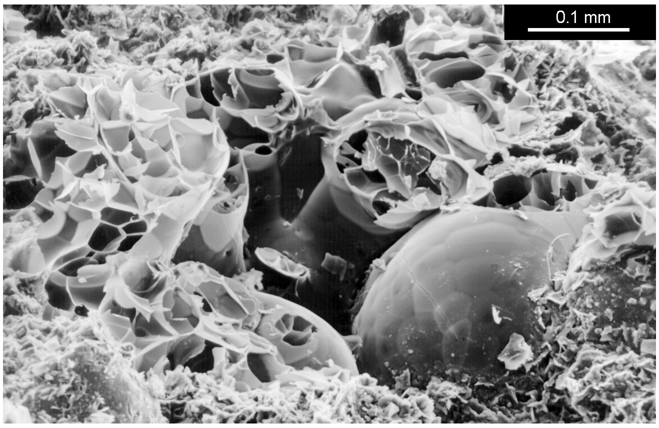

Figure 4.21 SEM picture of an agglommeration of perlite grains in a perlite - bentonite mixture. The view is about 0.6 mm across. Photo: Inger Søndergaard.

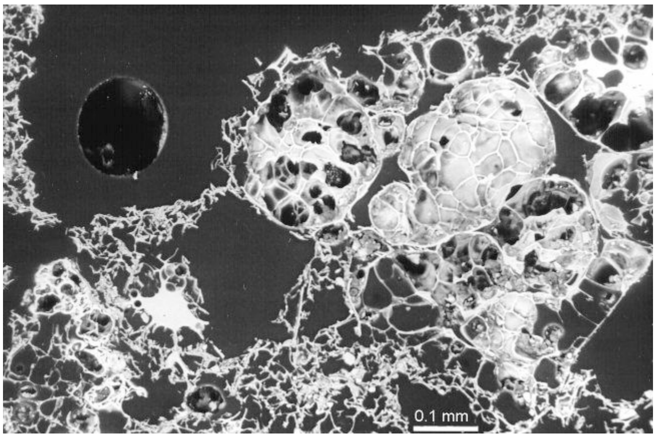

Figure 4.22 SEM image of a polished section of a similar structure to that shown in the previous figure. The clay particles form a filigree between the rounded outlines of the perlite particles. The clay content is only about one tenth of that of perlite by volume. Photo: Inger Søndergaard.

The material chosen as filler has only some of these ideal properties. It is perlite, an artificial glass froth made by heating granules of volcanic glass that contains water that originally was prevented from forming bubbles by the high pressure at the point where the glass solidified within the earth. The crushed glass is blown into a flame in a tall tube. The glass softens and the trapped water expands into steam, blowing the particle up into a frothy sphere.

The bentonite from the clay pit is a scarcely plastic, dense mass. It is first mixed with one and a half volumes of water to reduce it to a creamy consistency which can be mixed with ten parts by volume of perlite. The final mix occupies only five volumes, because the clay fills in the voids in the perlite and the mixing crushes some of the perlite. This mixture has some straw added at the last moment. A good mixer for this combination of materials is a baker's dough mixer. Finally the plastic mix is pressed into moulds and dried. The shrinkage is about 10%.

Figure 4.23 A clay tile, 180 mm square, made from bentonite, perlite and straw. A hole was cast into the tile when it was made and a plug was cast to fit the hole. The RH sensor was placed in the hole and the plug was inserted and sealed with moist clay mortar. The shallow hole is for the sensor at the back of the tile. The entire back and the sides of the tile were finally sealed with aluminium foil and polyethylene foil.

One tile was fitted with sensors at 9 mm and at 34 mm from the surface. The structure is more homogeneous than the ordinary clay tile studied in the previous section, so the sensor could be closer to the surface. This tile was then placed in the middle of a set of nine tiles which were stacked up against an aluminium back plate.

When the tile dries the bentonite component tries to shrink but is restrained by the perlite fragments. The loose glass shards and the partly crushed frothy particles form a very resistant interlocked mass which stops the tile from shrinking. The bentonite is therefore forced to take up an open porous structure, which is very difficult to distinguish from the perlite shards in a SEM picture. The individual clay particles are well below the resolution of the SEM and the chemical signature is rather similar to that of perlite. The section shown in figure 4.22 is chosen to match the structure shown in the broken surface of figure 4.21. Figure 4.24 shows a more typical area at lower magnification. This picture has been manipulated to increase the contrast and to show the solid matter in black. The structure has four components: damaged perlite particles and curved fragments, voids and an open structure of loosely stacked plates of clay particle aggregates. The intact perlite grains have closed pores and are impermeable. The humidity buffering is presumably provided by the mesh of poorly organised plates of montmorillonite.

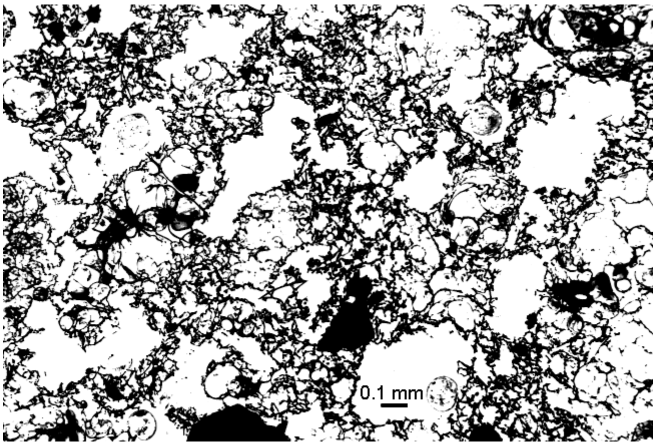

Figure 4.24 A typical section of the clay tile with solid material in black The density of the tile is 740 kg per cubic metre, about the same as cellular concrete.

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Figure 4.25 The bentonite - perlite mixture shrinks evenly if it is not restrained (bottom). It is therefore suitable for making clay bricks but less suited to cob methods, where the clay is applied in a plastic state. A formulation suitable for plastering walls has yet to be developed.

Bentonite with perlite is not a mixture recommended by earth builders. The exceptional shrinkage of bentonite on drying suggest that it will be difficult to use. The corresponding expansion on rewetting suggests that it will be unstable once the house is built.

The drying shrinkage indicates that building should be done with clay bricks, rather than by the cob technique, where globs of plastic clay are piled up and pressed together to make a wall. The dry stamping technique known as pisé may work but requires that the wet mixture be dried out considerably before stamping begins, introducing an extra, time consuming process.

The lightweight clay tiles are very similar in density to cellular concrete and could be used in much the same way. The compressive strength is quite adequate. The advantages over cellular concrete are that it can be recycled and it can be given great bending strength through incorporating extra, oriented fibres, making it quite suitable for shelving and arches.

The tiles are surprisingly resistant to water spray. The clay at the surface swells and seals off the interior.

The moisture buffering potential of lightweight clay tile

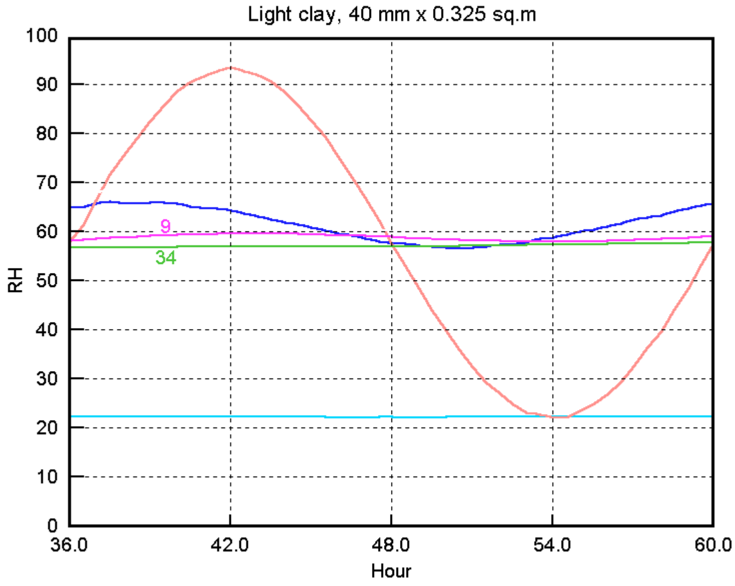

Figure 4.26 The daily cycle for lightweight clay tile.

The buffering of the daily cycle is so good that the RH at 9 mm hardly changes at all. The observed RH cycle is largely controlled by diffusion across the boundary layer between air and tile.

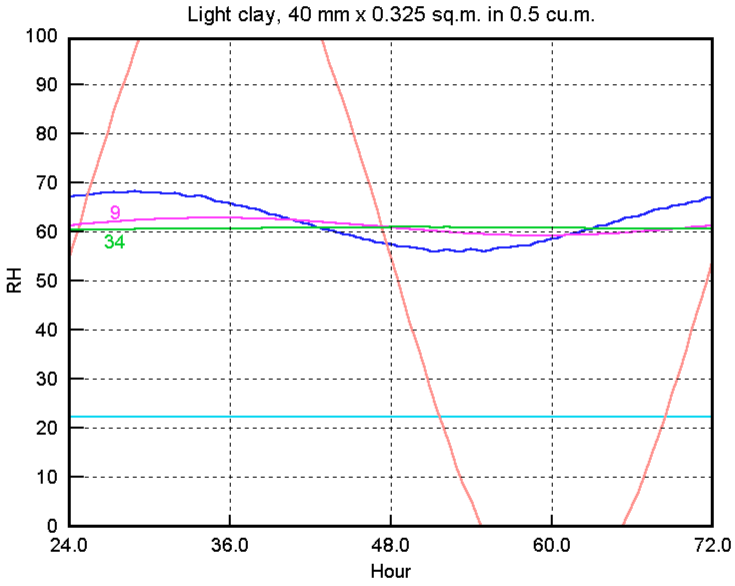

Figure 4.27 The two day cycle for lightweight clay tiles

During the two day cycle the amplitude of the chamber RH is hardly greater than in the one day cycle, in spite of the greater quantity of water injected during the cycle. This suggests that the main factor causing the observed RH swing in the one day cycle is the surface resistance to moisture transfer.

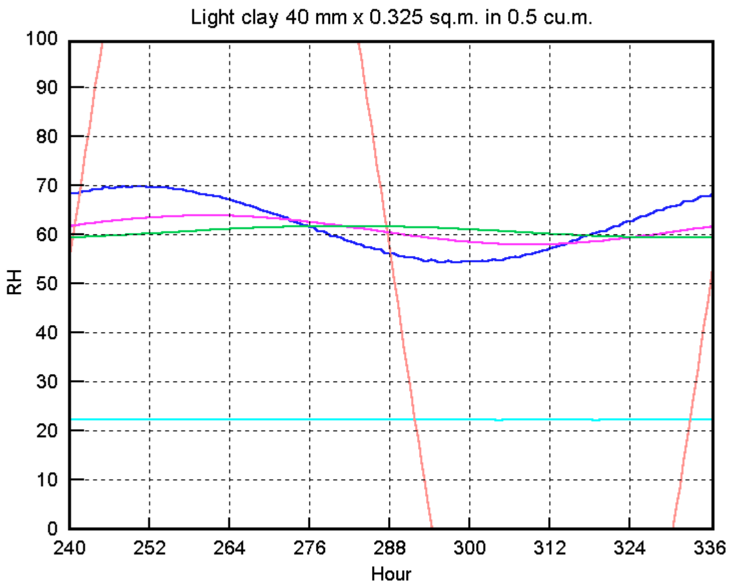

Figure 4.28 Four day cycle for lightweight clay tiles.

The four day cycle at last shows some influence on the deepest layer of the tile. The RH cycle is still within +/- 10% of the mean value, whereas the curve for the empty chamber shows that condensation would otherwise set in at an early stage in the cycle and would continue for many hours.

This last graph shows the exceptional buffer performance of lightweight clay as an interior finish.

Lime plaster

The traditional interior mineral surfaces are lime plaster and gypsum plaster. These have very inferior buffer capacity, compared with clay.

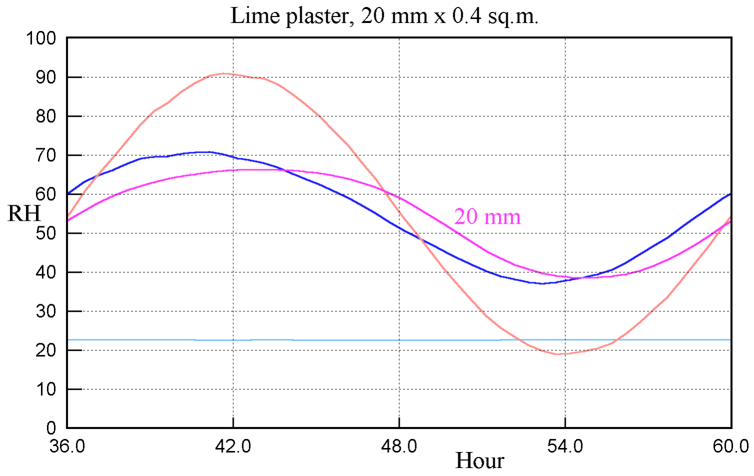

Figure 4.29 The daily cycle for lime plaster, made from approximately one part slaked lime in the form of lime putty, mixed with three parts of sand. The buffering is very poor.

The lime plaster is very porous. The RH at 20 mm follows close behind the RH in the chamber and is of nearly the same amplitude. This indicates that the entire thickness of the plaster is available to react to this daily cycle. The buffering capacity is fully used, and is not very impressive. The "empty" RH is halved by the presence of the plaster.

Gypsum plaster

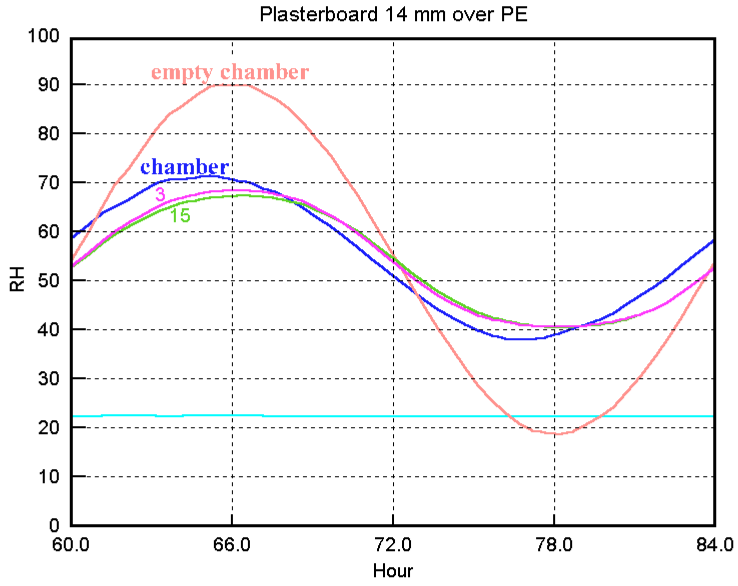

Figure 4.30 Gypsum board, made from two layers of paper with gypsum in between, has a rather similar pattern to lime plaster. The buffering effect is nearly identical. The porosity is difficult to compare because the gypsum board is thinner than the lime plaster. The entire thickness is in play in this daily cycle.

Cellular concrete

The last mineral material in this catalogue of building materials that can function as humidity buffers is cellular concrete. This material is made by mixing silica, calcium oxide, aluminium powder and water. After a few seconds of mixing the slurry is poured into a mould where it froths up as hydrogen is released by the reaction of aluminium with water in alkaline solution. The final product is a mass of interlocking needle crystals of calcium aluminium silicate with some residual silica particles and relatively large voids. The density of cellular concrete depends on the mix but is typically 750 kg/m^3.

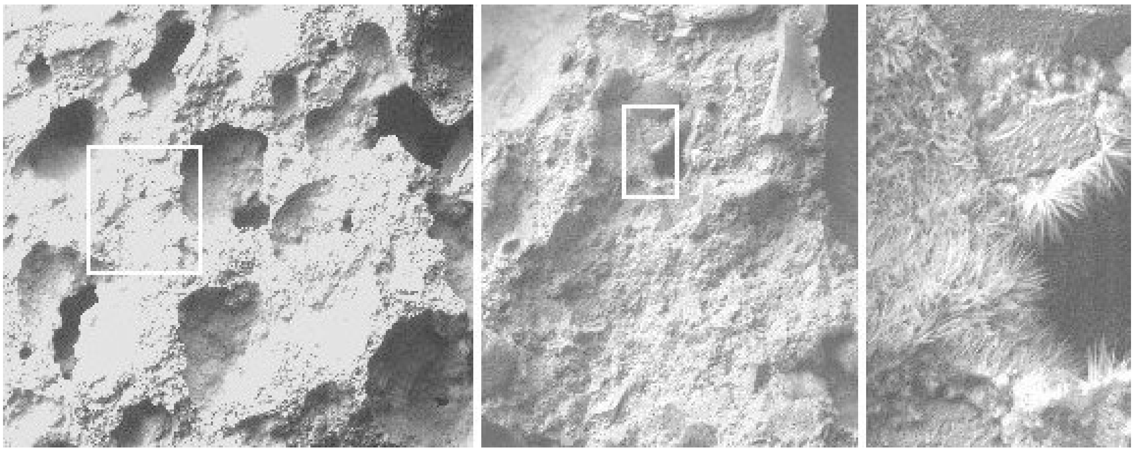

Figure 4.31 SEM images of a broken surface of cellular concrete at three magnifications. The picture on the left is 2 mm across. Photo: Ulrich Schnell.

The enormous surface area gives plenty of sites for water absorption, so cellular concrete is a moderately good buffer, as the next three diagrams show.

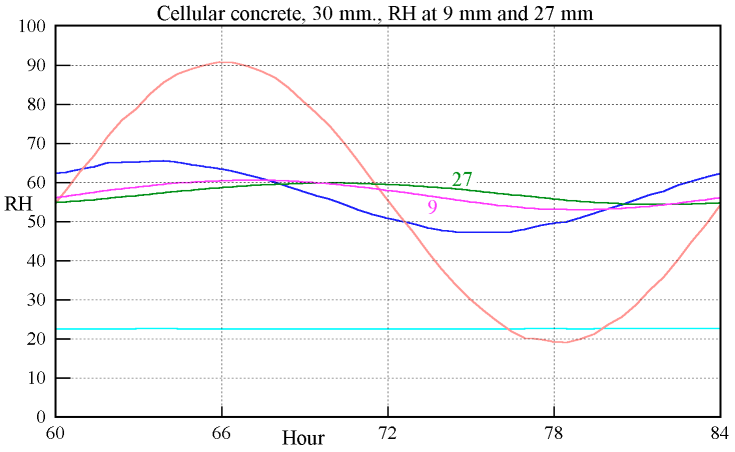

Figure 4.32 Cellular concrete, 24 hour cycle.

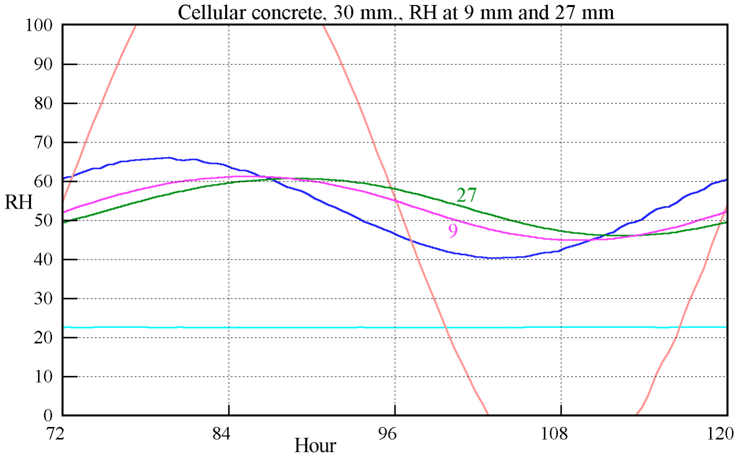

Figure 4.33 Cellular concrete, 48 hour cycle

The entire 30 mm thickness of the cellular concrete is working to buffer the 48 hour cycle. The 24 hour cycle also reaches down to the back of the tile, so this thickness is less than the optimal for buffering the daily cycle.

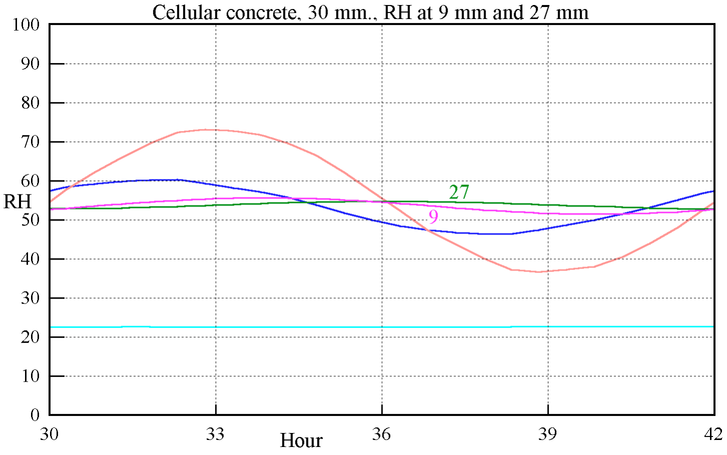

Figure 4.34 Cellular concrete, 12 hour cycle

During a twelve hour cycle the back of the tile does not exchange so much water. Approximately 60 mm of cellular concrete are needed to provide optimal buffering for the daily humidity cycle. This is not a problem because cellular concrete is usually used to build walls at least 100 mm thick. Cellular concrete walls covered thinly with gypsum plaster should give the best moisture buffering of the established industrial building materials and construction methods.

This hypothesis was tested by laying a 15 mm layer of gypsum plaster over the cellular concrete tiles. The tiles were moistened to prevent the tearing of the gypsum during application, through rapid drying by capillary suction. The gypsum was, of course, entirely water saturated at the beginning. The wall was then dried for two weeks in a room at 52% RH. After this the chamber was dropped down over the wall and the flux generator was set to condense water at a steady rate.

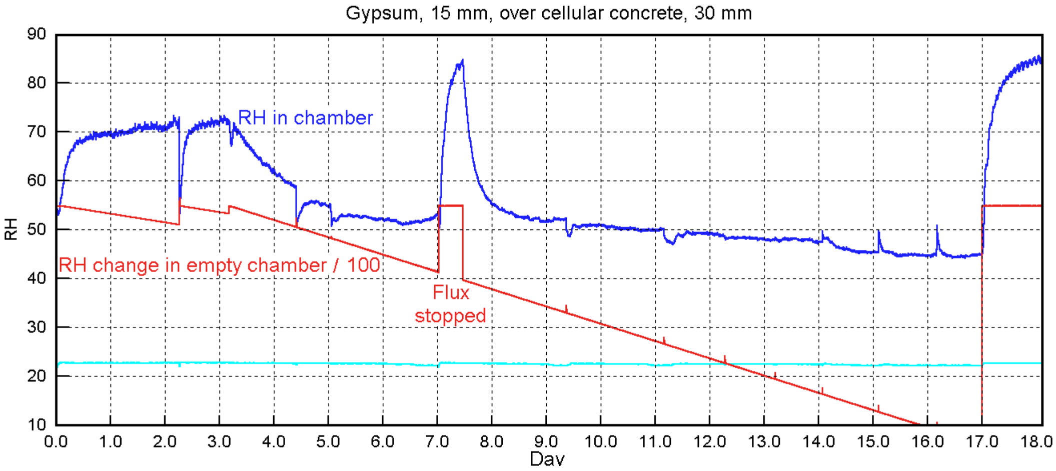

Figure 4.35 The drying of a wall of cellular concrete, 30 mm with a 15 mm gypsum surface layer. In this graph the 'inert' RH is divided by 100. This means that an indicated 1% change would actually be a 100% change in RH

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The result was surprising. Part of the graph is shown in figure 4.35. A flux of -2 g/hr was applied (that is 2g/hr of water was condensed into the tank). The RH fell quite quickly to about 50% but then continued to decline very slowly while many tankfuls of water were extracted from the wall. Extracting 2g/hr of water would make the RH in the empty chamber drop from 50% to zero in 2.5 hours, yet the RH only fell from about 52% to 48% over a week.

A plausible explanation for this almost constant RH in the chamber is that most of the water from the gypsum was absorbed into the cellular concrete soon after the setting of the plaster. During the initial period of ventilation a relative humidity gradient established itself through the gypsum, with 100% RH at the interface with the cellular concrete and a value at the surface which depends on the flux through the surface. This gradient will remain stable for weeks, while the cellular concrete gives up its stock of capillary moisture. This condition is due to the different pore size in the two materials: the gypsum has coarser pores.

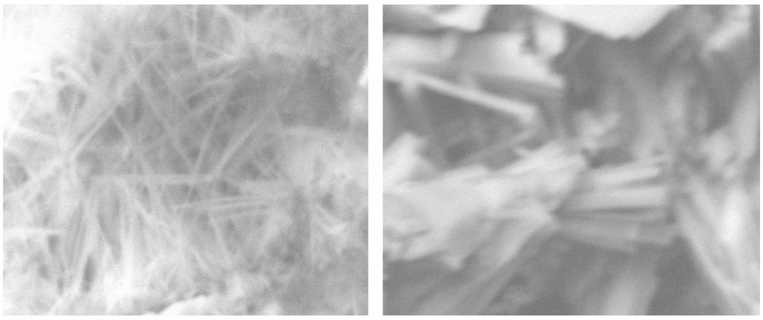

Figure 4.36 SEM pictures of cellular concrete, on the left, and gypsum plaster. Each image is 25 microns across. Photos: Ulrich Schnell.

This unintended experiment demonstrates that humidity buffering at moderate RH by absorbent porous materials is a minor phenomenon compared with the huge quantities of water that can be stored in the capillaries of materials, in a condition where the equilibrium RH remains at 100%, while a large amount of water is released, or absorbed. The significance of this for the indoor climate is that the process by which wet gypsum gives up its capillary water to the cellular concrete is not reversible in the way that buffering by a block of one material is reversible. If a brief episode of condensation in a bathroom, for example, is absorbed into the gypsum, the water will be transferred by a relatively rapid capillary flow to the cellular concrete. The reverse process will be slow because the water changes to vapour at depth within the wall, at the interface of the two materials. There is no air flow to boost evaporation: the water vapour must diffuse to the surface. This assymetry in the speed of wetting and drying can be advantageous if the cellular concrete can evaporate the moisture to the outside of the building.

Wool insulation

The materials discussed so far in this chapter have been stiff, structural materials. The catalogue ends with a soft material: wool.

Absorbent insulators are credited with many virtues and vices, according to which side of the green line one is standing. Advocates of environmentally friendly, organic insulation in houses point to the water absorption of wool as an asset, preventing condensation within walls and moderating the indoor humidity. Opponents from the mineral fibre industry argue that the water absorption allows rotting and encourages insect attack. I will return to this controversy in a later chapter.

Figure 4.37 Wool insulation. This picture shows a 70 mm section of wool insulation. Notice the laminations parallel to the surface of the slab as it would be installed in a wall.

Wool has a steep absorption curve and is therefore a good humidity buffer. Wool insulation, however, has a density of only 300 g per square metre of wall, if it is installed as a layer 200 mm thick. It is, however, very porous, so the entire thickness of the wool is brought into play, even during a daily flux cycle.

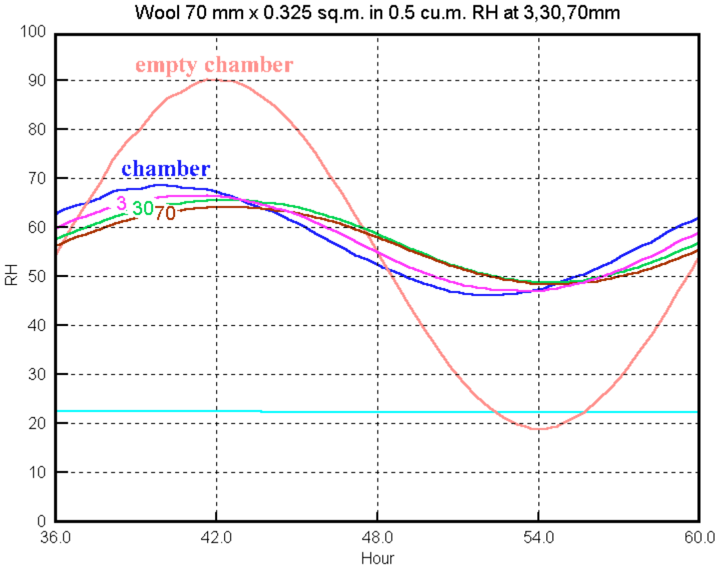

Figure 4.38 The daily cycle for wool. The interior RH cycles cluster closely behind the RH in the chamber. This indicates that the entire thickness of the wool is involved in the daily cycle.

All the RH curves, except the empty box one, are going up and down almost identically, with a small phase delay for the sensors embedded in the wool. The buffering is considerable, but it is also all that the wool can offer: there is no reserve for longer flux cycles.

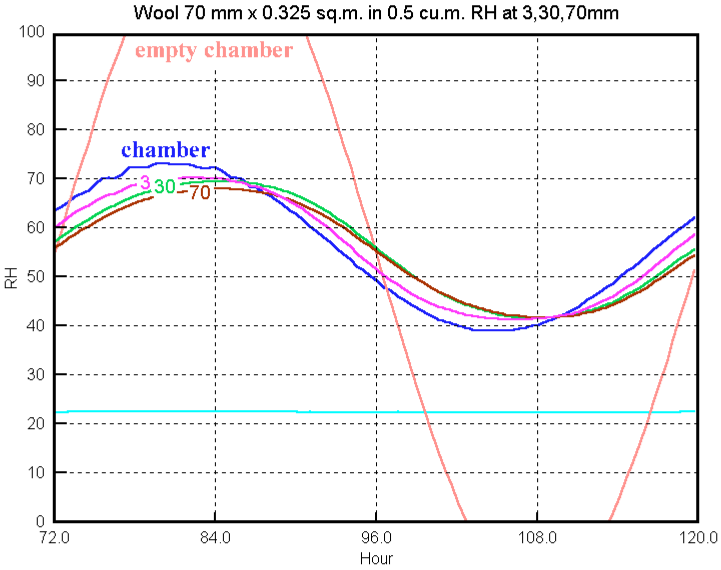

Figure 4.39 Wool insulation: 48 hour cycle

The two day cycle resembles the pattern of the 24 hour cycle with the important difference that the amplitude of the chamber RH is greater.

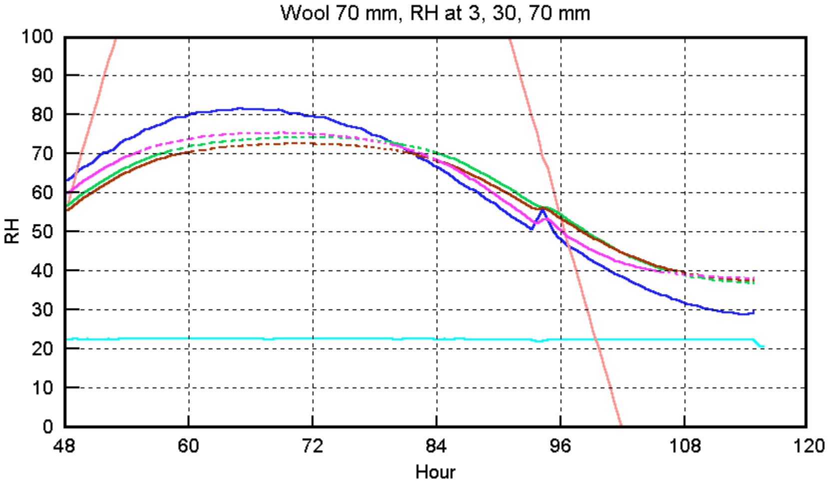

Figure 4.40 Part of a four day cycle with wool insulation. The RH is now swinging with a large oscillation, though there is still no danger of condensation. The curves for the RH inside the wool are flattened at the extremes (dotted lines) and are no longer accurate: the sensors are outside their linear range

The four day cycle shows an even greater swing, but there is still no danger of condensation. The wool is therefore effective as a buffer at any frequency. Its efficiency continues to increase with thickness, because the rate of moisture diffusion is much faster than that for clay or wood planks. Compacting the wool would also work to some extent, though eventually the greater density would affect the permeability.

Wool insulation encapsulated

Figure 4.41 A detail from an 18th century French tapestry in the Royal Palace, Copenhagen. Photo: Roberto Fortuna

Walls of exposed wool are a very presentable form of interior decoration, though expensive. Tapestries have for centuries been regarded as the most prestigious wall covering for a grand house in Europe. Curtains are a more mundane form of wool moisture buffer.

The density *per square metre* of tapestry is not so far from that of wool used as insulation and so its buffer capacity is similar, and very useful because it is immediately available to fight acute water vapour fluxes.

Sheep's wool is one of the insulating materials that is recommended as an environmentally friendly replacement for mineral fibres. Advocates of moisture absorbent insulators, such as paper and other vegetable fibre and wool, assert that these materials give a more pleasant indoor climate, through their moisture buffering action. This effect cannot possibly work if the wall is provided with an impermeable barrier, as is usually recommended to prevent condensation within the wall in heated buildings. A *moisture retarder*, which is moderately permeable to water vapour, is therefore recommended for these insulators.

A typical wall construction would be gypsum board as the interior finish, then a vapour retarder and wool insulation with some permeable outer sheathing to allow ventilation of moisture to the outside.

These materials are examined one by one, and in combination, to see how easily the room can receive the benefit of moisture absorption by the wool.

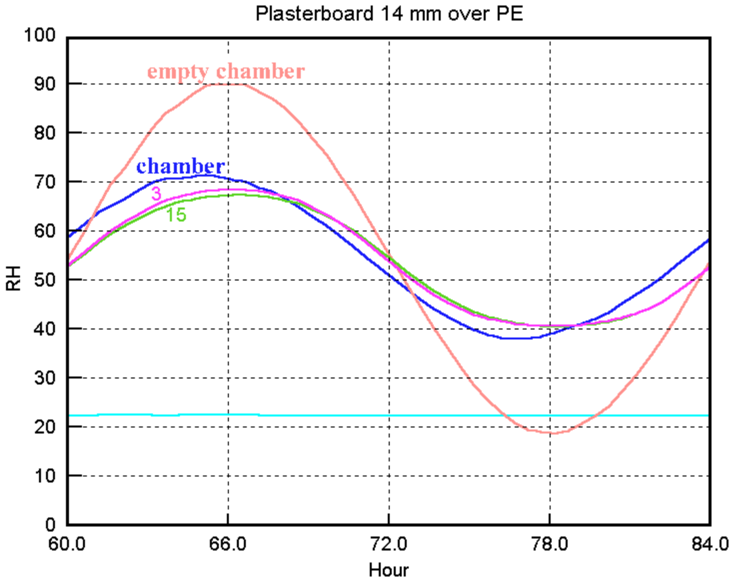

Figure 4.42 Buffer performance of plasterboard alone (a repeat of figure 4.30). Sensors are mounted behind the front layer of paper and behind the second layer, just in front of the polyethylene membrane that seals the back.

Plasterboard alone has a modest buffer capacity, mostly contributed by the layers of paper enclosing the gypsum. If it is unpainted, or painted with a thin paint with water permeable binder, it will perform as shown in the figure. One sensor is placed behind the first layer of paper and another sensor behind the second layer, just in front of the polyethylene film that seals the back. The capacity is modest and the permeability is such that all the buffer capacity is available to the daily cycle.

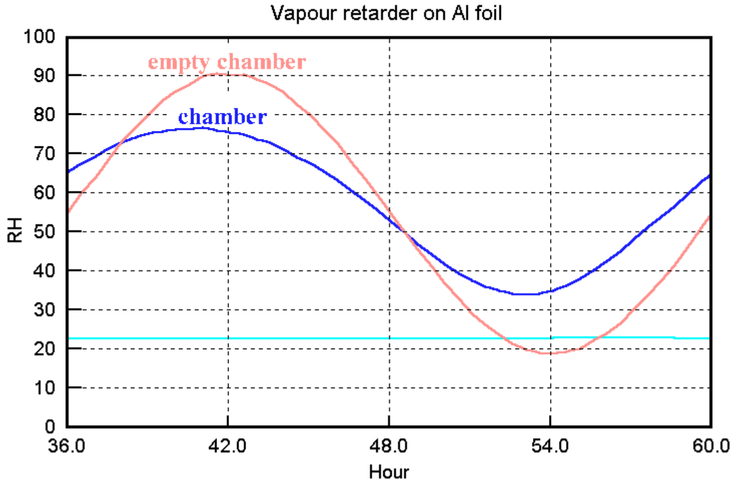

Figure 4.43 Buffer performance of vapour retarder alone

The vapour retarder is made from thick paper with thread reinforcement to limit tears. It also has a noticeable buffer capacity, but less than that of plasterboard.

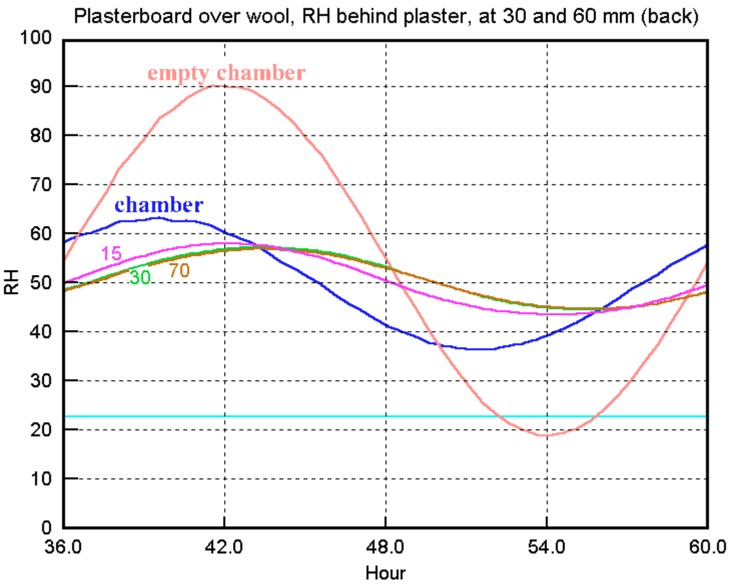

Figure 4.44 Plasterboard over wool, sensors behind the plaster, midway through the wool and at the back

Wool behind plasterboard can still influence the indoor climate, but only marginally. The clear swing in RH within the wool is as much due to its low capacity for water as to its buffering of the chamber air.

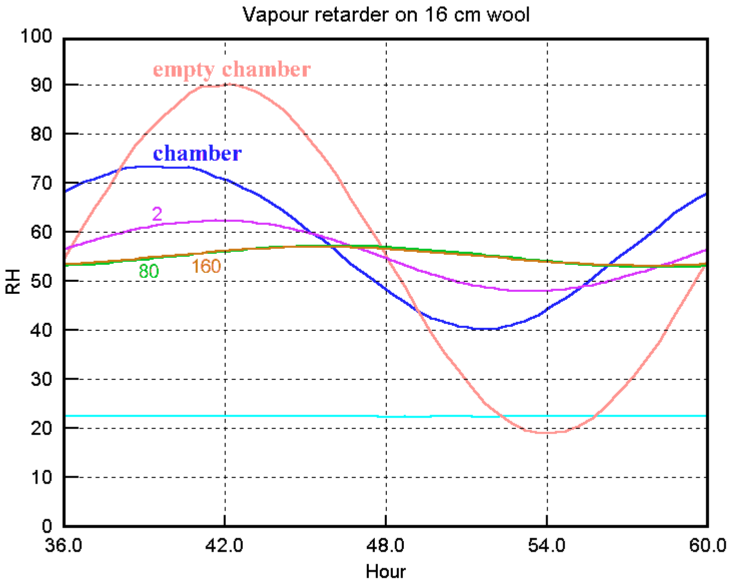

Figure 4.45 Wool behind vapour retarder. Sensors behind the retarder and within the wool at 7 and 15 cm.

Wool behind the vapour barrier has a negligible effect on the room climate.

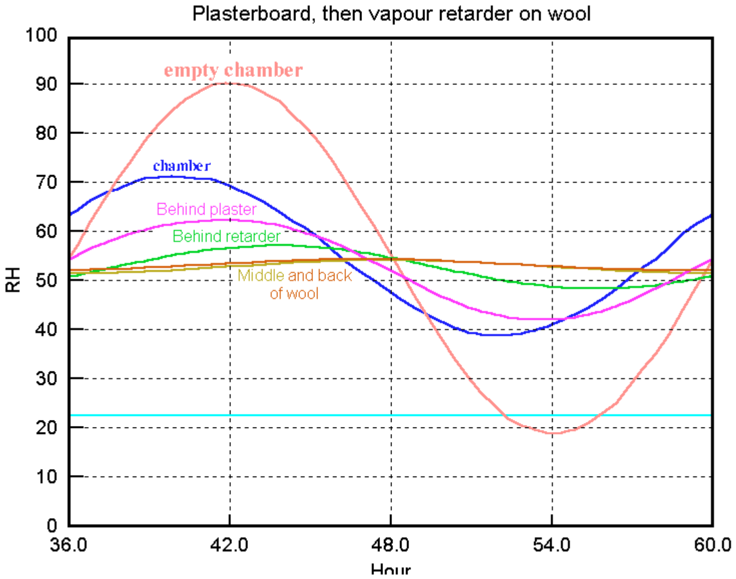

Figure 4.46 Plasterboard, vapour retarder and wool. Sensors behind the plaster, behind the retarder, half way through the wool and at the back.

When the orthodox combination of plasterboard, vapour retarder and wool is examined, the RH within the wool varies by just a few percent, indicating a negligible participation in the moisture exchange. The plasterboard and the vapour barrier provide what humidity buffering there is.

Reaction of a wall to a sudden injection of water vapour

The way in which the various components of such a complex wall react in turn to the flux in the room is shown by a different experiment in which a sudden pulse of water vapour was injected. The response of the wall is shown in the diagram below. At about hour 5 in the graph, water is added to send the empty chamber to "200 % RH", which is roughly the same flux as in the 48 hour cycle in earlier diagrams, but added all at once.

The plaster, more particularly its two layers of paper, does most of the moisture buffering in the early hours after the water is injected. Then this water diffuses through to the vapour retarder and eventually to the wool. The peak chamber RH is moderated from the expected 100% together with intense condensation that the empty chamber would experience, to 80% in the chamber with the wall. One can make a rough calculation of the moisture distribution at this time from the observed RH values within the wall and the absorption coefficients of the materials. The plasterboard holds about half of the sudden surge of water vapour. A little water is held in the vapour retarder and about half is in the wool. When everything has come to equilibrium after about two days the wool has pulled the chamber RH down to less than 60%. Put rather crudely, the plasterboard has moderated the RH from about "200" to 80% as a quick buffer. Later, the water capacity of the wool provides most of the water absorption and the chamber RH stabilises at 57%.

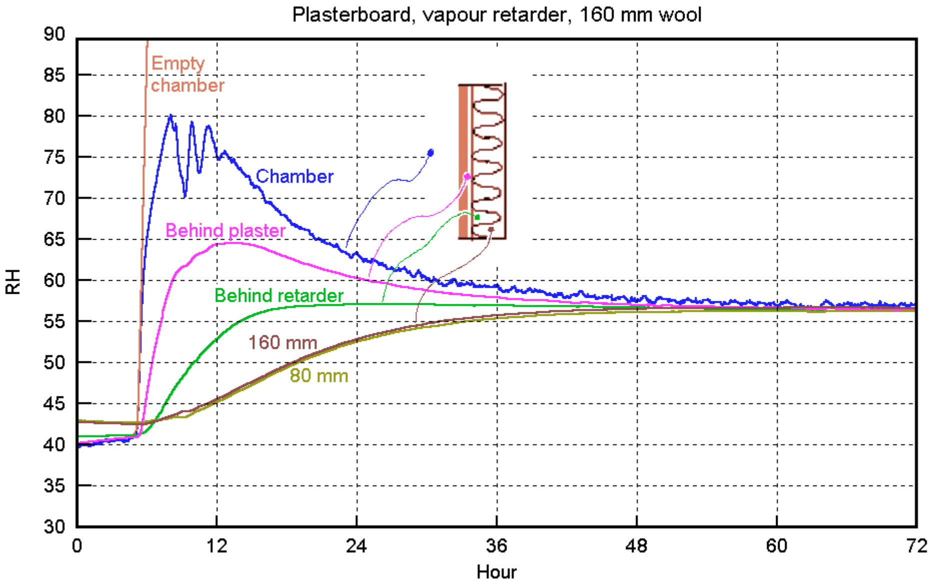

Figure 4.47 The effect of suddenly adding enough water to bring the empty chamber to "200%" RH. The rapid fluctuations at the peak are due to instability of the flux controller. The wall is made of plasterboard, vapour retarder and wool insulation.

Summary of chapter 4

The response to the release of water indoors has been measured for several materials used in buildings. The material is put in a chamber into which water vapour can be injected, and then removed in a continuous cycle. The exposed area of material is about 0.6 m^2 per cubic metre of air. The materials moderate the RH in the chamber, by absorbing the injected water vapour and then by releasing water vapour to compensate for that withdrawn from the chamber. A series of graphs gives a visual impression of the relative efficiency of different materials in moderating swings in indoor relative humidity, by comparing the RH swing in the empty chamber with the actual cycle.

All the materials exert some moderating effect. The least effective was lime plaster, which reduces the swing to about half that in the empty chamber. The most effective RH buffer is more difficult to define, because it depends on the cycle time. End grain wood is very effective at moderating a daily cycle, because of its great porosity. Bentonite clay tile was excellent at all cycle times because of its very high absorption, combined with moderate porosity. Wool insulation has very high absorption per unit weight and very high permeability but when used as insulation its very low density reduces its practical usefulness.

The reaction to the daily cycle by the single materials is collected in a summary diagram in figure 4.48 below. As an aid to translating these sinusoidal curves into the potential of these materials for moderating the indoor climate one can take as an example a house in winter. The house is warmed to 23°C and is by chance at 50% RH. The water content is about 10 g/m^3. The outside air is at 0°C and 100% RH. Its water content is 5 g/m^3. The maximum rate of change of moisture content of the inside air in the diagrams is about 1.6 g/(m^3.hr). This is equivalent to 0.3 air changes per hour. This is the exchange rate for a fairly well sealed, modern house. It is immediately clear that the RH in the non-absorbent house is going to fall quite rapidly, though exponentially, to the 22% RH which is the RH that the outside air will acquire through warming to the room temperature. The process will be substantially complete within 6 hours, but will be about ten times slower in a house panelled with end grain wood. The winter in the author's latitude is much longer than this, so absorbent walls in houses are strictly for moderating an indoor climate whose average value, measured over a few days, is acceptable. Store houses are another matter: it is quite practical to design them to buffer over the whole year, as reported in a later chapter.

Summary of the performance of the materials

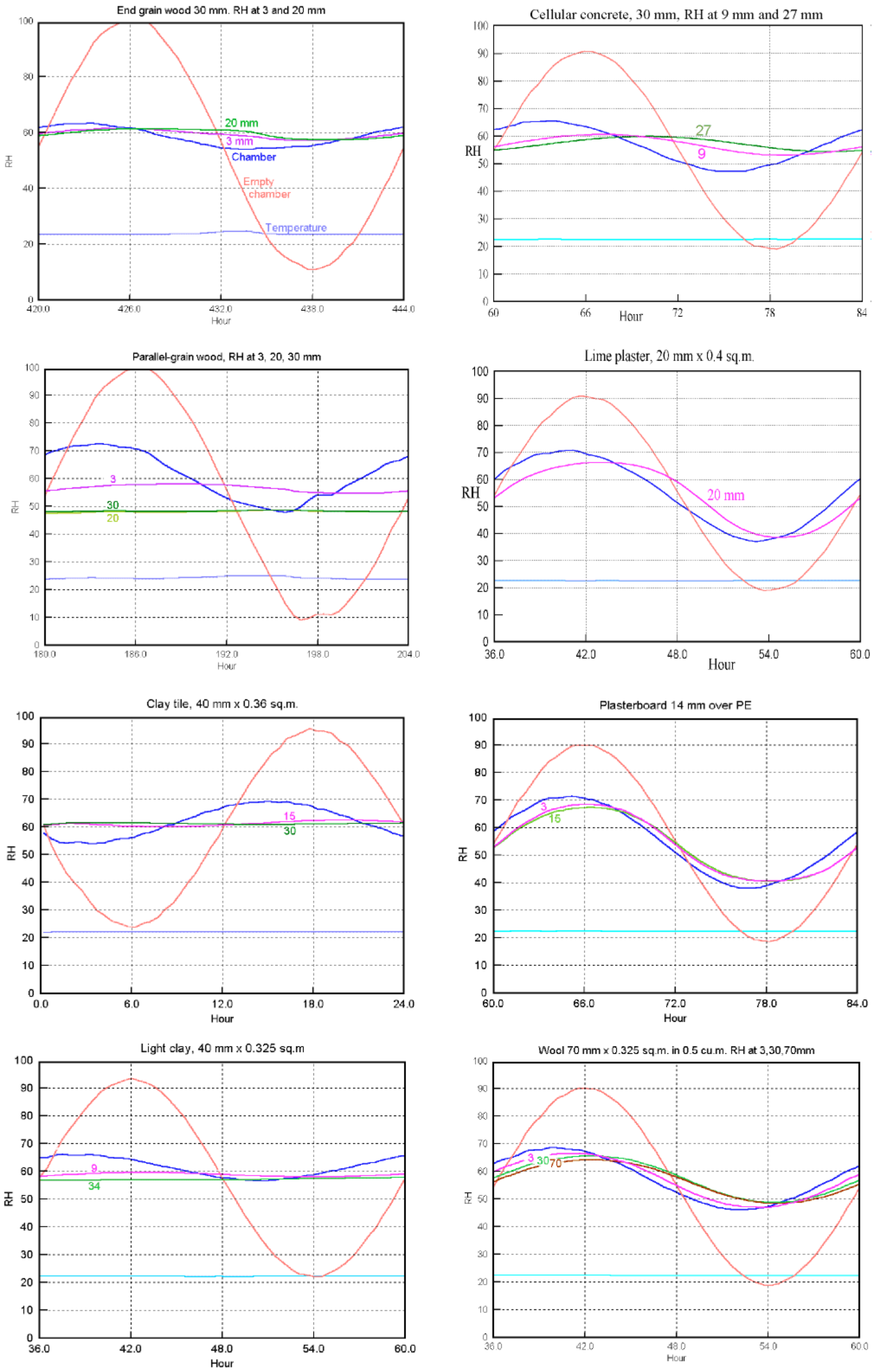

Figure 4.48 A collection of the 24 hour cycles for the simple materials.

5

COMPARING MODEL WITH MEASUREMENT

Definitions

Two material constants are needed for the calculation of the buffering effect of absorbent materials: The *water capacity* as a function of relative humidity and the *water vapour permeability*. One other constant is required: the *boundary layer permeability*, which depends on the air speed over the wall surface and the roughness of the surface.

Water capacity

The water capacity is mainly dependent on relative humidity with a slight temperature dependency. The water capacity is usually given in the form of a sorption curve, because it varies a lot with relative humidity. However, in the RH range of interest in this enquiry the curve can be simplified to a straight line, without significant inaccuracy. This is illustrated by the isotherm for bentonite shown below.

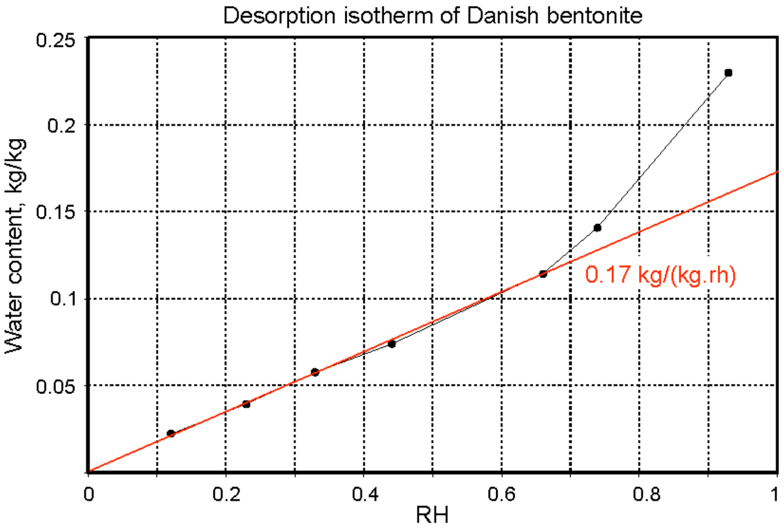

Figure 5.1 The sorption isotherm for sodium-bentonite from Rødby, Denmark.

The graph is usually drawn with weight percent against RH percent. In this chapter the water content is given in kg/kg and the RH is expressed as a fraction, instead of the percent used in the previous chapter.

For bentonite the curve is almost straight in the region between 0.4 and 0.65 RH, which is the region of interest for indoor climate.

There is one important complication with the sorption curve: it takes a different route according to whether the material is being dried or wetted. The route also depends on the starting point. This variation, known as hysteresis, can be quite significant when the RH cycle is wide, as can be seen from the curves for wool and paper insulation in figure 5.2

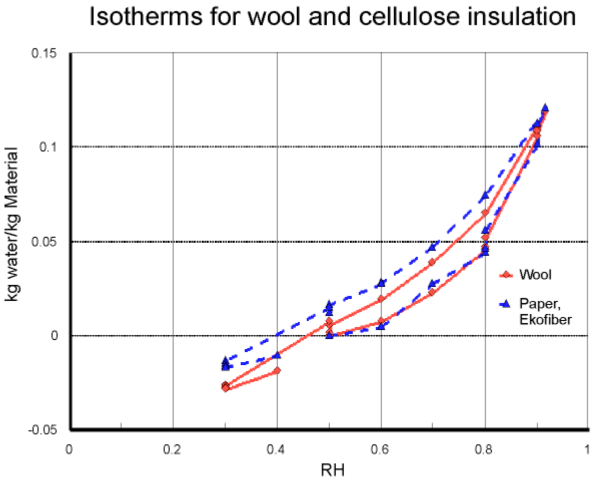

Figure 5.2 Sorption curves for wool (solid line) and for paper fibre insulation. The cycle starts at about 0.5 RH and goes up.

If the cycle is between narrower limits the RH follows a shallower slope. The slope used as the moisture capacity should therefore vary according to the recent history of RH change. In this model the problem is sidestepped by measuring the slope of the sorption line when the materials are cycled repeatedly between 0.4 and 0.65 RH, representing the region in which they cycled in most of the experiments reported in chapter 4. The values are shown graphically in figure 5.3

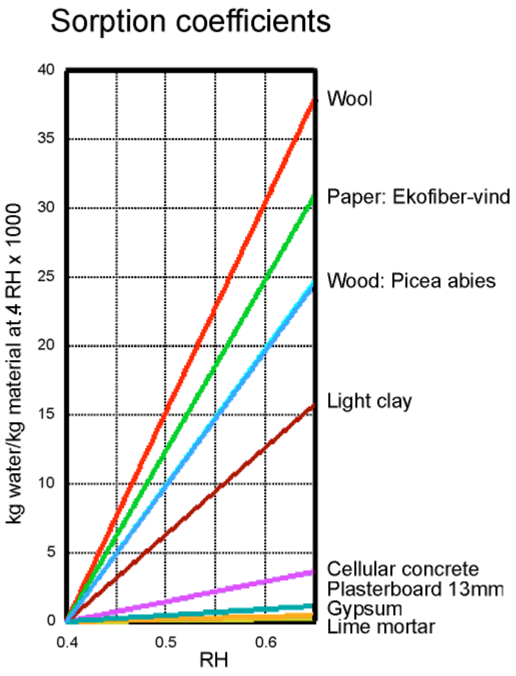

Figure 5.3 Sorption of water by various materials as a function of relative humidity. The RH is cycled between 0.4 and 0.65. The materials will not actually follow the lines shown on the diagram but will trace out a narrow elipse with sharp limits, as in figure 5.2. The slopes of these lines give values for the water capacity which is used in the computer simulations.

The materials shown in figure 5.3 can be grouped into three types.

An organic group is represented by wool and cellulose. These materials have very high water capacity, attributable to hydrogen bonding sites on the polymer molecules.

The clay and the cellular concrete represent silicates with a large surface area per kg. Here the water is also bound to hydrogen bonding sites but because they are only on the surface the water sorption is moderate to poor.

The final group, represented by lime and gypsum plaster, contains coarse grained mineral aggregates which are wettable by water but which have very little capacity for absorbing water at moderate RH.

There is one group which is not represented in the diagram. This is materials which are naturally water repellent or are treated with chemicals to make them water repellent. Examples are perlite insulation and Leca pellets, both of which are treated with silicone to make them water repellent and therefore useful in places where water would otherwise be drawn into structures by capillary suction.

The water vapour permeability

The water vapour permeability is quoted as weight of water transmitted per second through a metre cube of material with a vapour pressure difference of one Pascal across it The unit is kg/(Pa·m·s). This is a very small number which is usually multiplied by 10^{12} for visual clarity.

The water vapour permeability is dependent on the prevailing relative humidity and generally changes rapidly at high RH. However, in the RH range of these experiments the permeabilty can be considered constant, an assertion that was tested by measuring several of the materials at several gradients: 0 - 0.5 RH, 0.5 - 0.76 RH. The difference for wool insulation, for example, is 6 percent.

The water absorption coefficient and the water vapour permeability are not well defined for commercial building materials because of variations in composition and in production technique. The density also varies considerably. The relevant properties, in the relevant RH range, were therefore measured for nearly all the materials used in these experiments. A summary of the values is given in table 5.1.

The permeability of wood in a tangential/radial direction was taken from Kumaran (22). The values for Falkenlowe brick are from Poul Klenz Larsen (22a). This brick is made with a traditional slow firing, which gives it an unusually low moisture absorption.

The water capacity of the bentonite - perlite mixture is much lower than that of the pure bentonite, although perlite contributes almost nothing to the density of the product, and should therefore not influence the value, because it is itself non-absorbent. There is certainly scope for improving the moisture absorption of light clay mixtures by using different fillers and maybe different mixing techniques.

Material	**Water capacity** **kg/(kg.rh) x 10^3**	**Diff. coeff.** **kg/(Pa.m.s)x10^{12}**	**Density** **kg/m^3**	**Remarks**
Wool insulation	152.0	140 (.5-.76)	19	Scandan
Wood, radial/tangential	98.0	2	384	Picea abies
Wood, longitudinal	98.0	88 (.5-.76)	384	Picea abies
Light clay mix	63.0	22 (.5-.76)	876	Bentonite/perlite
Cellular concrete	14.0	32(.5-.76), 22(0-.5)	782	
Gypsum board	4.8	30(.5-.76), 16(0-.5)	685	
Gypsum, cast	1.6	32	1235	
Lime mortar	0.4	18(.5-.76), 15(0-.5)	1818	1:3 sand
Brick, Falkenløwe	0.6	13	1725	From ref. 22a
Vapour retarder	120	0.03(0-.5)	400	Miljøisolering B2

Table 5.1 The essential properties for modelling the behaviour of the materials used in the experiments.

Water vapour transport through the wall surface

The other constant used in the modelling is the diffusion across the boundary layer of air at the surface of the wall. This constant depends on the air speed and on surface texture. The various experimental values have been reviewed by Wadso (14). At 0.2 m/s, which is just a breath away from still air as we understand it in everyday life, the boundary layer thickness is changing rapidly with air speed, so the moisture transfer rate is not well defined. Extrapolations from curves made at higher velocities suggest a value of $4\cdot10^{-8}$ kg/(Pa·m^2·s). The results of the buffer calculations are not strongly influenced by variation in this number. Notice that the unit is different from the material diffusion constant described above, having square metres in the denominator. This is because the boundary layer thickness is hard to define and is therefore removed from the unit.

In the model, the wall surface slice uses this value, which is a property of the room, to calculate the water streaming into it, without invoking its own thickness at all. This is permissible because the slice is made very thin. The danger then is that the surface slice absorbs so much water into its tiny volume during a single iteration that it attains an unreasonably high RH. This approximation therefore forces a rapid cycle time.

Scaling the dimensions

The free space in the chamber is taken as a constant 0.5 m^3. It varies a little with the thickness of the individual test walls. This volume was measured with a wall of about 50 mm thickness and 0.5 m^2 area. The wall area did vary somewhat because of the different natural sizes of the various tiles under investigation.

The program assumes one square metre of wall in a room which is a long square prism, one square metre at the end, extending in depth to give the correct ratio of volume to wall area. The flux cycle was usually of 4.8 g half amplitude for the 24 hour cycle, changing proportionately for longer or shorter cycles, so that the steepest rate of change of flux on the sine curve was always about the same. This flux was divided by the wall area before insertion into the simulation program.

Simulation of the performance of the lightweight clay tile wall

The four day cycle for the lightweight clay tile wall is taken as an example for detailed analysis, because it shows a reasonable cyclic variation from all sensors.

The starting data for the simulation are listed here:

Wall area 0.325 m^2
Volume corresponding to one square metre: 1.54
Actual flux: 0.0192 kg half amplitude, corresponding to 0.0592 kg at 1.54 m^3
The wall thickness, 40 mm., is divided into slices: 0.5 mm, 0.5, 1, 2, 2, 3, **3**, 5, 8, 9, **6,** (0.1 impermeable back). The bold numbers mark the slices which will be compared with the data from the buried RH sensors.
Diffusion rate through the surface: 40,000 x 10^{-12} kg/(Pa.m^2.s)
Diffusion coefficient of the wall 22 x 10^{-12} kg/(Pa.m.s)
Water capacity of the wall 0.063 kg/(kg.rh)
Density of the wall 876 kg/m^3

Comparison of model with experiment

The static data does not match the experimental data. The two graphs are shown side by side below.

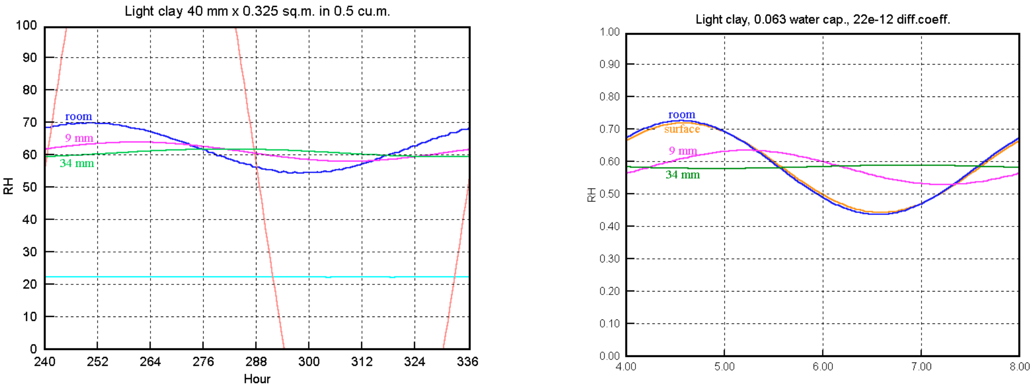

Figure 5.4 On the left is the measured performance of the lightweight clay tile wall over a four day flux cycle. On the right is the performance calculated according to the statically measured values for water capacity and diffusion coefficient. The very steep curve on the left graph is the 'inert' RH for the empty chamber.

The model seems to give the clay too small a water capacity, because the room and the 9 mm curves are swinging more than the measured values. The diffusion coefficient also appears to be too low, because the RH at 34 mm has a smaller amplitude, and a much more delayed phase, than the measured curve.

The diffusion through the boundary layer is not an important influence, as indicated by the closeness of the curves for the room RH and for that in the surface layer of the wall.

The next two graphs show attempts to get a better match by changing the two material constants.

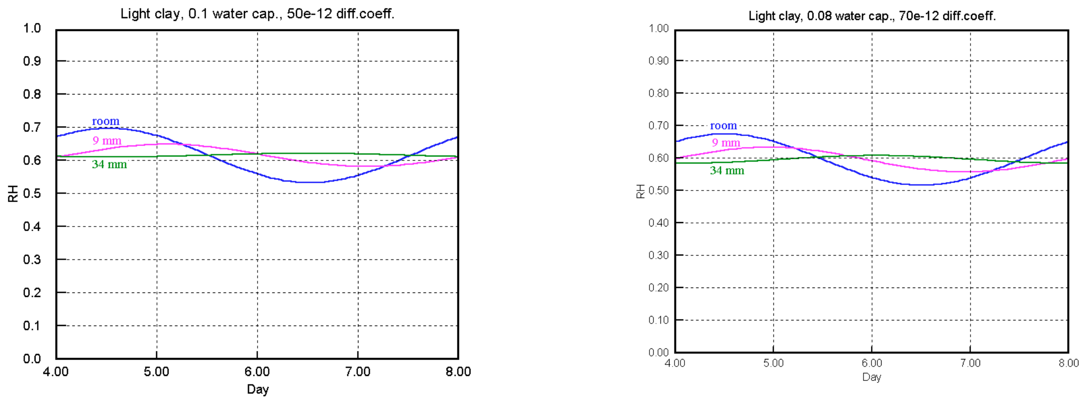

*Figure 5.5 A***:** *On the left: both water capacity and diffusion coefficient have been increased over the statically measured values. The fit to the measurements is better but the phase shift is too great in the RH cycles within the wall.*

The best match is obtained with a slightly raised water capacity and a much greater diffusion coefficient. Even then the calculated phase shift in the deeper layers of the wall is somewhat greater than the observed values.

The greater diffusion coefficient is not unexpected. The static measurements were made on a perfect, crack free specimen, whereas the tiles had many shrinkage cracks and had air channels through and alongside the straw reinforcement. The real wall would certainly have a higher permeability but the three times higher value is unlikely.

There is one assumption in the program which seems to be questionable. The program assumes instant equilibrium with the water diffusing through. This seems unlikely when one looks at the microphotographs of the clay tile structure. There are large voids with clumps of much more finely grained material. One can speculate that water vapour travels easily through the net of large pores, losing, or gaining only a little water by interaction with the tightly packed clay particles which are the real absorption sites. Full equilibrium with the interior of the tight packed zones would come more slowly and only approximate to the model prediction deep in the interior where everything happens very slowly.

Another possibility is air flow within the wall, driven by the slight density difference of the air at different RH at different depths and also by the turbulent air movement within the chamber.

The revised set of basic constants was then applied to the one day cycle and compared with the experimental data.

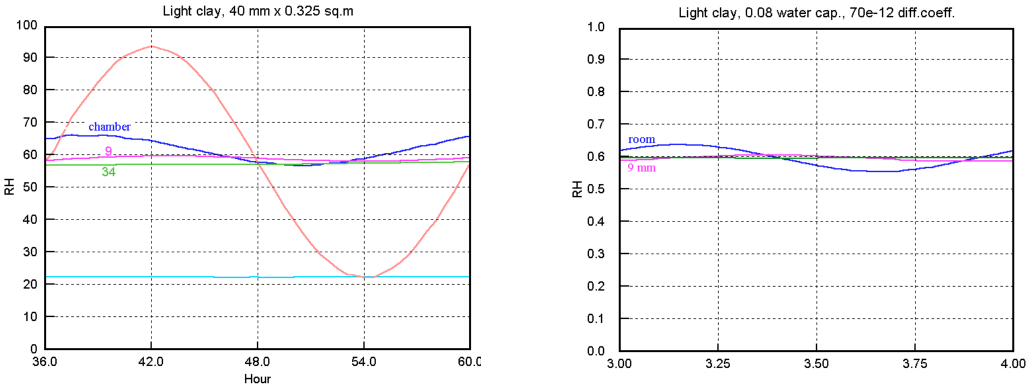

Figure 5.6 A: On the left is the measured performance of the test wall under a daily flux cycle. B: On the right is the modelled performance, which shows a slightly too good stabilisation of the climate.

The one day cycle shows good agreement between model and reality. The model predicts a slightly smaller than measured RH cycle in the chamber. The RH cycles within the specimen are now very flat and cannot be interpreted quantitatively.

Any delay in the sorption process will have more effect at this short time scale so the direction of the error is consistent with this hypothesis. The data, particularly the depth of the measurements within the tiles, are not well enough defined to allow a more profound analysis of these results. The RH sensors are physically large relative to the thickness of the wall and the wall itself is not homogeneous enough to allow one to assume that one sensor can give a true account of the state of the material at a given depth.

Extension of the model to longer climate cycles

The next section extrapolates these short measurement times to years. The purpose is to examine the feasibility of using clay walls as stabilisers for the climate in houses, with their moderate air exchange rate and in museum stores and archives, with a very small air exchange rate. The model is not intended to be a quantitative design tool but to illustrate the decisive influence of ventilation rate on the performance of absorbent walls.

Houses typically have at least one quarter of an air change per hour. The next diagram shows the performance of a house with light clay walls 400 mm thick, sealed on the outside so that the weather has no influence except through the air exchange.

The RH outside is set to 0.2, which is typical for the winter air, brought to the indoor temperature. This graph therefore represents the resistance of the house to drying at the onset of winter. There are no indoor water sources to resist the drying process, which is unrealistic for an occupied house. The rather impressive buffering performance must therefore be regarded as quite realisable in practice.

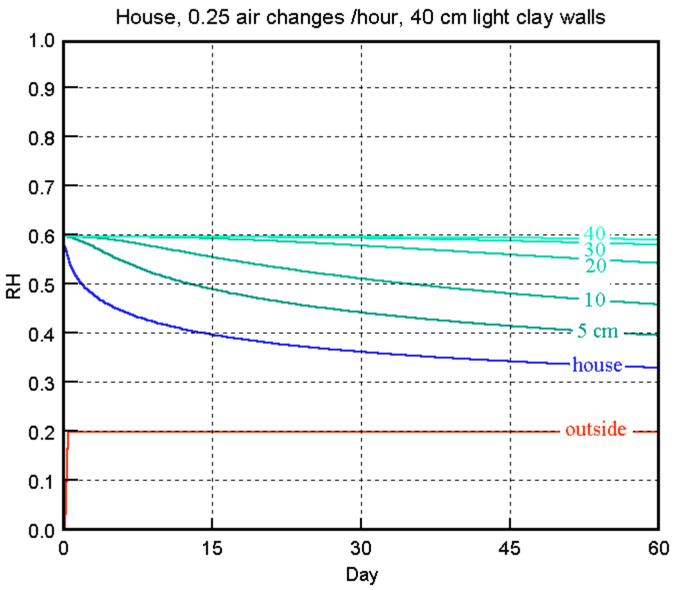

Figure 5.7 The climate in a house with one quarter of an air change per hour, 400 mm thick walls of lightweight clay mix, sealed on the outside. There is one square metre of wall to one cubic metre of room volume. The outdoor climate is set at 0.2 RH to imitate the RH of winter air brought up to the constant 22.6°C of the house.

The performance is quite impressive. It suggests that modern houses, which are sealed only to reduce heat loss, would benefit from humidity buffering by porous walls.

The wall thickness is a little excessive, from the point of view of humidity control, because by the time the surface has half lost the battle with ventilation and has let the room descend to 0.4 RH, after about two weeks, the deepest layers of the wall have hardly released any water at all. The optimum thickness for humidity buffering is about 20 cm.

If the outer wall were not sealed on the outside orthodox wisdom would suggest that it will lose water to the outside, diminishing its effectiveness in buffering the interior. This is probably not so: there should be a movement of water vapour through to the interior, reinforcing the good performance shown in the diagram. This matter is discussed further in a later section, where a model is used which includes the effect of a temperature gradient through the wall.

At this ventilation rate the annual climatic cycle overwhelms the buffering effect of the wall, regardless of its thickness. The simulation is shown in the next diagram, with the warning that this is an extreme extrapolation of a four day measurement and must not be taken as more than an order of magnitude calculation.

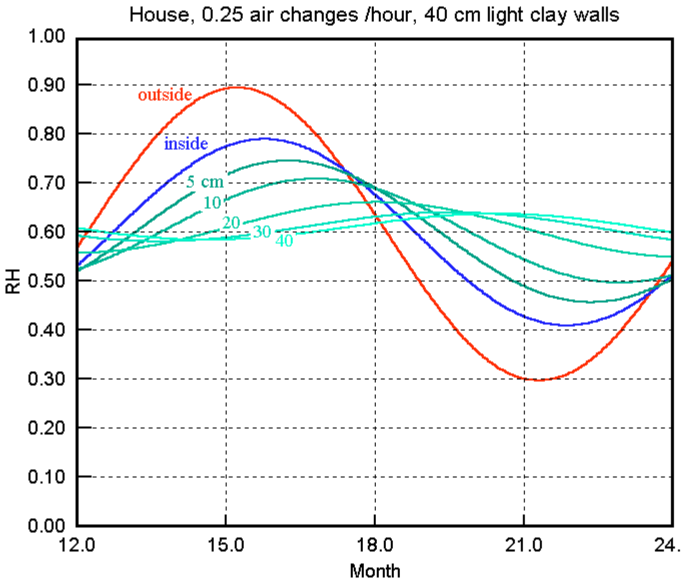

Figure 5.8 One year's climate in a house with one quarter of an air change per hour, 400 mm thick walls of lightweight clay mix, sealed on the outside. There is one square metre of wall to one cubic metre of room volume. The outdoor climate is varied from 0.3 to 0.9 RH to imitate the RH of the outside air brought up, or down, to the constant 22.6°C of the house.

Humidity buffering in archives and stores

Buildings, or rooms, that do not have permanent residents do not need a quarter of an air change per hour. The practical limit for air change that is achievable without building a house like an aeroplane is one air change per day. Christoffersen reports one air change in 20 hours for the State archive in Schleswig, which he investigated rather thoroughly (4).

Christoffersen's measurements established that an archive full of papers will easily buffer the yearly cycle of the climate to an acceptably low amplitude among the archive boxes. His data are given in the next chapter. There is no need for a mud wall in the Schleswig archives. But suppose that the archive contains only metal, like the Smithsonian collection of patent models. Can the walls provide stability through the year?

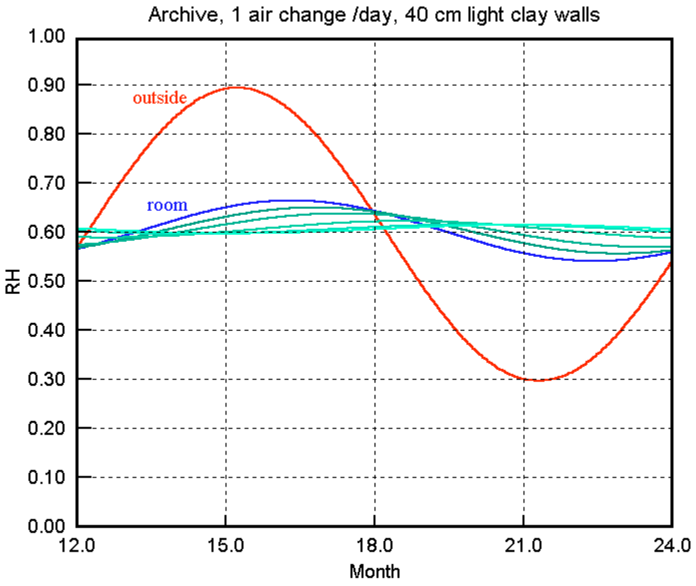

Figure 5.9 The annual climate in an empty archive, or a store with unabsorbent material. The air exchange rate is once per day.

No problem! Notice that at this long cycle time and low exchange rate the full 400 mm thickness of the wall is involved in the buffering. A thicker wall would not, however, significantly increase the stability, which is already very good indeed.

Let us now consider a historic collection of steam locomotives. Can these be safely exhibited in a building made of lightweight mud?

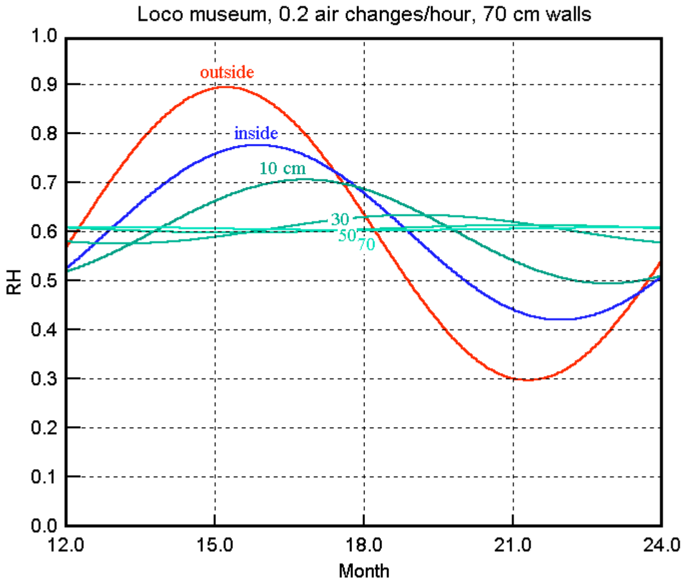

Figure 5.10 The railway museum with earth walls.

The ventilation rate has been set at 0.2 changes per hour because there is public access but the building is vast, so that this exchange rate provides ample cubic metres of fresh air per person, as required by the regulations.

The buffer will certainly protect against short periods of unusually wet weather, and winter dryness is no problem in a museum devoted to metallic machinery. A combination of passive buffering by absorbent walls with dehumidification at a steady rate during the summer would certainly provide an excellent climate for the machinery.

These modelled results are an extreme extrapolation from the original experiments in a half cubic metre steel box with slabs of dried mud stacked up inside. I emphasise that they are shown here to demonstrate the potential of the concept of buffering with absorbent walls.

Adding the temperature gradient through outer walls

The experiments and the model runs have been made with equipment and program code that works at a constant temperature. This is fine for walls used as separators within a house but the outer walls represent a considerable fraction of the wall area which is controlling the inside climate. The effect of a temperature gradient through these walls cannot really be imitated by putting in an unrealistically low outside RH to imitate cold air brought up to the indoor temperature. There is an interaction between heat and moisture flow which needs to be modelled to give a complete impression of the various effects that contribute to the buffering of the indoor climate.

What is the driving force for moisture movement?

The additional calculations needed when modelling the effect of temperature on moisture movement through outer walls have been summarised in the last section of chapter 3. A consequence of these calculations is that moisture should flow through a porous, absorbent wall driven by the relative humidity gradient, rather than by the concentration gradient.

In a temperate climate the relative humidity gradient is usually inwards during the winter and spring, changing to a weaker reverse gradient during the summer. If water diffuses through the wall under the influence of the RH gradient the indoor relative humidity will be higher than that calculated for outside air brought directly in and warmed to the indoor temperature. Consequently, the water vapour concentration is higher than that outside. Water movement through definite cracks in the structure will, on the other hand, tend to even out the water vapour concentration. This competing process tends to reduce the inside RH.

The purpose of the next computer simulation is to evaluate the relative magnitudes of these two processes. If the water pumped in by the RH gradient is very small compared to that lost by ventilation then the question of which gradient, RH or concentration, should apply is of only academic interest. If the two processes are of similar magnitude then it is important to test the program against an experiment, because clarification of this mechanism is an important issue in the design of walls containing absorbent materials, or in walls designed deliberately to use absorbent materials to move water against the vapour pressure gradient.

The mechanism invoked to move water against the concentration gradient in the market leaders in computer simulation of moisture movement, WUFI and MATCH, is capillary movement of liquid water.

Another way of looking at the matter is to ignore the possible mechanism and concentrate instead on the measured fact that the sorption isotherms for absorbent materials lie close together, if relative humidity is used as the controlling variable (see cotton as an example, in figure 1.8). A logical consequence of this is that if there is a temperature gradient across an enclosed mass of absorbent material the RH should be almost the same at both surfaces. If the RH at the cold side is increased, then there will be movement of water towards the hot side, even though the water vapour concentration is higher at the hot side. Water is being pumped against the concentration gradient, while the heat flows the other way.

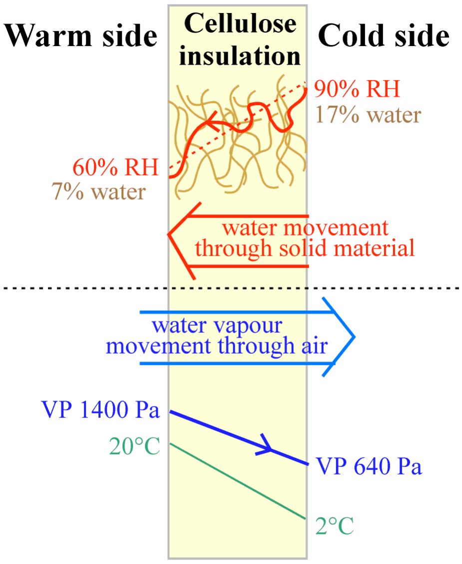

Figure 5.11 The two mechanisms by which water vapour can move through an absorbent, porous material. At the top: molecular movement through the material. At the bottom: diffusion through the pore spaces, driven by the concentration gradient.

This mechanism allows transfer of water against the concentration gradient at all values of RH, whereas the other programs put a stop to the process at a middling RH, so that the water gets trapped in a sort of whirlpool between the limit for capillary movement and the high RH side of the wall, usually the outside. Here the water moves as far as it can inwards by capillarity, then gets caught up in the outward moving vapour stream in the pore space.

It is quite likely that the two processes leading to outward and inward movement respectively occur together in walls that combine absorbent materials with unabsorbent insulation, for example.

The RH driven mechanism requires that the material in the wall be hygroscopic right through. This is far from the case in modern buildings. Most building materials are nonabsorbent, even if they are porous: gypsum, mineral fibre and brick have very little absorption at the 60% RH that is typical of the indoor climate. Cellular concrete is the only commonly used materials which is both porous and absorbent at moderate RH. Wood and concrete are absorbent but not very permeable. It is therefore not surprising that condensation is often encountered in modern buildings, because there is no absorbent material available to pump back the water that enters the wall from the inside of the building. There is abundant evidence that most of the water in walls gets there by flow of air through openings in the construction, or by flow of liquid water from the outside, so the question of which *diffusive* transport mechanism dominates is not yet decided (31).

Moisture movement in a wooden hut

The first diagram, 5.12, shows the climate in a room lined with wooden panelling. All parts are at the same temperature. The diagram shows the good stabilisation provided by the wooden panelling.

Figure 5.13, on the next page, shows the same room, but now the wooden panelling is also the outside wall, subjected to a temperature gradient.

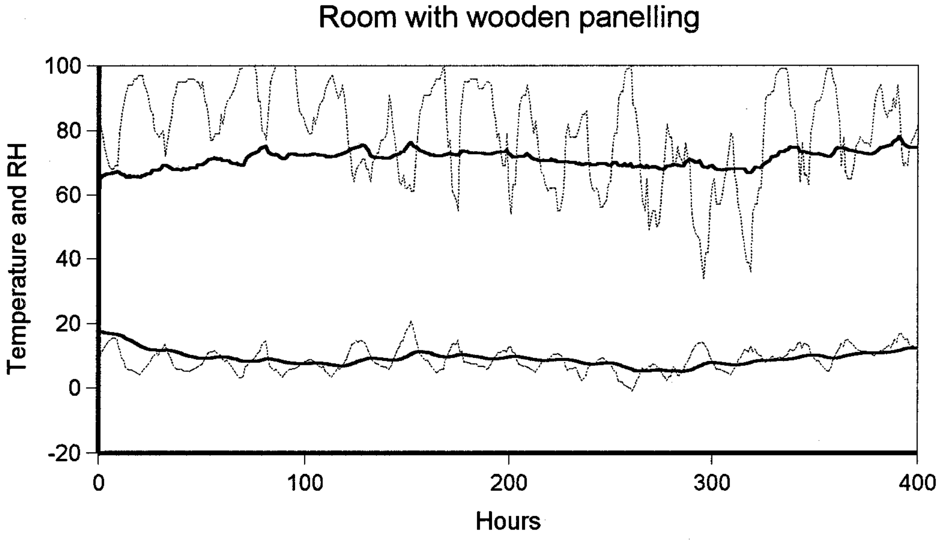

Figure 5.12 The climate over 12 days inside a room 10 x 10 x 2 m high with all surfaces faced with unvarnished wood, 0.1 m thick, sealed at the back. The air exchange rate is 0.2 per hour. The outside climate (dotted) is typical for Danish weather in April. The room (bold) is unheated so the temperature and the RH follow the outside (dotted) values.

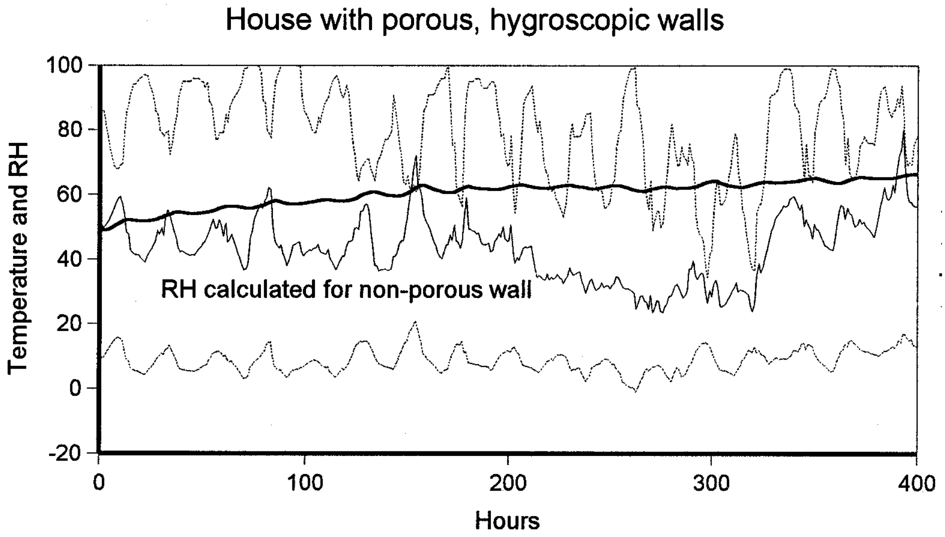

Figure 5.13 The climate in a wooden hut of the same dimensions as in figure 5.12, with walls 0.1 m thick, porous right through. The air exchange rate is now 0.1 per hour and the room is warmed to a constant 18°C. The wood has the longitudinal direction oriented through the wall, to increase the diffusion rate of water vapour.

The upper dotted curve is the outside RH and the lower dotted curve is the outside temperature. The middle fine curve is the inside RH calculated for air at the inside temperature with the outside water content. The smoother, bold line is the inside RH, calculated on the assumption that water is diffusing through the wall driven by the RH gradient.

It is immediately apparent from this second diagram that water diffusion through walls as a result of a relative humidity gradient is comparable with the rate at which water leaves through cracks in the structure. It must be acknowledged that end-grain wood is an unusual building material, but the results of this theoretical exercise are interesting and provocative.

The only experiments that I know which support the assertion that the RH gradient is the driving force for diffusion across a temperature gradient were made by Martin Krus (12, pp 54-55) and by Siau and coworkers (31). Krus set a 16 mm slice of particle board, presumably pressed wood shavings, over a cooled bath of a saturated salt solution. The temperature was 13°C below, and 23°C above the board. He measured the RH below and above the board. The actual value of the RH is not stated but he quotes a dew point excess above the board of between 1 and 2 degrees.

This result is so important to the understanding of moisture movement through porous walls that it needs to be confirmed and quantified for several materials. Krus' explanation is that water flows along the walls of capillaries against the vapour flow through the centre. A chemist's explanation might be that water moves from absorption site to absorption site according to the vacancy density, which is greater at a lower RH but is hardly affected by temperature. If one thinks of RH as a chemical potential and the movement of water molecules as a reversible reaction with receptive sites on the stationary phase it is not hard to believe in RH as the driving potential. Siau invokes a thermodynamic explanation for his experiments on diffusion through solid wooden blocks.

Summary of chapter 5

This chapter begins with a comparison of the measured and the modelled moisture exchange between air and a clay mixed with lightweight filler. Agreement between theory and measurement for the dynamic experiment can only be attained by tripling the statically measured diffusion coefficient. This is a large discrepancy. However, the model, once modified, predicts the observed RH at 24 and at 96 hour cycles with reasonable agreement.

The model parameters were then applied to a house with a leak to the outside air. The predicted buffering against two weeks of cold, dry (in kg/m^3) air infiltrating at 0.25 changes per hour was quite impressive and suggests that the concept of moderating climate against short periods of unusual weather is well worth investigating on a larger scale.

Buffering of specialised buildings which can be run with very low air exchange rates, such as museum stores and archives, is impressive. A significant flattening of the yearly cycle of RH can be achieved by a wall of 70 cm thickness, provided the air volume to wall area volume is about one to one.

The flux through a wooden wall which is porous right through and subjected to both a RH and a temperature gradient is modelled to show that the theoretically predicted pumping of water against the concentration gradient is of comparable magnitude to the exchange of water vapour through leaks. This is a theoretical exercise which certainly needs experimental verification.

Taken as a whole, the evidence and arguments presented in this chapter suggest that humidity buffering by porous walls is a significant unused potential in common building materials.

6

CASE STUDIES IN HUMIDITY BUFFERING BY POROUS WALLS

Humidity buffering in the real world

The purpose of the experimental part of this thesis has been to give some quantitative support to the concept of using interior walls as buffers for the interior climate, particularly in museums and archives. In this chapter I describe some case histories where the principle of using porous materials as a buffer has been applied in real life. In some of these examples buffering has not been the intent of the builder.

Humidity buffering by the walls of Fanefjord Church

Figure 6.1 Fanefjord Church, Møn, Denmark, from the south west. Photo: Poul Klenz Larsen

There are few buildings which are porous right through. Stables and churches are just about the only buildings which have a porous inner surface to the outer walls. They are limewashed and many of the churches are also decorated with ancient paintings. It is the challenge of preserving these paintings that has provided the opportunity to study their microclimate in some detail.

The first example is Fanefjord Church on the Danish island of Møn (23). The walls are made of brick, with lime plaster inside and outside. The ceiling is brick vaults.

The climate inside and outside the church is shown in figure 6.2. The inside RH is lower than that outside, as expected, because the church is heated. The diagram also has a line showing the expected inside RH, calculated from the water content of the outside air, operated on by the inside temperature

The observed RH is higher than it should be and is remarkably stable at about 45%. There must be some source of water which humidifies the church, so that the interior water vapour concentration is higher than that outside.

Churches are simpler to study than houses, because there is very little man made moisture added to the inner climate. It would be easy to explain the phenomenon as water from the ground ascending into the floor and up the walls but there is no quantitative evidence for this.

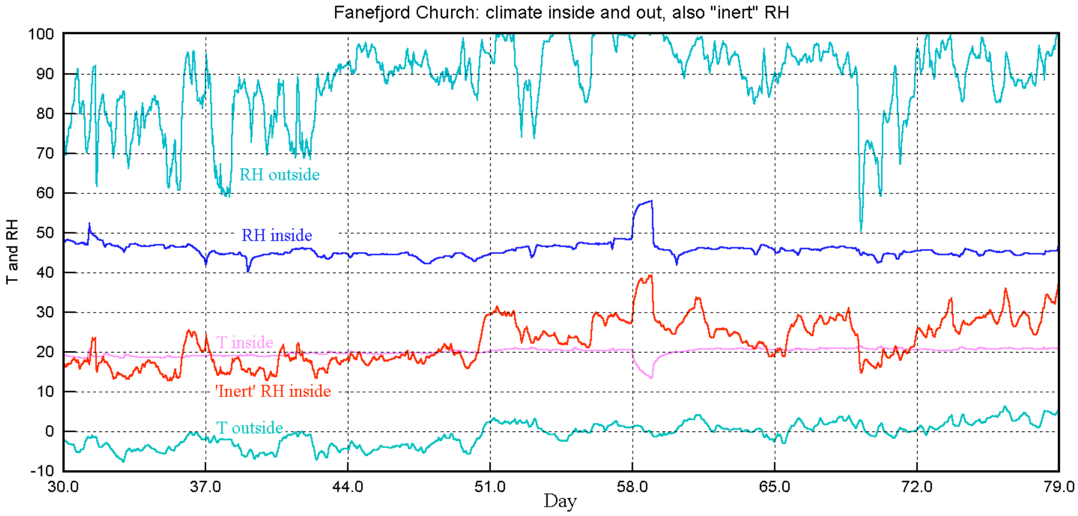

Figure 6.2 The climate inside Fanefjord Church. The red line marked 'Inert' RH is calculated from the water content of the outside air raised to the inside temperature. The measured RH is much higher. This humidification is attributed to movement of water inwards through the wall, so that the RH across the wall tends to equality, rather than the vapour pressure, as orthodox theory would suggest. Climate data from Poul Klenz Larsen.

The observed buffering cannot be explained by buffering by the wall in the moderate RH region of the sorption curve. This can only provide buffering for about a day. A model prediction of the performance of a brick church is shown in the next diagram.

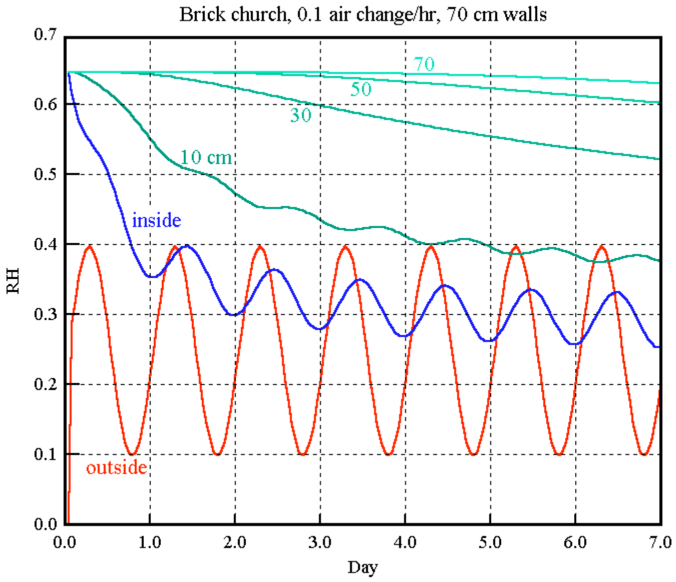

Figure 6.3 A computer model of a brick building with 0.1 air changes per hour, as measured in Fanefjord Church. The model simulates the onset of the heating season by using a very low outside RH of air at the same temperature as the church interior.

The computer model predicts that the interior RH will only be buffered by the walls over a period of about a day, with the long term adjustment to the average prevailing RH substantially complete after about a week. The observed buffering must be caused by another mechanism altogether.

Gundsømagle Church

The same pattern of climate occurs in Gundsømagle church in Zealand, Denmark (figure 6.4). This church is built mainly of lime tufa, which has a very open, porous structure and is reputed to hold water and give damp interiors. The wall is covered on both sides by lime mortar and limewash.

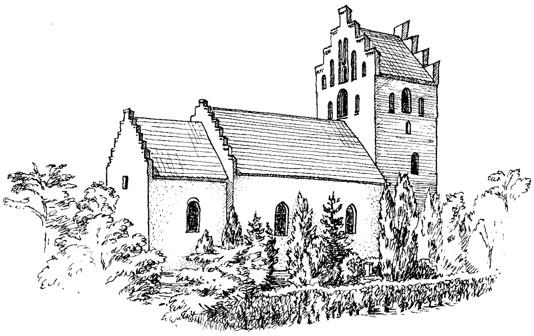

Figure 6.4 Gundsømagle Church, north of Roskilde, Denmark. The choir and nave are built of lime tufa.

The indoor climate in winter has a much higher RH than would be expected by calculating the RH of outside air raised to the inside temperature. The graph for a seven week period in autumn is shown in figure 6.5.

The pattern is the same as in Fanefjord: when the church is heated in winter the RH falls from the high summer humidity but remains moderate and surprisingly stable.

The climatic stability of Gundsømagle church was investigated in a two year campaign by Eshøj and Padfield (24,25,26).

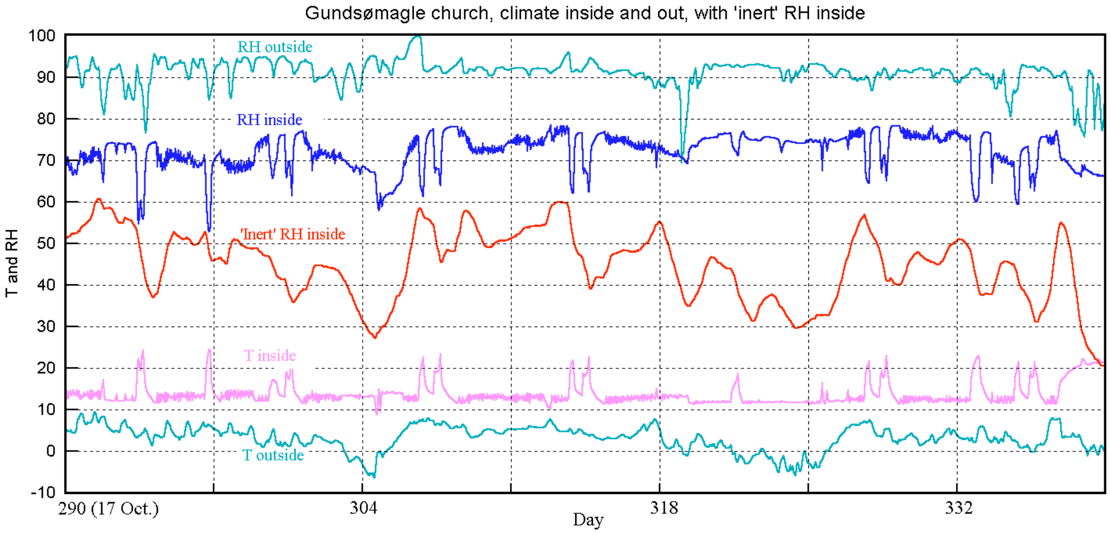

Figure 6.5 The microclimate in Gundsømagle Church, Zealand, Denmark. The curve in the middle shows the theoretical course of the RH in the church if the only source of moisture were the outside air. The curve is smoothed to take account of an air exchange rate of about 0.1 per hour.

The results are summarised here because they show the ability of supposedly relatively unabsorbent materials to contribute a very significant stability to the indoor climate. The mechanism for this stabilisation is, however, not established beyond doubt.

The influence of the walls on the microclimate in Gundsømagle Church

The reason for measuring the climate in the church was the conservator's concern about damage to the very delicate (in both the æsthetic and the material sense) wall painting, from the 12th century. A small corner of this painting is visible in figure 6.6. which also shows some temporary 20th century additions to the wall decoration.

The white box hanging from a string and resting very delicately indeed against the painting, is measuring the surface temperature of the wall and the RH and temperature of the room air. It can do both because the boundary layer, that is the transitional layer of air between wall and room, is only about 20 mm thick. The round device is a shallow acrylic cup, 200 mm in diameter, with its opening against the wall. A silicone membrane is stretched slightly around the perimeter to give an elastic seal against the irregular plaster surface. The temperature and relative humidity are measured inside the container.

With this arrangement in place we waited patiently for the few short periods which would reveal how the building behaves climatically. Such critical periods are often caused by unusual behaviour by the weather, or by people.

Figure 6.6 Measuring devices resting against the north wall of the choir of Gundsømagle church. The white box measures surface temperature and room temperature and RH. The circular cup measures temperature and RH in the enclosed space within 10 mm of the wall, and also measures the surface temperature.

Our opportunity came: for one week the heating was left on. It was a long sermon, or a mistake, but the physics is the same.

The series of pictures that follows builds up the interpretation of the climate step by step. The first picture shows just the measured climate in the church and outside.

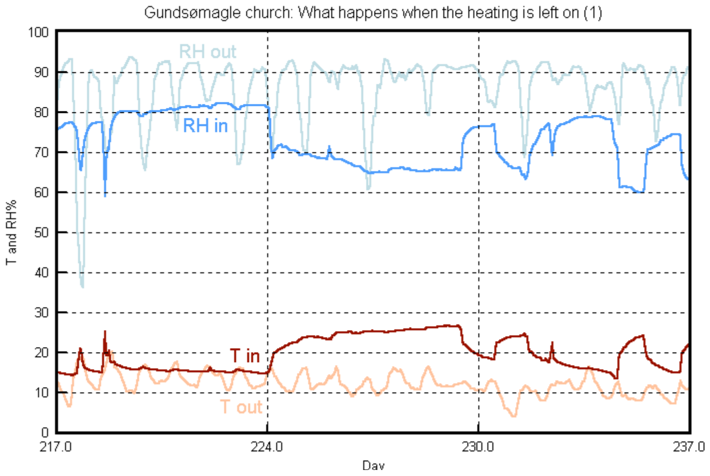

Figure 6.7 The climate during a three week period. In the middle week the heating was left on. Notice how the inside RH varies in the opposite sense to the temperature, as expected for the RH in a mass of air subjected to a varying temperature.

The next graph adds the theoretical RH calculated from the water content of the outside air and the temperature of the inside air.

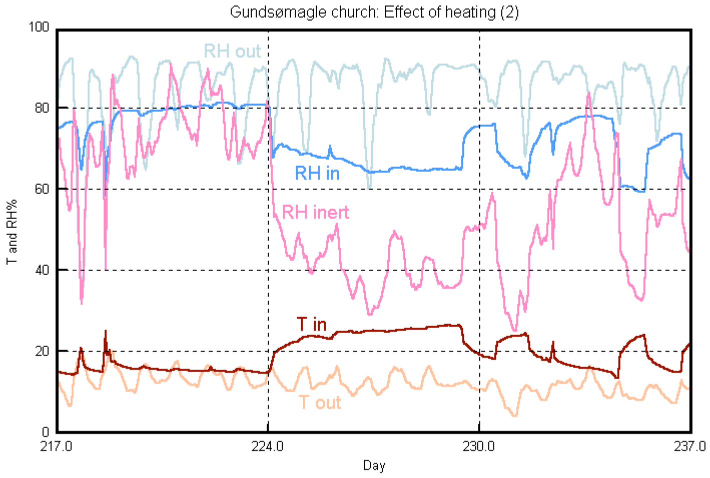

Figure 6.8 The new curve is the imaginary course of the RH calculated with the water vapour content of the outside air raised to the inside temperature. The calculated RH drop caused by heating is twice the measured drop.

There must be a source of water in the church to keep the RH considerably higher than that achieved by warming up air from outside to the inside temperature.

One possibility is that the walls release water vapour. When the RH falls because of the sudden rise in temperature, the wall should release water into the air to compensate. The wall will only release water vapour until the RH *at its surface* is again in equilibrium with its water content. In the next diagram the RH at the wall surface is calculated. This is obtained by taking the temperature and RH of the air in the church and calculating the water vapour content. This water vapour content and the wall temperature are then used to calculate a wall surface RH.

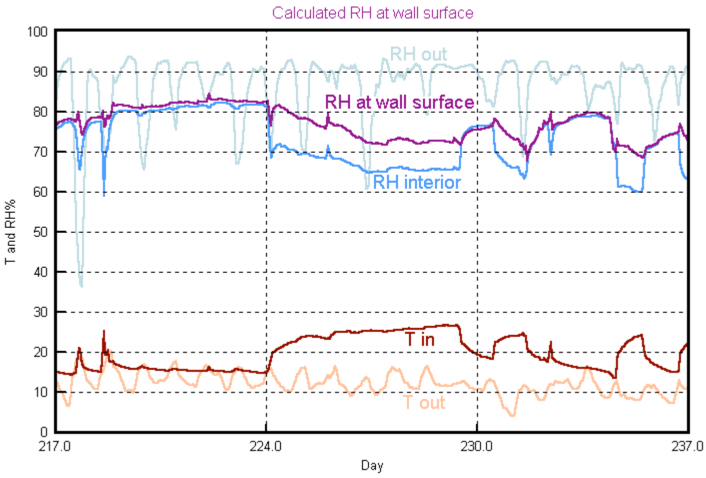

Figure 6.9 The RH calculated for the wall surface is added. This cannot be measured because the boundary layer is thin compared with the bulk of a RH sensor, which would also disturb access to the wall at the point of measurement.

Notice that there is no sudden jump in RH at the wall surface when the heating period starts. The RH gently descends, partly because the water reserves in the surface layer of the wall are released into the air but also because the temperature is slowly increasing throughout the period of warming.

The wall appears therefore to be buffering the RH perfectly *at the wall surface*. The remaining drop in RH in the church is due to the temperature difference between wall and room air, which is quite high because of the lack of insulation and also because of the suddenness of the heating, so that the thermal inertia of the thick wall keeps it relatively cool.

The hypothesis that it is the wall that is the RH buffer for the church climate is reinforced by data from the cup sealed against the wall.

The sensor within the cup, though close to the wall, is outside the boundary layer of cool air and yet cooler than the church air, because of the insulating value of the acrylic plate and the still air within the cup. The RH does therefore drop as the temperature rises but then remains steady, as one would expect, because there is no loss of water from the enclosure. When the heating is turned down the RH in the cup bounces back immediately.

The case for humidity buffering by the wall is reinforced by a separate experiment in which the same cup was placed against the floor. The RH in the cup did indeed rise, but at a rate so slow that the floor could not function as the main source of water.

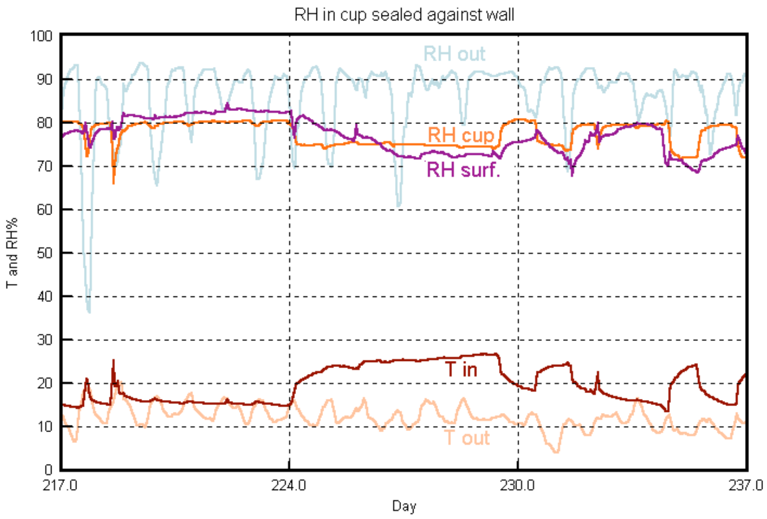

Figure 6.10 The RH within the cup sealed against the wall is shown in this diagram. In the stagnant air within the cup the RH is buffered perfectly by the wall. The small step down during the heating period is caused by the position of the RH sensor within the boundary layer.

The final graph in this series, figure 6.11, shows the climate over a longer period. The climate in the sealed cup is compared with the climate in the church. On about day 260 and again at day 285 the church was aired. The climate in the cup does show the influence of this influx of dry air, but not nearly as much as the room air.

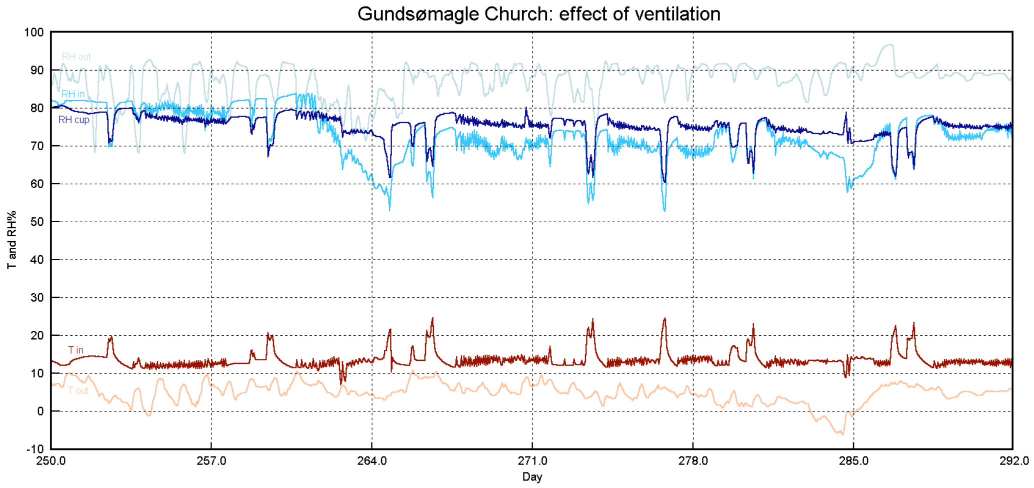

Figure 6.11 A longer extract from the climate record, showing two periods, around days 260 and 285, when the church was ventilated. The RH in the cup, the upper bold line, responds a little to the ventilation but much less than the air in the church. The church RH does not fully recover from the ventilation beginning on day 260. Recovery after day 285 is aided by a period of high outside RH.

How the church climate is controlled by the walls

The experimental evidence suggests strongly that the porous wall buffers the church air very effectively. This is surprising because the materials involved: lime plaster, brick and porous limestone, have very little buffering capacity at the moderate RH within the church. The surface area and the thickness available is large, because these materials are very porous. Even so, the rapid recovery after ventilation shown in figure 6.11 suggests considerable water reserves. An explanation of the phenomenon must also account for the continuous excess water content in the air within the church, compared with that outside.

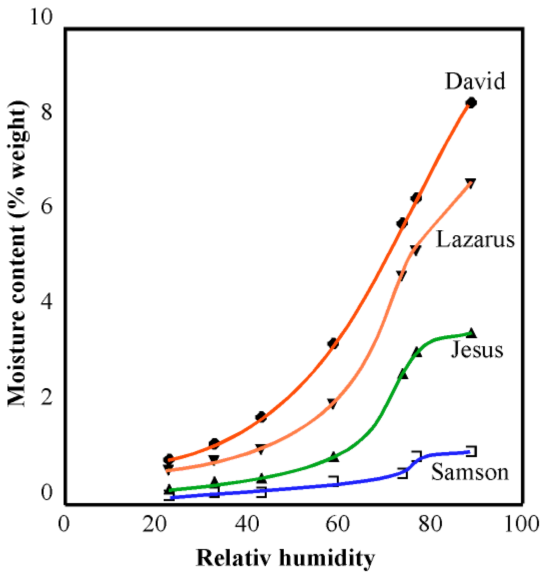

Figure 6.12 The sorption isotherm of lime mortars from Fanefjord Church (23). The samples are taken near the figures painted on the vault.

The three steepest curves are for mortars with close to 1 mol/kg soluble salts. The lowest curve is for a relatively pure mortar with about 0.15 mol/kg.

Data from Poul Klenz Larsen.

One possible mechanism is provided by the hygroscopicity contributed by the salt content of normally non-absorbent materials. But there is another mechanism that does not depend on contamination of the bricks. At high RH the moisture content of clean brick reaches less than 10g/kg. Brick is however easily wetted and the capillary water content is about 150 g/kg, depending very much on porosity. Fog, dew or rain will wet the outside of the wall to this condition. The water will now move by capillarity inwards to a point where the temperature is higher. The vapour pressure at this point will be higher than that outdoors. Further inward movement of liquid involves smaller pores where the RH over the meniscus is lower, so the vapour pressure will fall again. In addition the capillary movement will be slower through the finer pores.

At some point within the wall the capillary movement of water becomes insignificant in comparison with the vapour diffusion. At this point, according to Poul Klenz Larsen, the vapour pressure is still higher than that outside and higher than that in the interior of the church, so further movement of water to the interior is down the vapour pressure gradient all the way.

My way of looking at the matter starts off in the same way, with a reservoir of capillary water towards the outside of the wall, with a fairly definite boundary where vapour diffusion takes over. The vapour diffusion, however, follows the relative humidity gradient into the interior of the church.

Both theories give the same result so the only way to decide the matter, or to reveal a completely different mechanism, is to make an experimental wall or bore holes in an existing wall and measure temperature and RH through the section.

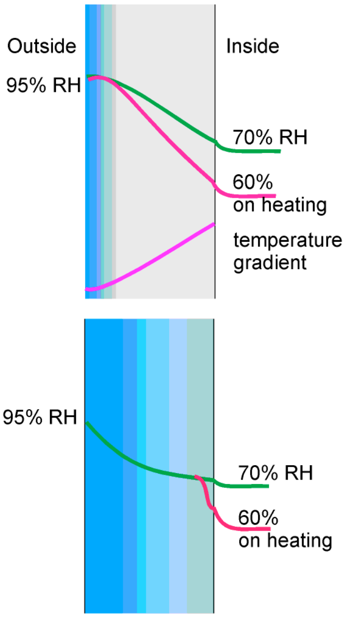

Figure 6.13 Two models for RH buffering by church walls during brief periods of heating.

In the top diagram a reservoir of capillary water just within the outside surface of the wall feeds vapour into a linear vapour pressure gradient through the scarcely absorbent pores of the wall.

In the bottom diagram a more absorbent wall has buffer capacity right through to the inside. The gradient is more unpredictable, depending on the history of the weather. Only the inner surface responds to episodes of heating. This model fits the data from Gundsømagle church, except that the measured properties of the materials do not provide enough hygroscopicity. Soluble salts within the wall do, however, increase the buffer capacity.

The observed response to heating of the church interior can be explained in this way: at a steady state one would expect that the RH gradient would fall in a linear manner through the wall. The greater part of the thickness of the wall, which will be below 90% RH, will contain very little water compared to the outside layer. It will function as a nearly inert, porous medium which allows steady diffusion of water vapour from the reservoir in the outside surface layers. The linear gradient is established by water vapour passing into the church under the influence of the lower RH caused by heating the outside air that leaks in. When the church is suddenly heated further for a service the air falls in RH, thus steepening the gradient through the wall. The establishment of a new equilibrium is quite rapid in a porous wall with low buffer capacity.

On the other hand one could imagine a situation in which the wall has an enhanced buffer capacity, due to small quantities of water soluble ions such as nitrate, chloride, magnesium and calcium. These will generate a liquid at moderate RH which gives the wall substance a much steeper sorption curve. Another source of buffer capacity is the organic polymers which are a product of the rich fungal and bacterial life in the walls of churches.

Such a wall will have a less uniform RH through it, because the water capacity ensures a slower movement of water, controlled by the history of the weather. Such a wall has a buffer capacity at the inner surface. The moisture stress imposed by sudden heating will be taken up by the inner surface layers of the wall.

The two models are shown in figure 6.13. A combined model could be constructed in which the water reservoir at the outside functions as a slow supplier of water, accounting for the higher than expected RH in the church air through the year. The relatively brief episodes of warming for services would extract water from the limited but definite buffer capacity of the interior surface of the wall, which would then be re-supplied from the capillary reservoir towards the outside.

The observed microclimate is compatible with this model, which does not invoke water vapour movement by diffusion driven by vapour pressure difference, though it does not exclude it as a competing process. Vapour pressure driven movement alone will give a high humidity near the outer surface of the wall but can only explain the high RH indoors by invoking a region of the wall at 100% RH and at a higher temperature than outside. This mechanism should give a much higher RH within the cup against the wall than is observed.

Experimental confirmation of the conflicting ideas put forward in this chapter would involve considerable effort in putting sensors within the wall and would require removing a statistically reliable number of specimens of material from the old walls. It would also require firm control over the operation of the building, particularly the heating and the ventilation.

The first mechanism proposed, that for the nearly unabsorbent wall, is an extension of the isothermal experiment reported in chapter 4, figure 4.35: cellular concrete with gypsum plaster over its surface. This figure is interpreted as showing that the cellular concrete contains capillary water. This means that it is at equilibrium with a very high RH. The gypsum plaster coating it cannot share this moisture because it has a coarser capillary structure. A steep linear RH gradient develops within the gypsum, which functions as a porous retarder of vapour movement, with almost no sorptive capacity at all. The gradient remains stable as the reservoir of water in the cellular concrete shrinks, because the RH at the surface of this reservoir is close to 100% over a very wide range of water content. This gives a very stable inside RH, so long as the vapour flux leaking from the church through openings in the building is constant.

The church as a whole seems to function as a heat driven pump: water moves inwards through the wall to give a higher interior water content, which leaks out through cracks in the building. The balance between these two processes gives the observed moderately high RH within the building.

The climate behind pictures mounted against the outer walls of the Chapel of Ledreborg, Denmark

The experiment with the cup mounted against the wall in Gundsømagle church can be criticised as unrealistic, because the diameter of the cup was small compared with the thickness of the wall. This section describes the climate in a much wider, but not much deeper enclosure.

The chapel of Ledreborg, the country seat of the Holstein-Ledreborg family, a few kilometres south of Roskilde in Denmark, is a remarkable contrast to the pastel simplicity of the Lutheran churches described above. It is an exuberant baroque construction, and consecrated to the Catholic faith. The microclimate is also more lively, partly because of the greater area of window and the lack of protection for the entrance door. Another important factor contributing to the more variable climate is the complete lack of absorbent surfaces in the interior.

Figure 6.14 Ledreborg House, near Roskilde, Denmark. The chapel is at the right (west) end of the main house. Photo from Ledreborg brochure.

There are, however, hidden absorbent surfaces. The oil paintings that cover much of the interior are set in shallow recesses in the outer walls. These recesses have just lime plaster covering the brick wall. The brick is coated on the outside with a cement render, from early in this century.

Conservators are generally rather anxious about the welfare of pictures that hang on the outer walls of houses. This anxiety proved reasonable, in this particular building. When the conservator took down one painting for repair a baroque addition to the original architecture was revealed: a well grown fruiting body of the dry rot fungus, *Serpula lachrimans,* clinging to the back of the canvas.

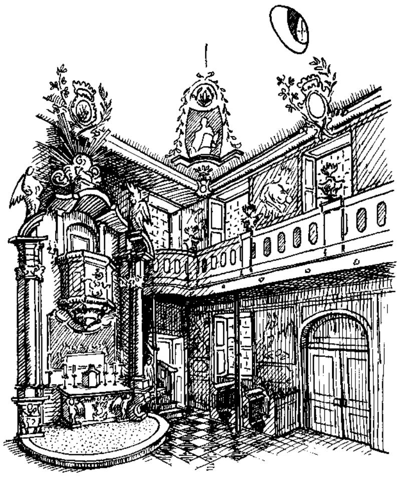

Figure 6.15 The interior of the chapel of Ledreborg house.

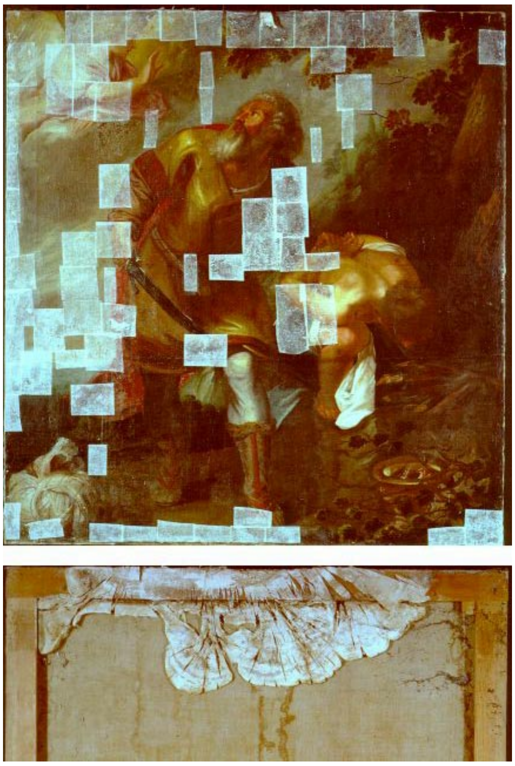

Figure 6.16 An 18th C. oil painting by Isaac Isaacsz. The white squares are temporary repairs. Below is a portion of the back of the picture showing the dried remains of the fruiting body of the Dry Rot fungus.

The National Museum had, at that time, a student, Annabel Robinson, who was interested in microclimatic matters relevant to the conservation of art.

We decided to investigate the microclimate behind the pictures with full scientific rigour (27).

The climate measurements

While the damaged canvas was in intensive care in the National Museum's workshop we put in the vacant niche two paintings, one designed to imitate the original, the other with a polyester film stretched over the back of the frame, to exclude water vapour coming from the direction of the wall.

The two pictures were set side by side in the recess, as shown in figure 6.17. Temperature and humidity sensors were placed in front of these pictures and in the air

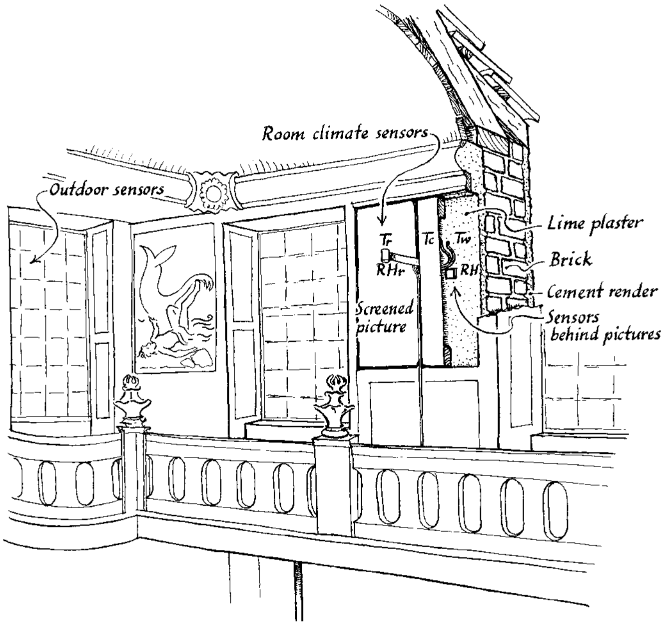

Figure 6.17 The wall structure, showing the placing of sensors to investigate the microclimate behind the painting. The sensor assembly behind the test pictures consisted of a RH sensor and thermocouple within a radiant heat shield in the middle of the space (about 40 mm) and two springy thermocouples, one touching the back of the canvas, the other touching the surface of the wall.

space between the canvas and the wall. The outside climate was measured in a shaded spot on the flat roof of the west wing, just outside the chapel.

The microclimate around the pictures

The climate measurements are summarised in three graphs. Figure 6.18 shows the outside (dotted) and inside temperature and relative humidity (RH) for a 15 week period starting on the 14th. March 1994. The inside relative humidity is generally a moderated version of the outside RH. The daily cycles of RH are caused mainly by the daily temperature cycle acting upon room air that is rapidly exchanging with outside air. The outer door has no lobby, the door at the balcony level is poorly fitting and the windows are not particularly airtight. The room is high and open, encouraging convective air exchange (the "stack effect").

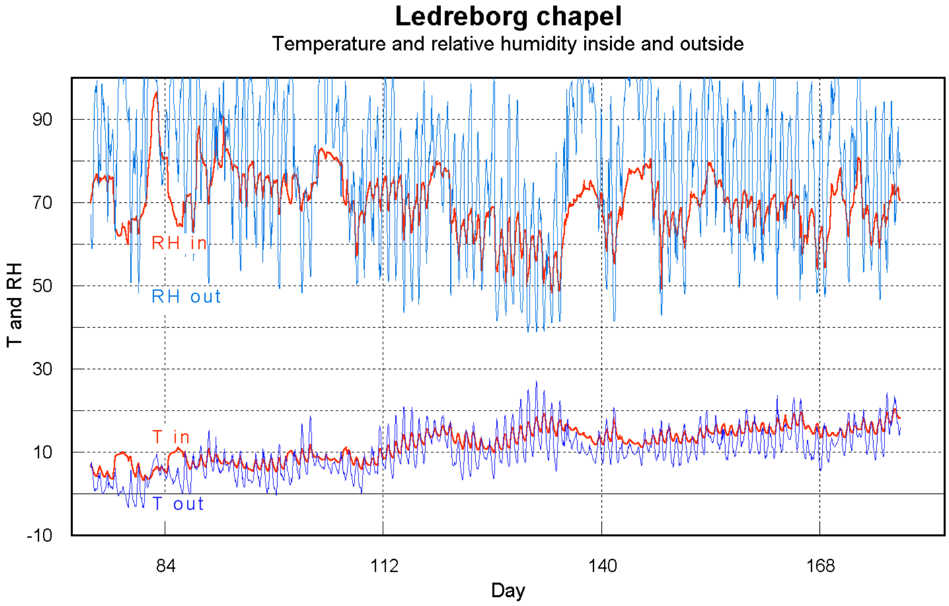

Figure 6.18 Temperature and relative humidity inside the chapel and outside. The chapel was only heated on two brief occasions at the beginning of the period.

The temperature and humidity cycling is only moderately damped out by the room. The abundant wood panelling is a fairly good thermal insulator, reducing the stabilising influence of the thermal inertia of the wall. The paint on the wood prevents moisture movement which would stabilise the relative humidity.

Figure 6.19 shows the microclimate around the paintings. The upper curves show the RH in the room (dotted) and at the back of each of the two experimental paintings. Both the polyester-protected canvas (the line rising from 30% RH) and the unprotected canvas (bold line) had been stored for several weeks in a room at about 40%RH. The unprotected canvas came rapidly to equilibrium close to the running average of the RH in the chapel, while the protected canvas came slowly to equilibrium with its new surroundings over a period of about two months. At the end of the measuring period the two RH traces have converged. The RH behind both canvases is more stable than that in the room.

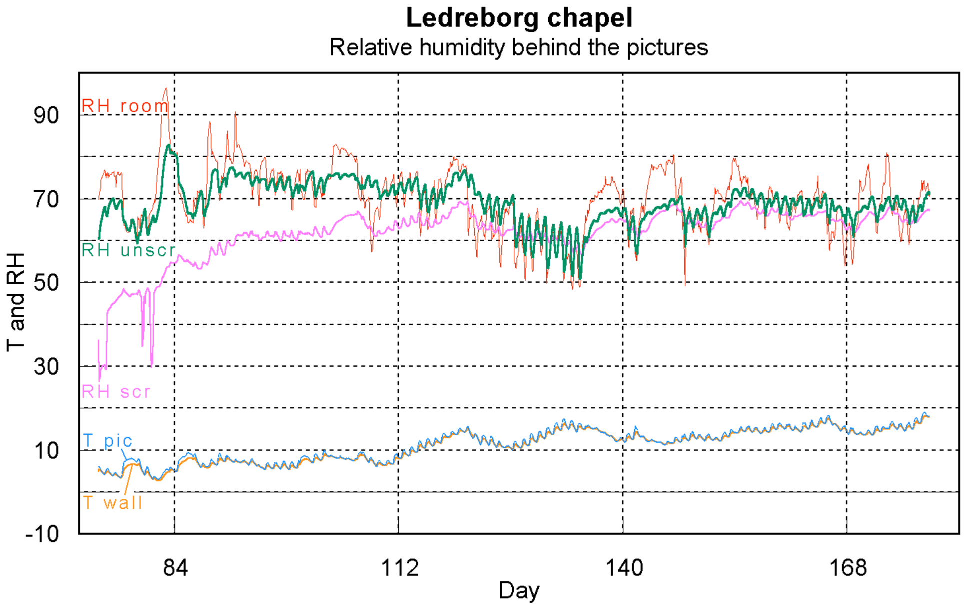

Figure 6.19 The microclimate behind the two test pictures. The protected picture comes much more slowly from the 40% RH of the painting workshop to the high RH of Ledreborg. After a few weeks, however, both paintings have much the same RH behind the canvas, within the accuracy of measurement of the sensors.

A detailed study of figures 6.18 and 6.19, together with a close up of a shorter period, shown in figure 6.20, suggests that the canvas of the polyester protected picture is stabilising the RH of the air trapped behind it but that the wall is actively stabilising the RH behind the unprotected picture, and therefore behind all the other pictures in the room.

The lowest line in figure 6.20 is the temperature difference between the pictures and the wall surface (the two pictures have identical thermal environments). Notice that the RH behind the unprotected canvas (the top curve) is cycling up and down with minimum values that coincide with maximum values of the temperature difference between the picture and the wall (the picture surface is warmer than the wall surface). At first glance this could be attributed to air exchange with the room, because the RH in the room goes up and down in the same pattern. However, a closer look at figure 6.19 shows that the relationship between RH in the room and behind the painting is not easily explained by this theory. Around day 130 the RH behind the picture is varying more than that in the room but the peaks in room RH on days 105, 137 and 145, when the temperature was rather stable, do not penetrate behind the canvas.

These observations can be explained by assuming that the wall is controlling the RH to a constant value *at the wall surface*. This air then convects away from the wall to the back surface of the painting, keeping the exact water content it acquired when it came to equilibrium with the wall surface. Because the picture canvas is at a higher temperature than the wall, the air warms up and therefore drops in relative humidity.

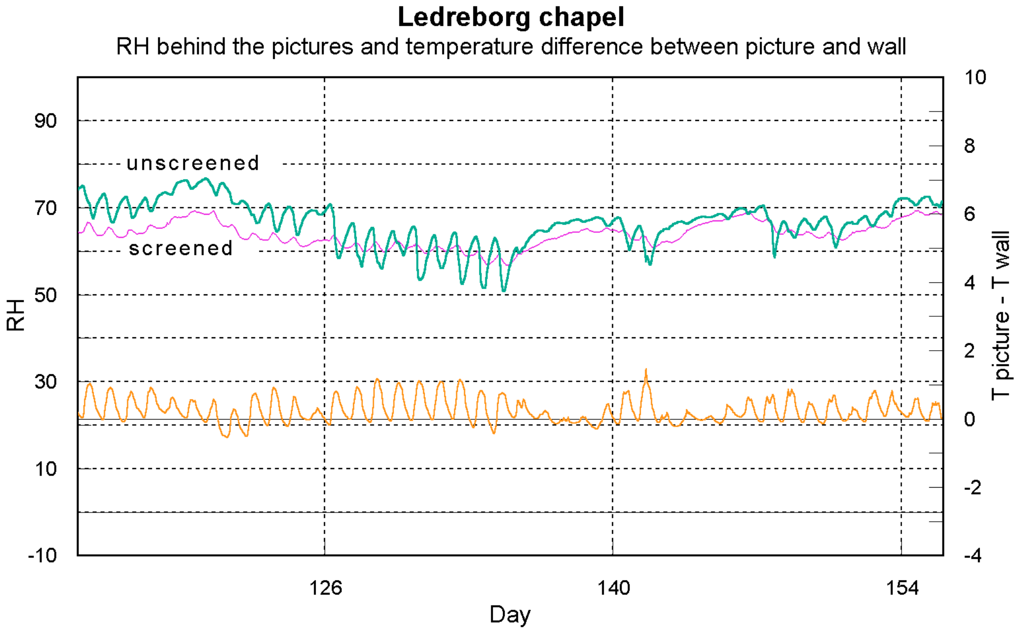

Figure 6.20 Relative humidity in the space between the picture canvas and the wall. Notice just after day 121, for example, that the RH cycles are in opposite phase. This is the evidence for buffering by the wall behind the unscreened picture. The screened picture has small RH peaks that approximately coincide with temperature peaks at the canvas. This RH pattern is characteristic of a closed container filled with abundant buffer, in this case the canvas. The unscreened RH has larger RH peaks when the temperature difference is at a minimum. This can be attributed to buffering of RH by the wall ***at the wall temperature****. This buffered air warms up to the canvas temperature with consequent fall in RH.*

This explanation may seem very indirect and speculative but it is supported by a consideration of what happens at the back of the protected painting. Here the wall plays no part in the moisture transfer, because of the impermeable polyester sheet which separates the wall from the air space behind the picture. The air trapped behind this picture exchanges water vapour only with the canvas of the picture itself, so the RH at the back of the screened picture is much more constant. There is just a slight increase of RH as the temperature rises, which is a known property of cellulosic fibres in a confined, nearly airtight space.

The opposite pattern of the RH cycle behind the unscreened painting confirms that the reasonable RH stability cannot be due to poor air circulation, because this would allow the canvas to buffer the RH just as it does for the screened picture. The wall is actually such a powerful stabiliser of RH that it overrides the influence of the canvas.

Summary of the Ledreborg experience

The climate measurements are unexpectedly reassuring: the climate behind the pictures is actually more stable than the climate in the room and is not significantly moister. The fungus which formed such a dramatic embellishment to the back of the original painting had not significantly attacked the painting or its frame: the observed damage can be attributed to the moisture oozing from the fruiting body. The dried residue on the back of the picture was the fruiting body of mycelium that was probably digesting the lower part of the roof construction, which is not far above the level of the top of the picture. There is no evidence that the wall is unusually damp at the level of the paintings and panelling in the chapel but there are bad constructional details at the edge of the roof which have caused dry rot within the roof timbers.

The climate in the chapel can be described as far from ideal for preservation of the splendid interior but not acutely dangerous. In particular there is no ground for special anxiety over the microclimate around the pictures mounted on the outside walls. They have the most stable climate in the room!

This conclusion is not particularly original: there are hundreds of houses, hundreds of years old, with wood panelling in perfect condition hard up against outer walls. All that we could add to this body of experience is that if you must have wooden panelling in a room, the best place for it is against the wall.

The nervous insistence that there should be good ventilation behind art against outer walls is therefore probably unnecessary and even wrong. If, however, the wall is painted the advice to ventilate is probably right, because the wall behind the picture will, in the winter, be colder than the rest of the wall and therefore the first place condensation will occur. This is another reason to keep walls porous.

The idea of protecting the back of the painting with polyester is not so bad: the microclimate is a bit more stable than that behind the unprotected picture but a more important reason is that it would dissuade the protected bats of Ledreborg from setting up home behind the pictures.

This story does not shed more light on the processes occurring in the outer wall. The temperature is about the same on both sides of the wall, so there is no way of distinguishing between vapour pressure and RH as the effective driving force for moisture movement.

Buildings which deliberately use humidity buffering by porous materials

The museum stores in Brede

The churches described in the previous sections were not intentionally built to provide a stable relative humidity. This was a beneficial by-product of their construction and is preserved by a continuing tradition of using a porous surface treatment both outside and inside.

The buildings described in this section were designed to provide a stable relative humidity.

The National Museum of Denmark transformed some old factory buildings in Brede into storage for museum objects. It also built a new store for large objects.

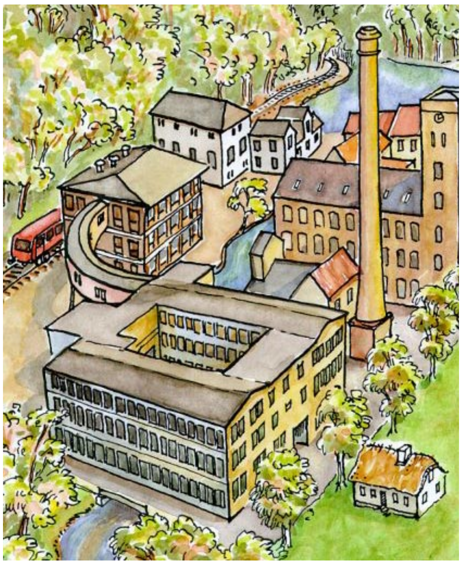

Figure 6.21 The complex of factory buildings in Brede, north of Copenhagen. The storage rooms are in the foreground.

The consulting engineering firm charged with doing all the technical things proposed an air conditioning system designed to maintain a constant relative humidity by adjusting the air temperature in the storerooms. This proposal is based on two ideas of doubtful validity. One is that museum objects are more sensitive to humidity variation than to temperature variation. The other is that it is possible to control the relative humidity by raising or lowering the temperature, to lower or raise the RH, respectively.

The first of these axioms, that RH is more important than temperature, is a complicated matter which I will not go into here. The second axiom, that RH in a storeroom can be controlled by adjusting the temperature, can be rebutted instantly by referring back to chapter 1, where the results of putting cotton into a sealed box are discussed. The RH in the empty box falls with rising temperature while the RH in the box full of cotton rises with rising temperature. A storeroom will surely contain a considerable, but not exactly known, quantity of cellulosic products, such as cardboard boxes and wooden shelves and wooden relics. There is therefore an ambiguity in the room's response to temperature change: it will either rise or fall in RH according to the ratio of available buffer to total volume, complicated by the effect of ventilation with outside air of unpredictable water vapour content.

There is therefore a risk that a rising signal from the RH sensor will cause heating that will cause a further rise in RH, a phenomenon known in the control industry as positive feedback.

The engineers were not convinced by this argument. It must be said that several conservators also expressed scepticism, pointing out that exactly this system, dignified by the name of "Conservation heating" has been used to keep the damp out of English country houses for several years. The English upper class, however, were never celebrated for putting comfort before pomp and their draughty ancestral piles are well enough ventilated, and coated on the inside with such heavily varnished art, that the buffer effect described for cotton does not happen. The climate graph for Ledreborg would apply to most country houses. The buffer effect of the few absorbent materials is swept away by the air rushing through the edges of the windows.

The Brede storerooms, however, were another matter. They would be built to be airtight, without windows and with a surrounding corridor to act as a buffer against infiltration through the old factory windows.

Computing the best control strategy for humidity control in a well sealed store room

Mechanical air conditioning is not an absolute necessity if one has a completely free hand. The building holding the archives of Schleswig-Holstein in northern Germany operates with great climatic stability without any mechanical climate control (this building will be described briefly later) but it was designed for the purpose. In the Brede buildings the natural humidity buffering by the building and by the stored objects is not quite good enough for a museum store. The concepts of passive humidity control needed to be supplemented by active control with a mechanical system. The aim of this research was therefore not the study of natural processes at work, as described up to now, but to develop a system of air conditioning that would use the natural processes to reduce the installation and running costs of the buildings.

Various alternative ways of controlling the RH in the store rooms were explored by computer simulations (28). These do not involve the outer walls of the rooms but calculate the humidity buffering by wood within the room, as an example of a common absorbent material. The temperature is of course included in the calculations and the wood could just as well be the walls of the room: the result would be the same. A certain zest was added to the computational effort by the knowledge that the results would be tested in reality.

The response of wood to changes of ambient RH and temperature was taken from unpublished work by Poul Jensen, who was studying the drying of wood during timber production. This core physics was written into a program which also calculated the heat and moisture changes in the room through diffusion and ventilations and as a result of the activities of various kinds of air conditioning methods.

The natural climate of the store

When we came on the scene the planning of the alterations to the old buildings was far advanced. The storerooms would be made of lightly built walls of gypsum board and plywood with mineral wool insulation. This wall was separated by a corridor from the original outer shell, from about 1920, which was of reinforced concrete with vast areas of window with a single layer of glass in iron frames.

The first exercise was to study the likely climate in the room if there were no climate control at all.

We used the following basic data in all the simulations: The room is 30 x 15 x 4.5 m high. It has two exterior walls of k-value (thermal transmission) 0.2 W/(m^2 ·°C) to simulate the outside weather moderated by the enclosing corridor. The ventilation is adjustable from 0.05 to 0.5 air changes per hour. The air is recirculated at one air change per hour and the air speed over the wood surface is 0.1 m/s. The apparently irrelevant air circulation rate becomes a necessary parameter when considering the effects of recirculation through an air conditioning device.

The natural buffering is provided by wood. Simulations were made with two levels of buffering. A lightly buffered room has 200 m^2 of wood , 10 mm thick, varnished on one side. A heavily buffered room is represented by 5000 m^2 of wood. This is a reasonable approximation to a well filled museum store with a mixed collection.

The starting RH, and the target for RH control was set to 50%, not as a suggestion for the ideal value but to simplify interpretation of the graphs.

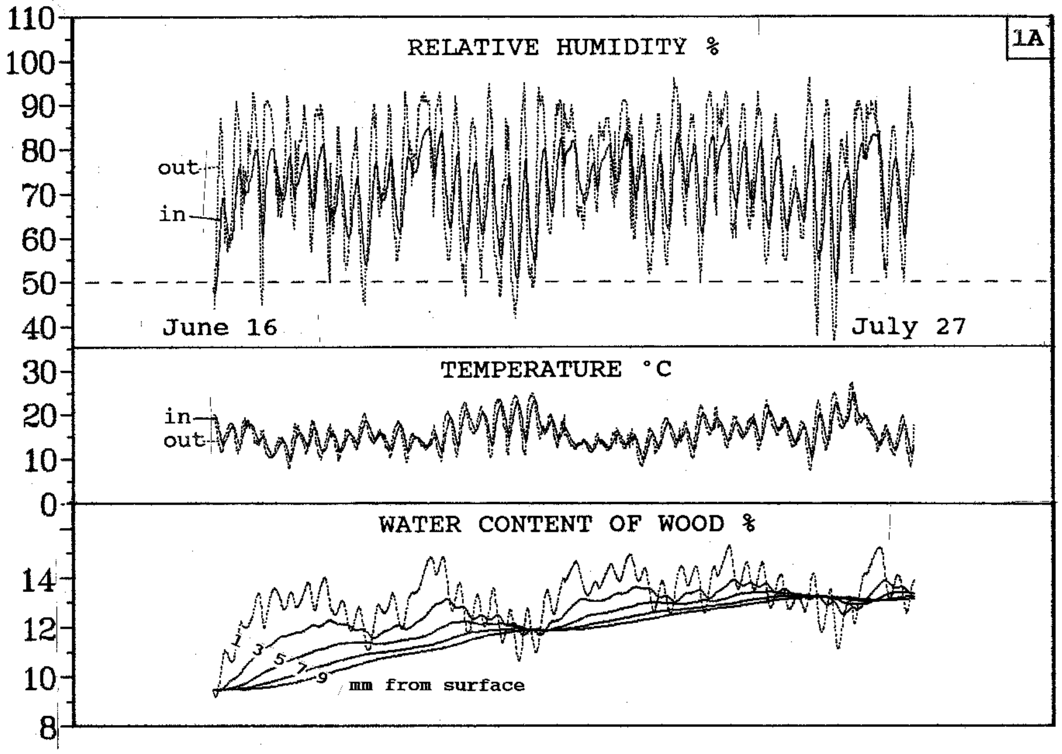

Figure 6.22 The modelled performance of the museum store with a small amount of wood. The outside climate is the dotted lines. The buffering is poor, worse than that of Ledreborg chapel shown earlier. Notice the rapidly varying water content in the surface layers of the wood: a sign of the physical stress suffered by museum objects stored in such conditions.

When the store room is reasonably full of objects and containers, including many that are water absorbent, the humidity buffering, and also the temperature buffering are much improved.

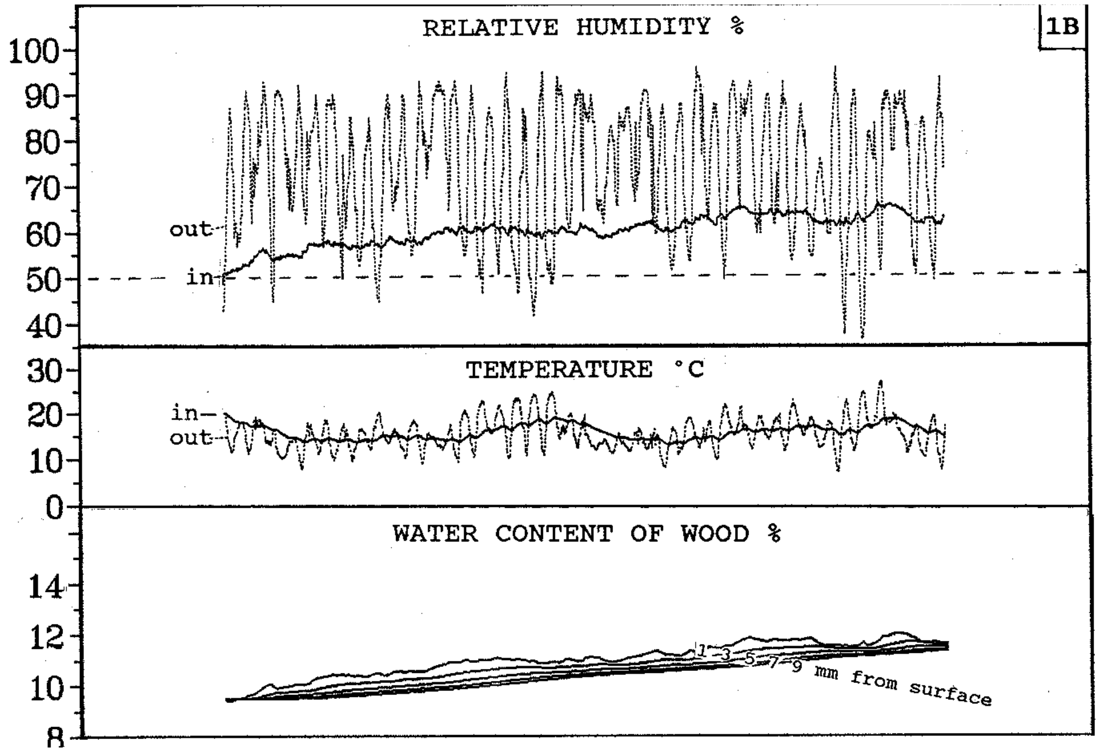

Figure 6.23 Climate buffering by an abundance of wood in a storeroom. Both RH and temperature are moderated but the room RH is slowly rising to the unacceptably high (for museum objects) average RH of the Danish climate.

The RH had risen from 50% to over 60% during the month and a half when the outdoor RH is at its lowest average value. This entirely passive climate control will not work.

There are several alternative methods of improving the situation. The one chosen by the design team was to heat to constant RH. This method relies on the fact that the saturation vapour pressure of water rises with temperature, while the actual vapour pressure of an isolated volume of air remains the same as it is heated. Therefore the ratio of actual to saturation vapour pressure, which is the RH, falls. This process works well in the lightly buffered room, as shown in the next diagram.

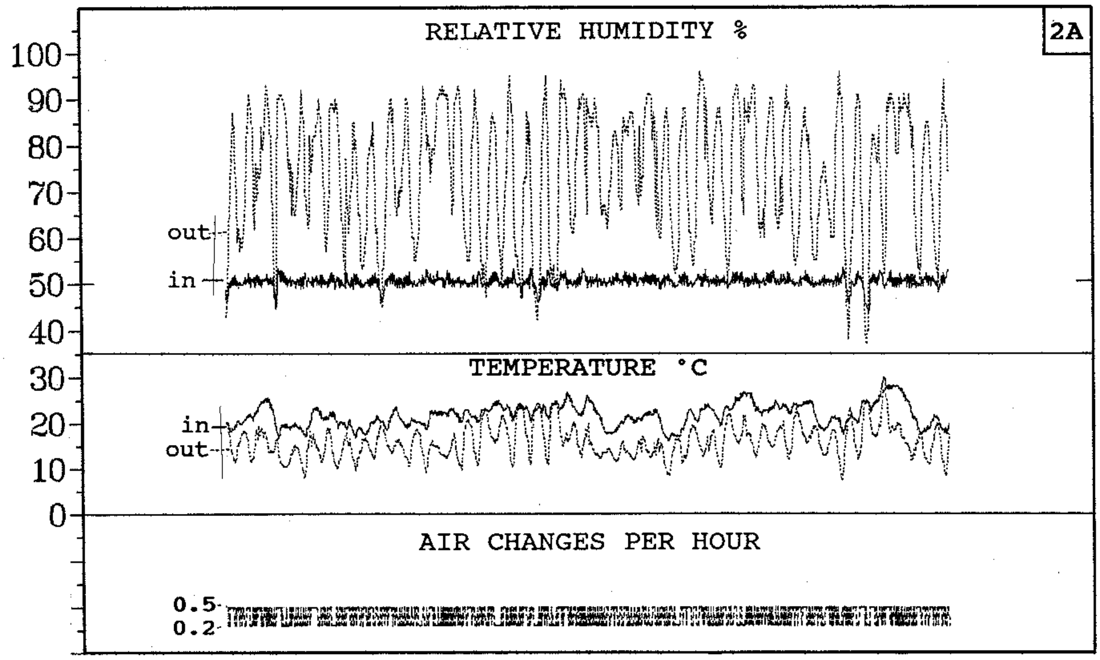

Figure 6.24 The control strategy used here is to warm the room to constant RH, using the fact that the RH of an enclosed body of air falls with rising temperature because the saturation vapour pressure increases while the actual vapour pressure remains the same. In the lightly buffered room the process works well.

When the room is filled with museum objects, some in cardboard boxes and laid out on wooden shelves, the climate follows a completely different pattern. Now the situation resembles that sketched in chapter 1. The air in the room can no longer be regarded as an isolated volume with no access to water. As the temperature rises the absorbent materials in the room will see a falling RH around them and will release water to maintain equilibrium with the air. They release so much water that the RH actually rises with increasing temperature, causing the control electronics to call for even more heat. The process runs amok in the mild, museum equivalent of a nuclear meltdown.

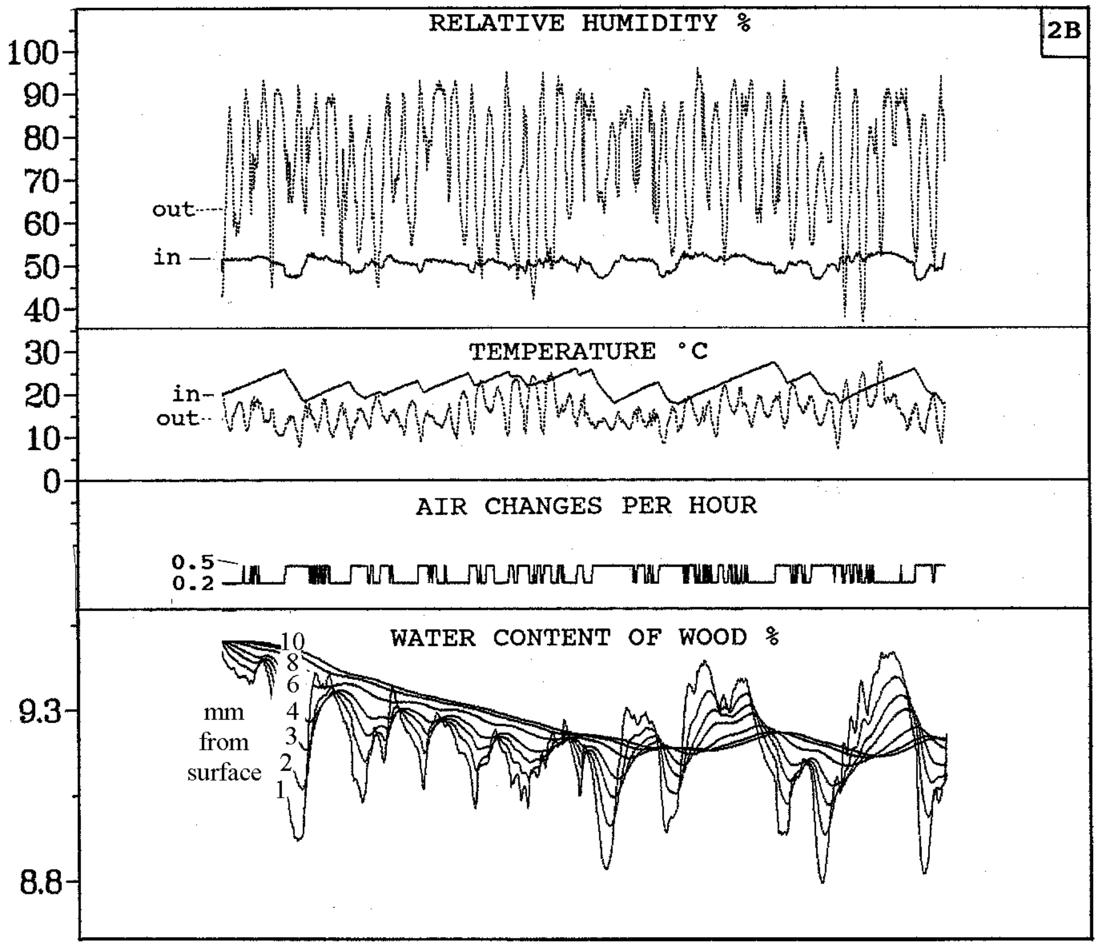

Figure 6.25 Heating to constant RH in a room full of absorbent materials. The sawtooth pattern of the temperature cycles is caused by positive feedback: a rise in RH provokes a rise in temperature, which causes a further rise in RH. The absolute water content of the air increases until the leakage of outside air with much lower water content puts a stop to the rise of the indoor water concentration. The temperature then nosedives as the fall in RH provokes a cooling response from the air conditioner.

All this was just theory. The system that heats to constant RH was installed in the only new building in the project. What happened next is not clear but at some point after the building was filled with the museum's collection of old boats and wagons a dehumidifier was installed. I watched the climate, ignorant of the modification, and wondered how I could have got my modelling so wrong.

One day, a year or two later, some visitors were taken round the showpiece museum storage facility. The Director of Conservation complained afterwards that it seemed very hot in there, so I looked up the recent data. It is shown in figure 6.26.

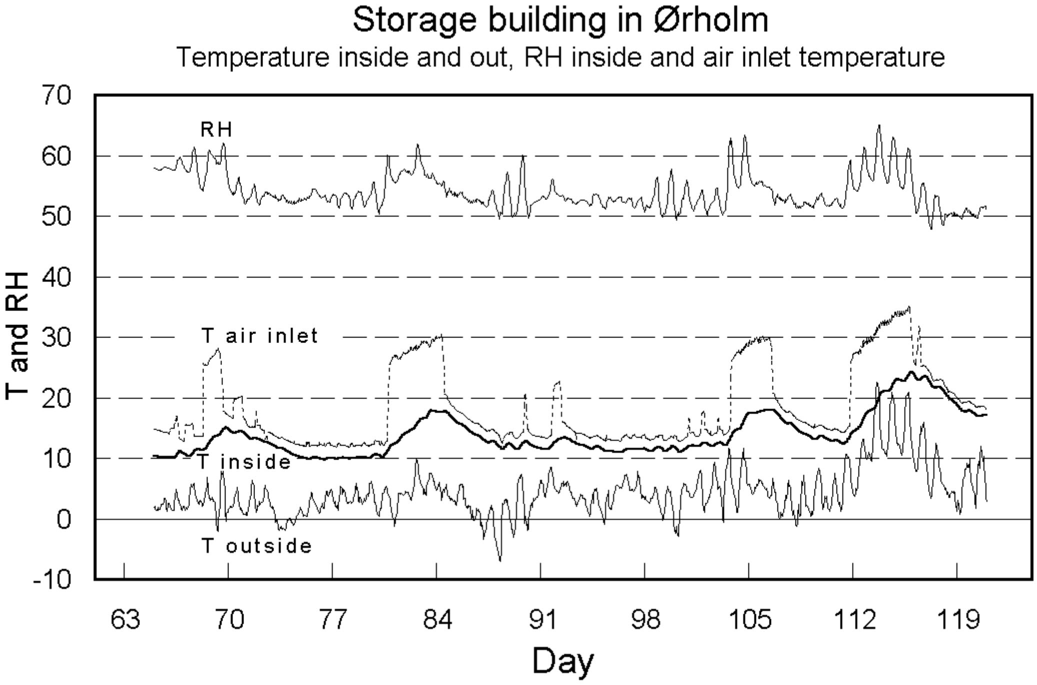

Figure 6.26 Climate data for nine weeks in the new museum storage building near Brede. Temperature oscillations are caused by positive feedback in the control system. A rising RH calls for more heating, which then causes a rise in RH because of release of water by the collected objects, supplemented by the cellular concrete walls. The dotted curve with sharp rise and fall is the temperature of air blown into the interior.

Further investigation revealed that the dehumidifier had failed. The control computer reacted to this failure by dredging up the old program which controlled the RH by heating. The real climate is a bit different from the model, but the model did not have the heating power of the real building, as shown in the sharp temperature rise of the air blown into the building (dotted line). Also, the model was capable of cooling the air by ventilation to the outside, a refinement not found in the real building.

I fed the actual outside climate data into the old computer model and got the graph shown in figure 6.27 (29).

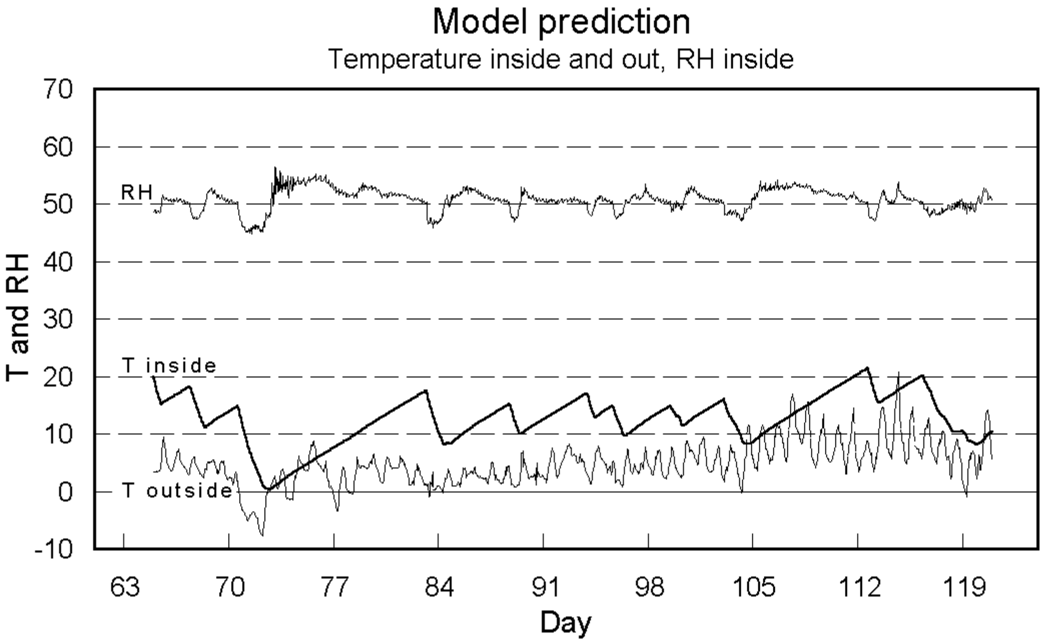

Figure 6.27 The computer model based on the outside climate for the period shown in figure 6.26. The heavy sawtooth line is the indoor temperature. The steeper decline in temperature is due to active cooling by ventilation in the model, which was not available in the real building.

There are two lessons to be learned from this affair. One of them is that mechanical air conditioning is only as safe as the quality of the supervision. The climate in this building ran amok for about three months without anyone noticing. This alone is a good reason to promote passive climate control. It may not be so accurate but it cannot go berserk nearly as effectively as mechanical systems.

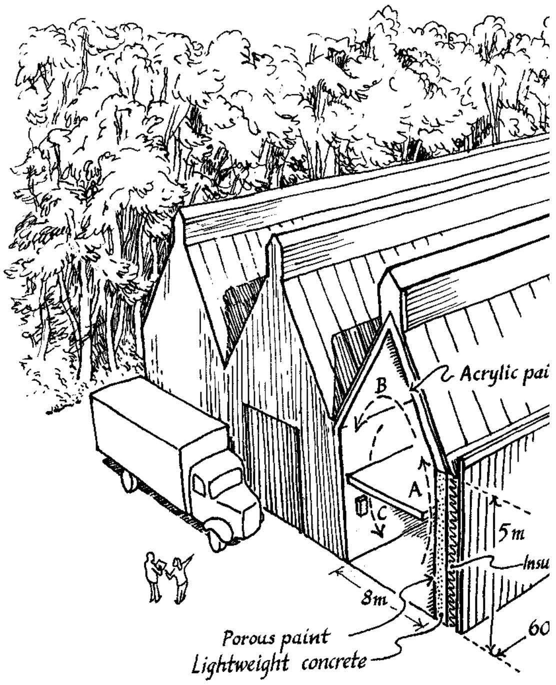

Figure 6.28 The large storage hall in Ørholm, north of Copenhagen. The climate is buffered to some extent by the cellular concrete walls, which are covered with limewash but most of the climate buffering comes from the stored objects. The mechanical air conditioning dehumidifies to achieve a reasonably constant RH.

Warming to constant relative humidity

The principle of warming to constant humidity can be used to control RH, so long as one does not use a RH sensor to control the air conditioning. The signal is ambiguous and cannot be used for direct control. Heating can be controlled according to the expected outside temperature and RH for the time of year. It can also be controlled by building a storage vault so massive that it responds only to the yearly average outside climate, moderated by waste heat from dim lighting.

This is the case with the State Archives of Schleswig-Holstein in Schleswig, north Germany. The climate control of this modern building is described by Lars Christoffersen (4). Briefly, the archival storage is built with a metre thick brick wall, insulated on the outside and with another brick rain shield outside that. This damps down and retards the annual temperature cycle very considerably. The waste heat from dim lights and people hunting down ancient documents provides exactly the right temperature rise to keep a moderate RH. The climate over a year and a half is shown in figure 6.29.

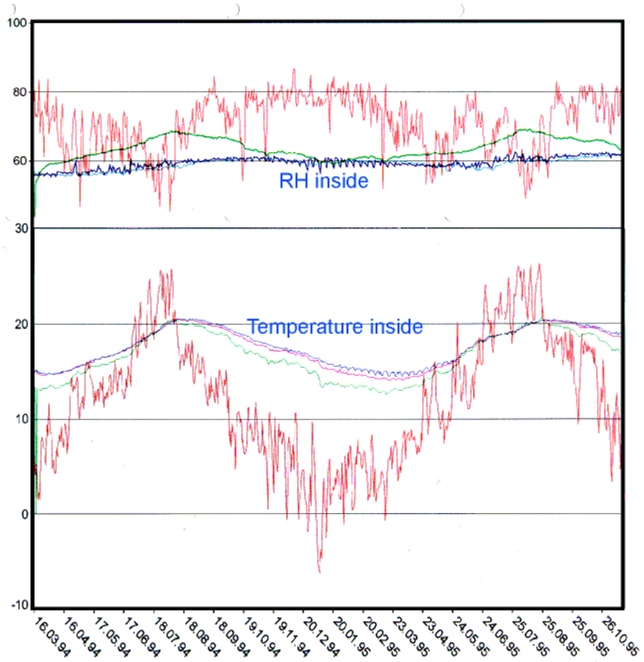

Figure 6.29 Climate in and around the State Archive of Schleswig-Holstein, in Schleswig. The massive brick building and the stored papers provide good temperature stability and very impressive RH stability. Data from Lars Christoffersen.

This building is a great success, compared with the Danish storehouse described earlier. One must point out, without detracting from the achievement, that the engineers did design an air conditioning unit, which lies with gleaming pipes, valves and dials, completely unused. The designer omitted to take into account the buffer effect of the stored items. The brick wall probably contributes very little to the humidity stability. It could be that half the number of bricks would have done the job, but this archive will resist heavy artillery.

Dehumidifying to constant relative humidity

The principle of warming to achieve a moderate RH is widely used, though it is difficult to control in rooms with good humidity buffering. In temperate climates human comfort also demands heating above ambient temperature.

The only reason for considering alternative strategies in a cool climate is to improve the durability of materials.

It is not really a good idea to heat an archive just to achieve a moderate RH. The higher temperature accelerates degradative chemical reactions: oxidation, hydrolysis and condensation reactions that slowly demolish many of the organic materials of museum and art collections, and particularly photographs and films.

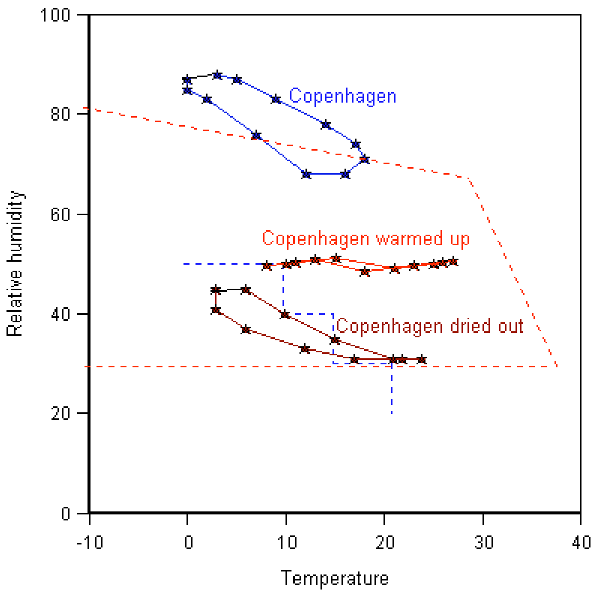

Figure 6.30 A diagram made by joining the RH and T values for each month into a ring of stars. The outdoor climate in Copenhagen, the upper constellation, is the starting point. If the air is warmed up to 50% RH the average temperature will rise, as shown by the rightward shift of the middle constellation. An alternative would be to dehumidify the air. This causes a smaller temperature rise, as shown in the lowest constellation. The zigzag line is the maximum RH and temperature allowed by the ANSI standard for storage of photographs. The large dotted trapezium encloses the area of non-destructive storage.

It would be better to dehumidify the air while keeping it cool.

The concept is summarised in figure 6.30, taken from Padfield and Johnsen (30). The dotted trapezium marks the boundary of the region of RH and temperature which can be regarded as responsible conservation.

The outdoor climate of Copenhagen is summarised by the ring of stars, each marking a combination of the monthly average RH and temperature. For most of the year the Copenhagen climate is too humid for the good of museum collections. It can be brought within the responsible limits by warming alone, giving the ring of stars in the middle of the diagram. The average temperature over the year has however increased from about 10 to 18 degrees.

A preferable strategy is to dehumidify the air. The temperature will still rise a bit, for rather technical reasons to do with the heat content of dry and wet air.

At this point the reader may wonder what this discussion has to do with porous walls. The answer is that the collaboration of porous walls, or porous materials in the room, is necessary for these simplified air conditioning systems to work. The outdoor climate often has a combination of temperature and relative humidity which is outside the limits for the warming or dehumidifying to a constant RH. The porous materials are needed to buffer the indoor climate during these periods when active control is impossible.

Dehumidification can reduce the temperature of a well buffered room at the same time as reducing the relative humidity. The standard condensation dehumidifier works by cooling the air below the required dew point, to condense the surplus water. The air is then re-warmed by passing it over the coil containing the hot, compressed refrigeration fluid. If the dehumidifier is outside the room it can lose this heat outside the room and pump the dehumidified, but still cold, air into the room. The RH of this air stream will be very high but if the balance of heat loss through the walls is right it will warm up to a temperature where the RH is correct but the temperature slightly below ambient.

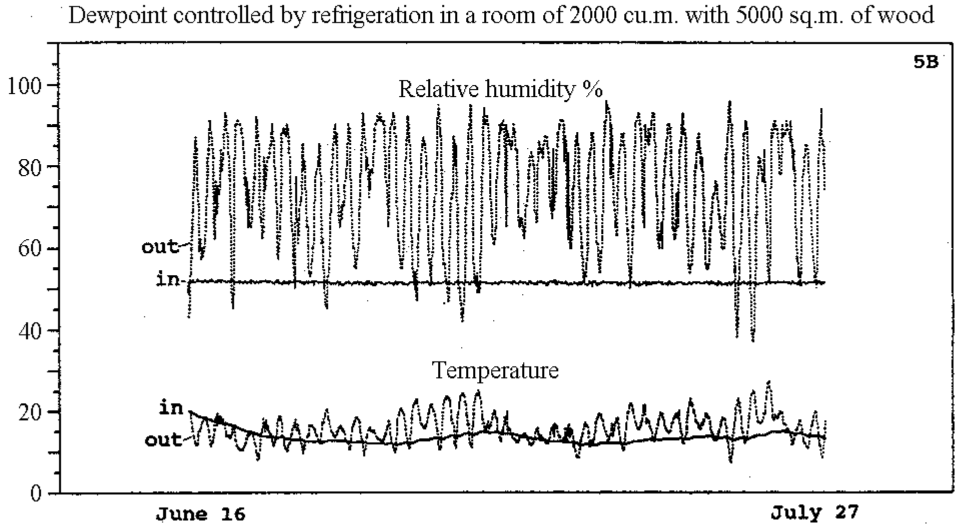

Figure 6.31 The calculated climate in a museum store dehumidified to 50% RH. The heat generated in the dehumidifier is discarded to the outside, rather than pumped into the room, as happens with a standard dehumidifier.

This method is modelled in the next diagram, which is taken from the set of calculations made to evaluate various methods of air conditioning the museum store in Brede.

This technique only works in a room with good humidity buffering. It is important to realise that absorbent porous walls are not only advantageous in houses without air conditioning, they also allow much simpler and more economical air conditioning in places where the requirement for accurate control does not permit a relaxed attitude to natural climatic forces.

Absorbent insulation

Absorbent insulation, like absorbent walls, is a traditional material that has fallen into disuse. A huge variety of plant fibres have been used for insulation, so has animal hair.

The important characteristic of absorbent insulation that sets it apart from absorbent solid building materials is that there is very little of it, by weight, per square metre of wall. Its buffer capacity is correspondingly limited. Furthermore, the little buffer capacity that it has is screened behind the hard interior finish of the house.

Absorbent insulation has an important role to play in buffering the climate in the interior of the wall. The volume is small, compared to the inner volume of a house, but the climate is more extreme. There is heat flow and water vapour flow. There is also radiant heating of exterior surfaces in the sun and there is driving rain forcing water into the wall.

The climate within the structure of walls is so extreme that the threats it poses seem to have deflected the attention of building engineers away from the interior climate of the house.

The basic problem, apart from faulty construction, is that warm air inside a house always contains more water, measured in kg/m^3, than the cool air outside. If the outside air temperature is lower than the dew point of the inside air, and the inside air moves through the wall and cools to the outside temperature then water will condense within the wall. This condensation inside the wall will threaten corrosion and rot and provide drinking water for plagues of insects.

If the wall is very open to air movement from the inside there is not much that absorbent insulation can do to ameliorate the situation. If, however, the wall is fairly well sealed against air flow, then the buffer effect of absorbent insulation can moderate the sudden swings of climate within the wall very substantially.

This is an assertion, based on calculations of the same type that have been presented for houses and for storage rooms. There is no body of research on the performance of absorbent insulation, because the modern building industry insulates almost exclusively with mineral fibre, mineral pellets and polystyrene. All these materials are non-absorbent. The paper fibre insulation industry has been established as a minor player in the business for many years but seems not to have sponsored research that really defines the properties of the material, as used within a wall.

All insulating fibres have roughly the same insulation value: that of the stagnant air between the solid fibres. The battle between the proponents of various materials has centred on issues of fire resistance and resistance to rot and insect attack. The subtle differences in performance due to moisture absorption at moderate RH has not figured in the debate.

It is difficult to find evidence for succesful performance. Disasters attract much more critical research. I therefore present a case history that emphasises the disadvantages of non absorbent insulation, with the purpose of opening a debate on the possible advantages of porous insulation. This may seem a weak excuse, but the story is amusing, and has not been told before.

The mysterious case of the building that rained inside, but only in fine sunny weather

The Arts and Industries Museum in Washington, D.C. was finished in 1881. It was designed as a museum, with ingenious use of the towers for ventilation. The advance of technology brought an orthodox air conditioning system with electric boilers for winter humidification.

Figure 6.32 The Arts and Industries Museum of the Smisthsonian Institution in Washington D.C. The south front showing the towers beside the entrance, used for cooling by the stack effect.

The museum's roof was replaced in the late nineteen seventies. The new roof soon showed a magical ability to shower rain down on the interior in bright spring sunshine. The reason for this phenomenon is a fascinating illustration of the problems that arise when the whole apparatus of modern materials, modern standards and modern regulations are applied to ancient buildings.

It is also an example of what happens when one mixes absorbent and non absorbent materials in a multi-layer sandwich exposed to large temperature variations.

The old roof was replaced by a box-sandwich construction of two layers of plywood enclosing mineral fibre insulation. The outer surface was of lead-coated copper. The wood was impregnated with a mixture of water soluble salts for fire and rot resistance. A polyester membrane was laid on the bottom plywood as a vapour barrier. The structure is sketched in figure 6.33.

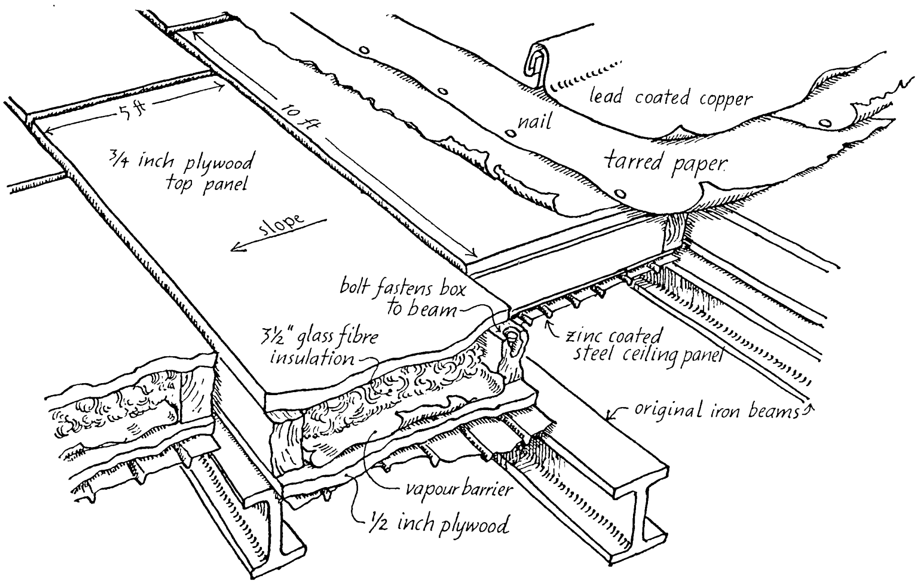

Figure 6.33 The design of the new roof of the Arts and Industries Museum

The rain in the building was not at first attributed to the roof but to some malfunction of the air conditioning. Eye witnesses reported seeing clouds in the high central rotunda.

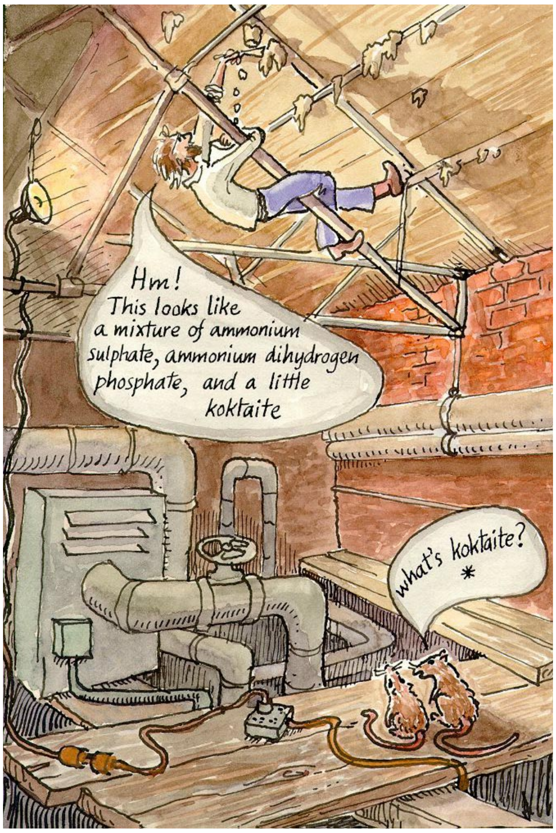

*Figure 6.34 Fireproofing salts formed stalactites hanging from the ceiling panels, revealing that the water came from the roof. *Koktaite is a hydrated calcium ammonium sulphate.*

An analysis of the rainwater, however, pointed to the roof as the cause of the problem. Ammonium and phosphate ions hinted at dissolution of the fireproofing salts in the plywood. A visit to the loft confirmed the suspicion.

In the U.S. all scientific evidence must be solid enough to be defended in court, so we set about installing sensors to reveal the exact processes at work within the roof. My colleague in this, and several other amusing technical detective jobs, was David Erhardt, a research chemist working at the Smithsonian Institution.

The temperature and RH was measured between every layer in the roof, and outside. Sensors for liquid water were placed on the vapour barrier and within the insulation. These were copper nails fixed close and parallel to each other. The direction of air movement was measured by placing an insulated tube through the roof with a temperature sensor in it. This sensor followed the indoor or the outdoor temperature,

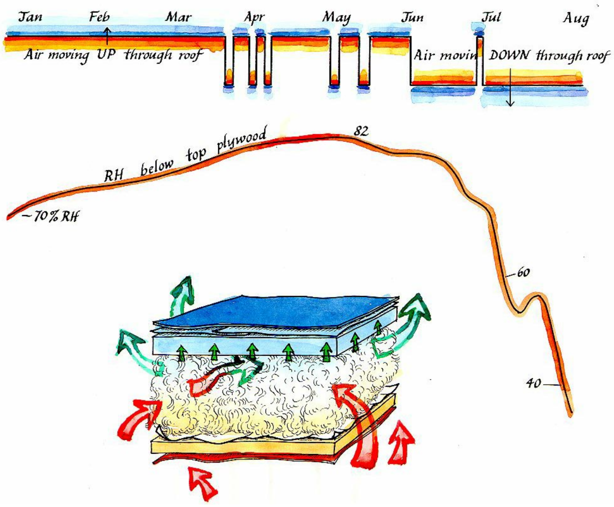

Figure 6.35 A plot of the direction of air flow through the roof is at the top. The curve below shows the steady increase of RH just below the upper plywood layer, indicating that water vapour from the humidified museum air is reaching the plywood and is being absorbed into the wood. The process is aided by the fireproofing salts that also absorb water at high RH.
In early summer the stack effect goes into reverse, air moves down through the roof, drying it rapidly.

according to the direction of air flow. Thermally driven air movement is a powerful process in buildings with high, unobstructed inside spaces.

Then we watched our tape punching data logger and waited for the hygrothermal crisis. The RH under the upper layer of plywood rose steadily through the winter and spring, while the air direction indicator showed nearly continuous outflow of air. In early summer the flow reversed and the roof began to dry out very quickly, as seen towards the right side of figure 6.35. It was just after the peak RH that the rain fell from the ceiling.

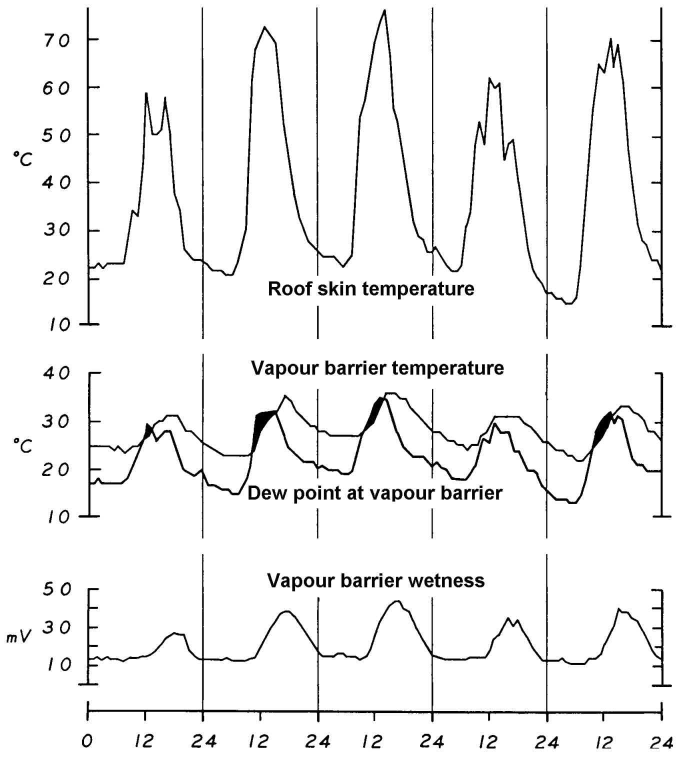

Figure 6.36 Traces over five days from several sensors mounted within the roof structure. Notice the solid black fill at times when the vapour barrier was cooler than the dew point of the air just above it. At these times water condensed on the polyester vapour barrier.

A composite diagram of the key sensor data for this short period is shown in figure 6.36.

The warm spring sunshine warmed the dark lead roof surface. The heat penetrated the upper plywood layer. The high moisture content of the plywood buffered the RH of the air just below it to about 70%, at the high temperature. This water vapour diffused through the air within the open structure of the glass fibre insulation, increasing its RH as it cooled. Dew formed on the lower part of the insulation or directly on the vapour barrier.

These short periods of dew formation are marked in black on figure 6.36. Notice that each period is quite short. There are two reasons for this. One is that the vapour barrier is heated by the condensation of moisture upon it. The other reason is that the dew point falls quite rapidly from its peak value in the early afternoon.

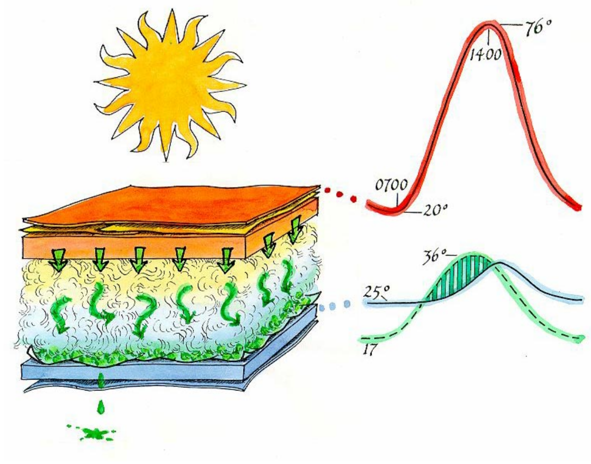

Figure 6.37 A pictorial summary of the condensation process in the roof of the Arts and Industries Museum on a sunny spring day.

Figure 6.38. Trickles of water emerging onto the roof. The water is distilled from the underlying damp plywood and condenses in periods when the roof skin is cooler than the wood below.

The same process occurs day after day until enough water has been evaporated from the plywood that the dew point never reaches the vapour barrier temperature.

The condensation process is summarised in figure 6.37.

One final detail is necessary to explain the dramatic rain showers. The condensate accumulated for some time as discrete drops on the water repellent surface of the polyester membrane. The roof tilts at a shallow angle, so a lot of water accumulates. Then, by chance two drops meet and coalesce, then run down into another and soon the entire mass of collected water streams towards the nearest downstream break in the construction.

This story encapsulates many of the themes touched in this thesis. Absorbent materials and unabsorbent materials interact in a temperature gradient. The absorbency of the plywood is artificially increased by the addition of fireproofing water soluble salts. The porosity of the unabsorbent insulation allows rapid moisture transfer through the temperature gradient. The discontinuous vapour barrier allows air to infiltrate from below. The humidification of the museum air increases the water uptake by the plywood. The amount of water released is limited by the hours of intense sunlight but also by the rather low permeability of the wood, which restricts the amount of water released on a single day but also allows a recharge rate that ensures daily rain during a period of two or three weeks, if the sun shines. The symptomless accumulation of condensed water during the whole winter is made possible by the absorptive capacity of the plywood, conceals the true nature of the problem.

There are also influences working against condensation. The roof dries rapidly when the direction of air flow reverses, so that dry (in kg/m^3) outside air comes easily through the unsealed seams of the roof covering. These same seams allow a portion of the water vapour to escape upwards, as shown in figure 6.38.

Such a relatively short period of rapid mobilisation of water in a structure is not uncommon. The conditions for condensation are usually only fulfilled in the transition from winter to summer. Nevertheless, much damage can be caused by these brief episodes. There was far more corrosion on the underside of the lead coated copper roof than on the outside. The fireproofing salts had migrated and recrystallised and a luxuriant growth of fungus wound its hyphæ around the nutritious crystals of ammonium dihydrogen phosphate while the borax added to prevent this had recrystallised far away.

The complexity of the roof was forced on the architect. The original roof was very thin, so the new roof had to match its dimensions while providing insulation and fire resistance to modern standards. It had to be placed in sections over a building that continued to function as a museum, making impossible the laying of a continuous air barrier. Given the circumstances there is no one to blame for this expensive mistake.

One solution to the problem was not only available but was being built just a few metres away at the same time, designed by the same architect. Another part of the roof of this vast building was constructed in almost the same way, but with slabs of foamed glass insulation instead of the glass fibre. This material is completely impermeable and so the distillation process described above cannot occur. The absorption of water vapour into the roof is certainly happening in the same way but the drying occurs predominantly to the outside.

One can speculate over other solutions to the problem. If there were no vapour barrier the condensate would be absorbed into the lower plywood. The process would go into reverse during the night so that no water would cascade into the interior. Another possibility would be to use absorbent insulation, such as wool or paper fibres. The

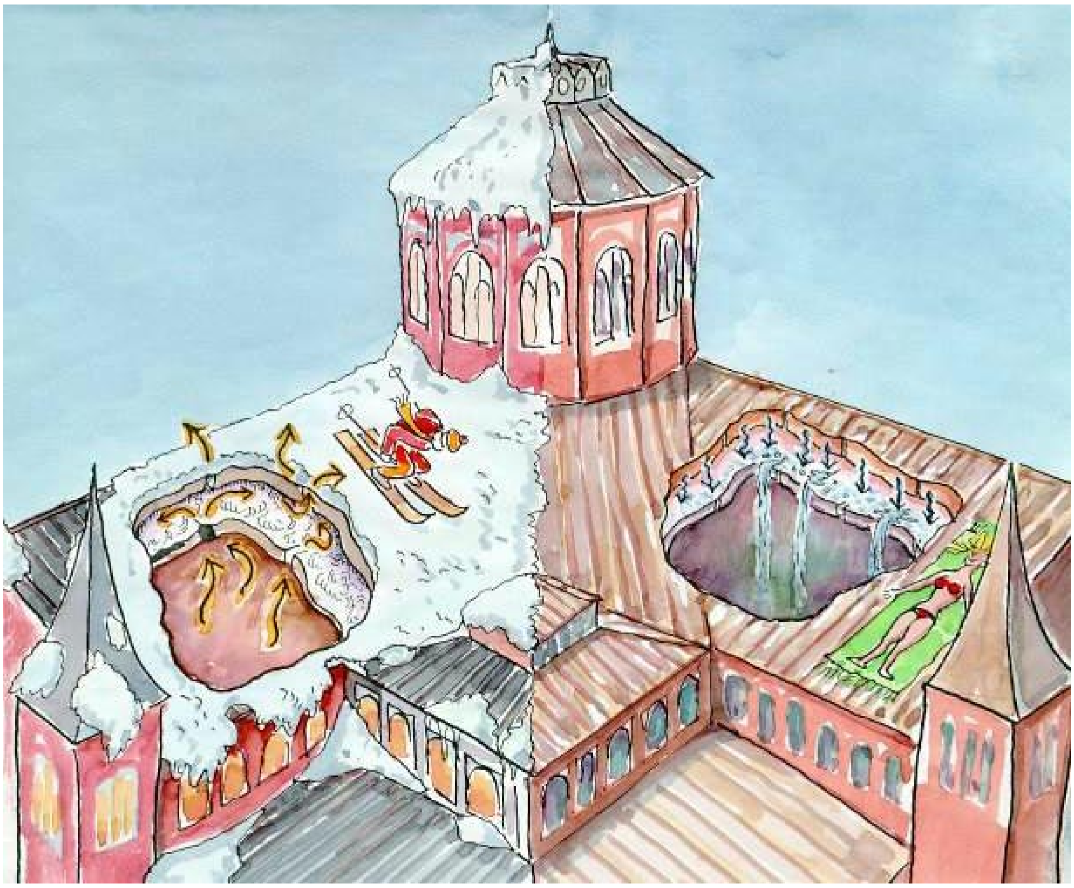

Figure 6.39 A summary of the annual cycle of water movement in the roof of the Arts and Industries Museum. In winter, on the left, warm, buoyant air forces its way up through the roof, depositing water in the cold upper plywood. In summer, on the right, the clear sunlight warms the roof. The water is released and diffuses down, helped by the downward flow of warm air into the now cooler interior. It condenses on the vapour barrier, accumulates in drops which, after a while, join together and move off down the shallow slope to the nearest crack in the ceiling. From there a shower of rain, with dissolved fireproofing salts from the wood, cascades into the exhibition hall below. The entire process is governed by the interplay of absorbent and non-absorbent materials in the complex roof structure.

lower, cooler parts would absorb water, possibly in sufficient amount to prevent the daily condensation. The insulation would dry out again during the night when the warmth of the building and radiation to the night sky from the dark roof would reverse the temperature gradient.

Such speculation can only be tested by making models, real models. It is difficult to imagine that a computer program could simulate the intricacy of water movement in the roof described above.

One can draw the conclusion from this tale that modern building practice has reached a degree of complexity whose consequences are unpredictable. There is a good case for investigating radical, but simple alternatives, such as massive walls which combine in one layer the functions of moisture absorption, thermal insulation, thermal inertia, fire resistance and physical strength.

Making a simple roof is more difficult, particularly in a cool, rainy temperate climate. Absorbent materials have a role to play in roof construction, because of their ability to absorb limited amounts of water, which can be released again when the temperature gradient reverses. The criterion for effective performance is therefore that the absorbent material must be able to take up the likely daily flux of vapour. The amount depends, of course, on the water capacity of the source.

Ideally the upper parts of the roof, those that are warmed in the spring sunshine, should have rather little water capacity, whereas the lower levels, at the relatively constant indoor temperature should be very absorbent.

7

DISCUSSION

The necessity of understanding natural processes in the man made environment

I have tried to convey in this thesis my fascination for natural processes in man made structures. Many engineers' attitude to the unwanted properties of the materials they have at their disposal is to ignore them, or deplore them. My view is that it is better to understand materials and use their properties fully, or choose another material for that particular purpose.

The key example which illustrates the consequences of ignoring the properties of materials is the turbulent microclimate in the roof of the Arts and Industries Museum. This story shows the intricacy of the interplay between permeability and water absorbency in materials that are put close together to provide that function described in constructor jargon as the building envelope.

Figure 7.1 One of the team of architects for the National Gallery of Art in Ottawa entertains some delegates from the conference of the International Institute for Conservation, while a bucket in the shadow (arrowed) collects the condensate from the well bringing light from the roof to the galleries

Attempts to control water vapour by denial of access are doomed. One cannot construct a building like an aircraft. The industry does not have a perfectionist tradition and it works mostly out of doors, often in weather that hampers precise work.

Designers have become wiser since the early eighties, when we were investigating the Arts and Industries Museum, and other building failures with similar causes. Greater care in the design does not necessarily show in the finished product. Figure 7.1 shows the interior of the National Gallery of Art in Ottawa, designed in a cold country that has put a lot of research into the control of condensation. In this building there are simply too many complicated details in the precautions against condensation.

Using absorptive properties of materials instead of combatting them

The alternative approach put forward in this thesis is to take the water absorption of materials, and their permeability, as fundamental properties that can be used to advantage, or that, in other parts of a design, are so disadvantageous that the material should not be used.

In the case of the Arts and Industries Museum one can propose, with hindsight, that the roof deck should have been unabsorbent, perhaps metal, while the surface directly supporting the glass fibre insulation should have been absorbent: wood, for example, rather than polyester membrane. The vapour barrier should have been laid separately, just over the ceiling panels instead of in discrete rectangles within the prefabricated boxes, which left regular gaps for air flow through the roof.

Testing the original design against this, or any other proposed alternative, by computer simulation is impossible in the present state of refinement of the models for heat and moisture flow through buildings. I have therefore used most of my time in designing and building a test chamber for studying experimentally the performance of porous, water absorbent materials.

The need for a climate chamber that allows the expression of material properties

The unique feature of this chamber is that it allows the material under test to influence its environment, in contrast to traditional experimental chambers which impose an environment and watch the material react to its instructions.

The chamber described here is a prototype of limited use. It can imitate the interaction of interior walls with the indoor environment. There are two important limitations to its usefulness in predicting the performance of outer walls: there is no temperature gradient and there is no air, or vapour pressure difference across the test wall.

The chamber was, however, designed to be part of an extendable system. The obvious next step would be to build two chambers which could bolt up to each side of a model of an outer wall, or a roof, sealed around the edges. The chamber representing the outdoor climate could be constructed in the traditional way: controlling the temperature and the relative humidity. This is how the outside weather is. We have no control over it, nor does any material which is less extensive than a million hectares of sea or rain forest.

The results obtained with the isothermal chamber show that the indoor climate can be substantially influenced by porous, absorbent walls. I use the double adjective 'porous, absorbent' deliberately, to distinguish the entirely different performance of porous unabsorbent materials.

The usefulness of water absorbent materials as short term buffers

The usefulness of water absorbent materials indoors is as a buffer against brief periods of human activity that threaten condensation: showering, cooking and partying. During these events an absorbent material can substitute for mechanical ventilation. The heat of evaporation is recovered by heat of absorption released at the wall surface, giving increased comfort in the shower and removing the risk from automatic ventilators which eventually stick, either on or off, with energy loss in the first case and mould growth in the second.

The behaviour of porous materials laid over porous, absorbent materials is interesting. Figure 4.35 shows how the combination of gypsum plaster over cellular concrete provides a sort of diode: allowing condensed water to penetrate but hindering its return. The gypsum plaster conducts liquid water, because it is wettable and has a system of large pores, if the spaces between fibres can be so described. The cellular concrete has the same structure on a finer scale and so hangs on to the water once it has reached it. Such a system seems worth investigating side by side with the two other systems for selective water transfer: the offset laminate (Hygrodiode) of Professor Korsgaard and the variable resistance polymer film from the team at the Fraunhofer-Institut für Bauphysik in Holzkirchen. The difference is that these last two are factory made foils, while the material laminates are a technique of building.

This use of gypsum or lime plaster reduces the efficiency of buffering at moderate RH, by screening the good absorber from the room air. The RH has to rise to 100% before the plaster becomes active, and then gypsum begins to dissolve, which is why lime plaster is recommended. The high RH at which stabilisation begins is maybe an advantage in a bathroom, where buffering to a lower RH will increase evaporation from the skin and so give a chilly sensation to the person in the shower.

Porous lime plaster in the upper parts of bathrooms, which direct spray cannot reach, was at one time required, or at least regarded as good practice, in Danish houses.

The process of slow diffusion through a porous, but unreactive material from a porous-absorbent material may be the mechanism behind the observed stability, and excess water content of church interiors.

Water absorbent insulation as a very short term buffer

Water absorbent insulation, in the form of wool, or paper insulation, may have a useful role to play in preventing condensation caused, as in the Arts and Industries Museum, by the cycle of intense solar heating followed by heat loss by radiation to the night sky. The water distilled from hot surfaces can be temporarily stored in absorbent insulation, without condensation, to be released again on the cooling part of the cycle when the bottom of the insulation is relatively warm.

A related subject has been briefly discussed: whether absorbent materials conduct moisture according to the gradient of the relative humidity or the vapour pressure. The isothermal experiments can shed no light on this matter but it is identified here as an important matter whose resolution is essential to a complete understanding of the behaviour of porous, absorbent materials.

The author's recommended material

The best buffer materials in this investigation were wood and clay. Neither is effective in its normal form. Wood in the form of planks has too small a permeability to give good buffering in a room with a normal ventilation rate. Clay is completely impermeable. To make an effective buffer the cross section of the wood must be exposed and the clay must be opened up by mixing it with a filler.

The material that comes out with the best all-round performance is bentonite clay mixed with perlite as both filler, stiffener and thermal insulator. This material can be formed into any shape and it has reasonable compressive strength, so that it can be used as a massive wall whose heat capacity also contributes to the stability of the indoor climate. When mixed with straw it can be given bending strength sufficient for built in bookshelves, or, if one dare, a TV or computer table.

The balance between water capacity and diffusion rate can be adjusted by altering the ratio of clay to filler, limited by the increasing drying shrinkage as the clay content is increased. The surface can be burnished to adjust its vapour permeability.

The disadvantage of clay is that it is very dusty and requires some surface treatment.

The performance of absorbent buffers over longer periods

Humidity buffering is always in competition with ventilation. Even a massive wall with a large water capacity cannot compete with rapid ventilation, because as the surface layers become depleted, diffusion from deeper down becomes slower and slower, while the ventilation rate is relatively constant, over the long term.

In a house with about half an air change per hour the buffer capacity is effective over a period of a few days at most.

Even the best buffer, the lightweight bentonite/perlite mixture, cannot long prevent the indoor dryness that comes with the onset of the heating season in cold and temperature climates. Low relative humidity has no disadvantage for human comfort but is not so good for the organic materials in houses: coins fall through cracks between the floorboards, pianos go out of tune and portraits of the ancestors wrinkle and crack.

Buildings which contain humidity sensitive objects but can have a low air exchange rate, such as archives, can moderate the climate with absorbent materials so well over the whole year that orthodox air conditioning is unnecessary. Museums require a suitable air exchange rate for people to breathe, but can also benefit from porous absorbent materials. They may well need mechanical air conditioning but the design can be simpler. An underdimensioned air conditioning system operating overnight would prepare the climate for human occupation during the day, during which time the climate would be stabilised by the absorbent construction. Indeed, an overdimensioned, fast reacting air conditioning system cannot work in a well buffered building, because of the risk of positive feedback in the control system, as described in the section on the Brede Museum Store in chapter 6.

The potential that lies in the combination of absorbent materials with air conditioning has lain dormant since MacIntyre's article describing lining the ducts in Hampton Court Palace with discarded fire hose (The fire hoses are clearly also a fire risk, but it was an old lady smoking in bed half a century later who actually burned part of the Palace).

The problem of chronically low RH in exhibition buildings during the winter can be, at least partly, ameliorated by massive, absorbent walls. These should, according to theory, pump water into the building against the concentration gradient of water vapour in air, if the computer model of moisture movement through porous absorbent materials in a temperature gradient is confirmed.

Surface treatment of porous building materials

Combinations, or rather laminates, of porous materials will be advantageous for indoor surfaces of walls. Mud is dusty, and porous materials generally collect dirt. Surface finishes have not been investigated in this thesis, but only through lack of time.

Decorated porous surfaces have been in eclipse since the extinction of the cheap post second world war distemper paints, made from oil emulsions with a low binder to pigment ratio. The best chance for aesthetically pleasing porous surfaces for buffer walls seems to lie in a revival of the north European tradition for porous lime painting, now confined to churches. Any research that offers alternatives to the current fashion for white plastic painted interiors cannot be entirely wasted.

Figure 7.2 A porous lime painting by Conny Hansen, 1996, after the early 16th. century original in Nibe Church, Jutland, Denmark.

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Equations describing the physical properties of moist air

This appendix covers these topics:

Water vapour pressure

In a closed container partly filled with water there will be some water vapour in the space above the water. The concentration of water vapour depends only on the temperature. It is not dependent on the amount of water and is only very slightly influenced by the presence of air in the container.

The water vapour exerts a pressure on the walls of the container. The empirical equations given below give a good approximation to the saturation water vapour pressure at temperatures within the limits of the earth's climate.

Saturation vapour pressure, p_s, in pascals:
$\mathbf{p_s = 610.78 * \exp(t / (t + 238.3) * 17.2694)}$
where **t** is the temperature in degrees Celsius

The svp below freezing can be corrected after using the equation above, thus:
$\mathbf{p_{s\ ice} = -0.00486 + 0.85471 * p_s + 0.2441 * p_s^2}$

The next formula gives a direct result for the saturation vapour pressure over ice:
$\mathbf{p_{s\ ice} = \exp(-6140.4 / (273 + t) + 28.916)}$

The **pascal** is the SI unit of pressure = newtons / m^2. Atmospheric pressure is about 100,000 Pa (standard atmospheric pressure is defined as 101,300 Pa).

Water vapour concentration

The relationship between vapour pressure and concentration is defined for any gas by the equation:
$p = nRT/V$
p is the pressure in Pa, V is the volume in cubic metres, T is the temperature in degrees Kelvin (degrees Celsius + 273.16), n is the quantity of gas expressed in molar mass (0.018 kg in the case of water), R is the gas constant: 8.31 Joules/mol/m^3

To convert the water vapour pressure to concentration in kg/m^3: (Kg / 0.018) / V = p / RT

kg/m^3 = 0.002166 *p / (t + 273.16) *where p is the actual vapour pressure*

Relative Humidity

The Relative Humidity (RH) is the ratio of the actual water vapour pressure to the saturation water vapour pressure at the prevailing temperature.

RH = p/p_s

RH is usually expressed as a percentage rather than as a fraction.

The RH is a ratio. It does not define the water content of the air unless the temperature is given. The reason RH is so much used in conservation is that most organic materials have an equilibrium water content that is mainly determined by the RH and is only slightly influenced by temperature.

Notice that air is not involved in the definition of RH. Airless space can have a RH. Air is the transporter of water vapour in the atmosphere and in air conditioning systems, so the phrase *"RH of the air"* is commonly used, and only occasionally misleading. The independence of RH from atmospheric pressure is not important on the ground, but it does have some relevance to calculations concerning air transport of works of art and conservation by freeze drying.

The Dew Point

The water vapour content of air is often quoted as dew point. This is the temperature to which the air must be cooled before dew condenses from it. At this temperature the actual water vapour content of the air is equal to the saturation water vapour pressure. The dew point is usually calculated from the RH. First one calculates p_s, the saturation vapour pressure at the ambient temperature. The actual water vapour pressure, p_a, is:

$p_a = p_s$ * RH% / 100

The next step is to calculate the temperature at which p_a would be the saturation vapour pressure. This means running backwards the equation given above for deriving saturation vapour pressure from temperature:

Let **w = ln (p_a/ 610.78)**
Dew point = w *238.3 / (17.294 - w)

This calculation is often used to judge the probability of condensation on windows and within walls and roofs of humidified buildings.

The dew point can also be measured directly by cooling a mirror until it fogs. The RH is then given by the ratio

RH = 100 * $p_{s\,\mathrm{dewpoint}}/p_{s\,\mathrm{ambient}}$

Concentration of water vapour in air

It is sometimes convenient to quote water vapour concentration as kg/kg of dry air. This is used in air conditioning calculations and is quoted on psychrometric charts. The following calculations for water vapour concentration in air apply at ground level.

Dry air has a molar mass of 0.029 kg. It is denser than water vapour, which has a molar mass of 0.018 kg. Therefore, *humid air is lighter than dry air*. If the total atmospheric pressure is P and the water vapour pressure is p, the partial pressure of the dry air component is P - p . The weight ratio of the two components, water vapour and dry air is:

kg water vapour / kg dry air = $0.018 * p / (0.029 * (P - p))$
$= 0.62 * p / (P - p)$

At room temperature P - p is nearly equal to P, which at ground level is close to 100,000 Pa, so, approximately:

kg water vapour / kg dry air = $0.62 * 10^{-5} * p$

Thermal properties of damp air

The heat content, usually called the *enthalpy*, of air rises with increasing water content. This hidden heat, called latent heat by air conditioning engineers, has to be supplied or removed in order to change the relative humidity of air, *even at a constant temperature.* This is relevant to conservators. The transfer of heat from an air stream to a wet surface, which releases water vapour to the air stream at the same time as it cools it, is the basis for psychrometry and many other microclimatic phenomena. Control of heat transfer can be used to control the drying and wetting of materials during conservation treatment.

The enthalpy of dry air is not known. Air at zero degrees celsius is *defined* to have zero enthalpy. The enthalpy, in kJ/kg, at any temperature, t, between 0 and 60C is approximately:

$h = 1.007t - 0.026$ *below zero:* $h = 1.005t$

The enthalpy of liquid water is also defined to be zero at zero degrees celsius. To turn liquid water to vapour at the same temperature requires a very considerable amount of heat energy: 2501 kJ/kg at 0C

At temperature t the heat content of water vapour is:

$h_w = 2501 + 1.84t$

Notice that water vapour, once generated, also requires more heat than dry air to raise its temperature further: 1.84 kJ/kg.C against about 1 kJ/kg.C for dry air.

The enthalpy of moist air, in kJ/kg, is therefore:

$h = (1.007*t - 0.026) + g*(2501 + 1.84*t)$
g is the water content in kg/kg of dry air

The Psychrometer

The final formula in this collection is the **psychrometric equation**. The psychrometer is the nearest to an absolute method of measuring RH that most people ever need. It is more reliable than electronic devices, because it depends on the calibration of thermometers or temperature sensors, which are much more reliable than electrical RH sensors. The only limitation to the psychrometer is that it is difficult to use in confined spaces (not because it needs to be whirled around but because it releases water vapour).

The psychrometer, or wet and dry bulb thermometer, responds to the RH of the air in this way:

Unsaturated air evaporates water from the wet wick. The heat required to evaporate the water into the air stream is taken from the air stream, which cools in contact with the wet surface, thus cooling the thermometer beneath it. An equilibrium wet surface temperature is reached which is very roughly half way between ambient temperature and dew point temperature.

The air's potential to absorb water is proportional to the difference between the mole fraction, m_a, of water vapour in the ambient air and the mole fraction, m_w, of water vapour in the saturated air at the wet surface. It is this capacity to carry away water vapour which drives the temperature down to t_w, the wet thermometer temperature, from the ambient temperature t_a :
$(m_w - m_a) = B(t_a- t_w)$
B is a constant, whose numerical value can be derived theoretically by some rather complicated physics (see the reference below).

The water vapour concentration is expressed here as mole fraction in air, rather than as vapour pressure. Air is involved in the psychrometric equation, because it brings the heat required to evaporate water from the wet surface. The constant B is therefore dependent on total air pressure, P. However the mole fraction, m, is simply the ratio of vapour pressure p to total pressure P: p/P. The air pressure is the same for both ambient air and air in contact with the wet surface, so the constant B can be modified to a new value, A, which incorporates the pressure, allowing the molar fractions to be replaced by the corresponding vapour pressures:

$p_w - p_a= A^* (t_a- t_w)$

The relative humidity (as already defined) is the ratio of p_a, the actual water vapour pressure of the air, to p_s, the saturation water vapour pressure at ambient temperature.

RH% = $100 *p_a/ p_s$ **$= 100 *(p_w - (t_a- t_w) * 63) / p_s$**
*When the wet thermometer is frozen the constant changes to **56***

The psychrometric constant is taken from: R.G.Wylie & T.Lalas, "Accurate psychrometer coefficients for wet and ice covered cylinders in laminar transverse air streams", in **Moisture and Humidity 1985**, published by the Instrument Society of America, pp 37 - 56. These values are slightly lower than those in general use.

Doing the calculations

There are tables and slide rules for calculating RH from the psychrometer and other climatic variables that are not measured directly, but a programmable calculator is very handy for this job. There is also a downloadable calculator in javascript:

www.natmus.dk/cons/tp/atmcalc/atmocalc.htm

It uses the equations listed here. The file can be used in a web browser even when it is not online. Psychrometric, or Mollier, charts provide graphical versions of all these formulæ and don't need electricity.

A list of the formulæ used in this article, in spreadsheet and calculator notation

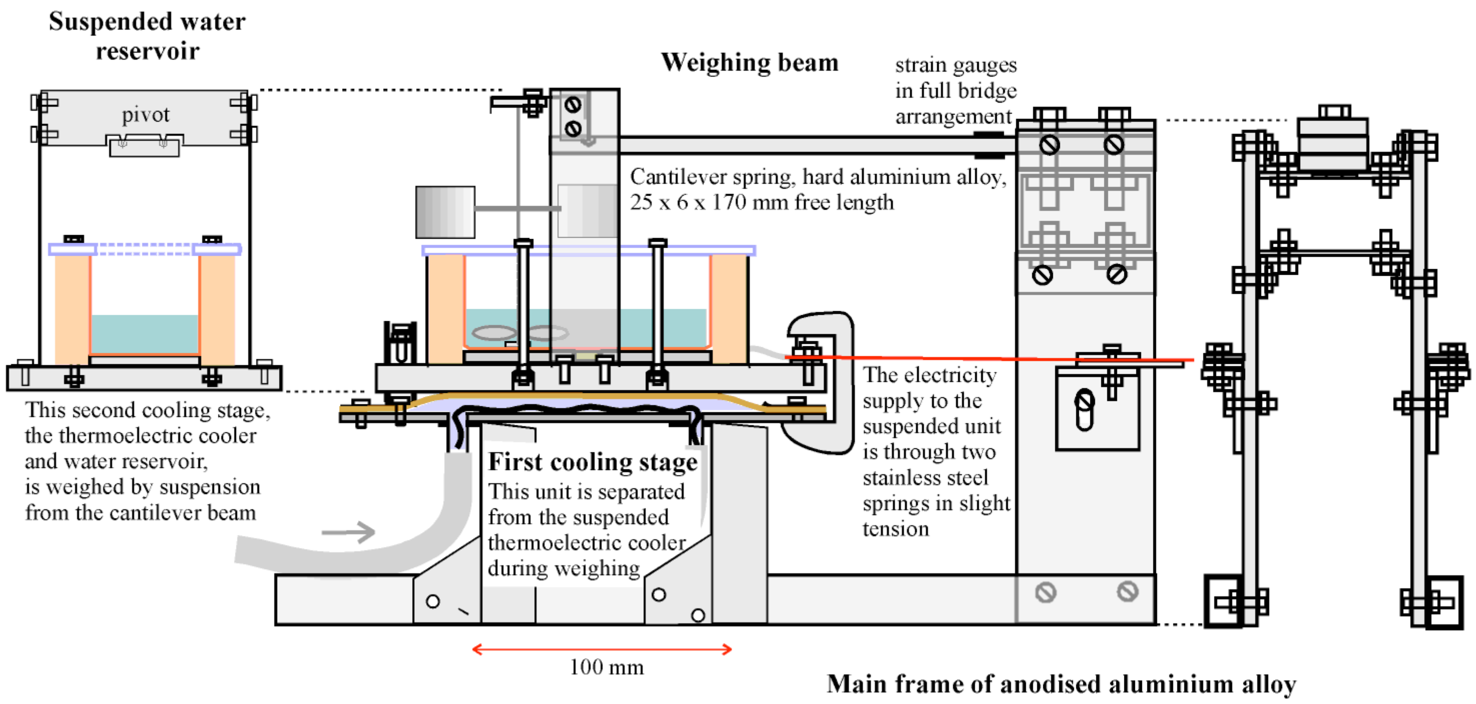
The following functions are the equations described above, rewritten in a format which can be further altered to suit the peculiarities of any particular spreadsheet or programmable pocket calculator. I don't recommend using a simple pocket calculator.

```
function TtoSVP(t) //saturation vapour pressure (svp)

svp=610.78*exp(t/(t+238.3)*17.2694);

function SVPtoT(vp) // dew point temperature (dp) from vapour pressure (vp)

w=log(vp/610.78);

dp=w*238.3/(17.294-w);

function VPtoKGM3(vp,t) //kg water/cubic metre from vapour pressure and temperature

kgm = 0.002167*vp/(t+273.16);

function WBtoRH(t,wb)//RH from dry (t)and wet(wb)temperatures

rh = (TtoSVP(wb) - (t-wb)*66.7)/TtoSVP(t)*100;

function VPtoKGKG(vp) // approx. vapour pressure to kg water/kg air at ground level

kgprkg=0.622*vp/(101300-vp);
```

To check your program, take air at 20C and 15.7C wet bulb temperature. The RH is 65%. The water vapour pressure is 1500 Pa. The water vapour concentration in kg/m3 is 0.011, in kg/kg it is 0.009. The dew point is 13C.

Weighed air conditioner

General view, showing details of the main frame and weighing system. Other diagrams show details of the two cooling systems

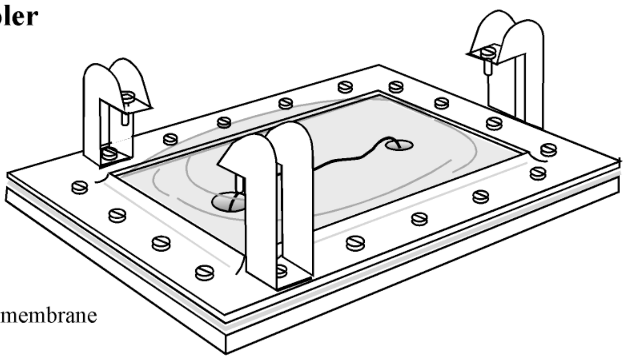


13/3/98

Thermoelectric cooler

The first cooling stage

12/3/98

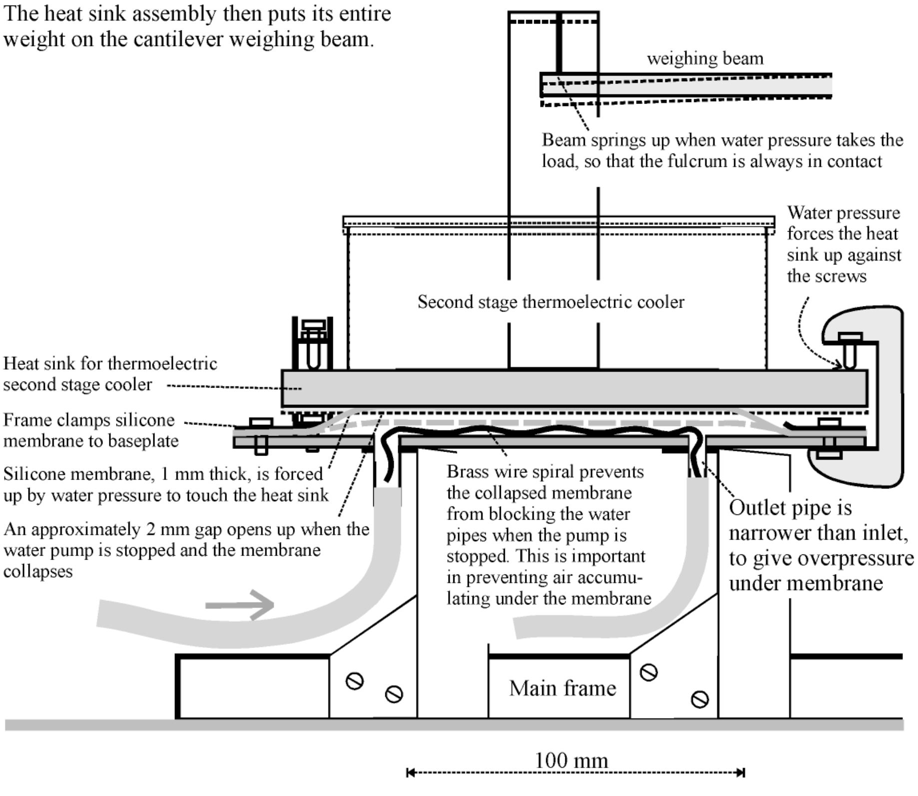


Perspective sketch
of the first stage cooling
plate with flexible silicone membrane

The heat sink is normally forced up against the screws by water pressure under the flexible membrane

The heat sink and the thermoelectrically cooled reservoir that is fixed to it are weighed periodically after the water pressure is removed, so that the membrane sinks clear of the heat sink.

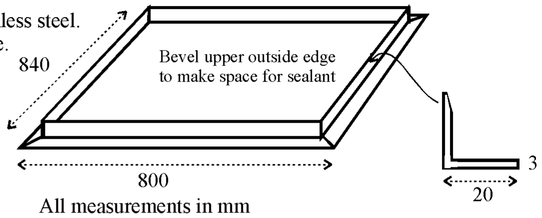
The heat sink assembly then puts its entire weight on the cantilever weighing beam.



Cover for climate chamber

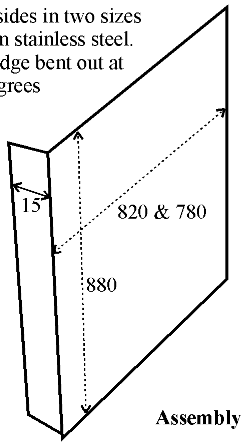
Tim Padfield, 27/7/97

Square base frame in 3 x 20mm stainless steel.
Flat on underside to seal to base plate.

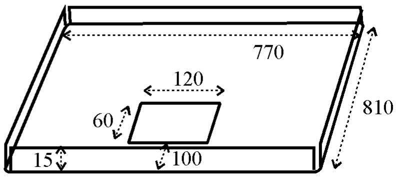


All measurements in mm

Four sides in two sizes
0.5mm stainless steel.
One edge bent out at
90 degrees

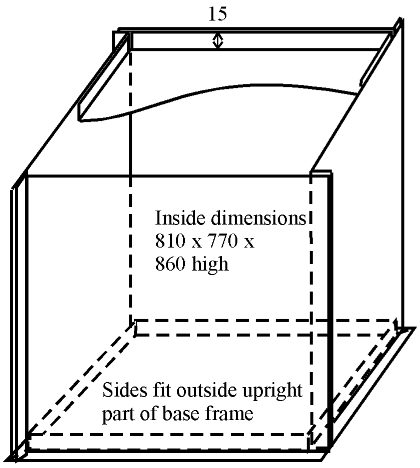


top in 0.5mm stainless steel.
All sides bent up at 90 degrees.



Top has inspection hole
covered with polycarbonate

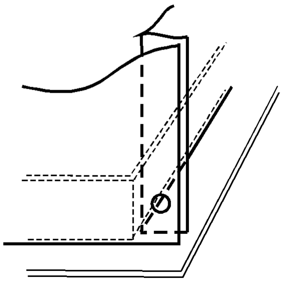
Assembly:



Inside dimensions
810 x 770 x
860 high

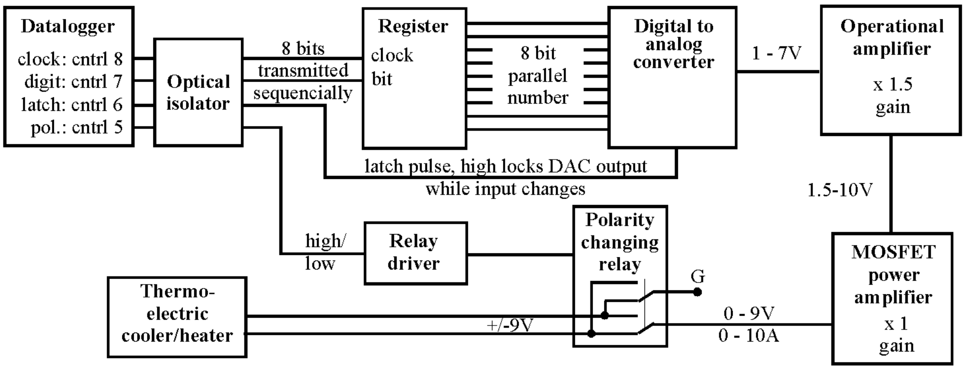
Sides fit outside upright
part of base frame

Spot weld just for rigidity: airtightness
is by sealing with silicone.



Hole at each bottom corner
for mounting lifting cords,
4mm dia., 10mm from base

Block diagram of the controller, which converts an 8 bit binary number into 10V - 10A power to the thermoelectric cooler



Appendices on the CD-ROM (in html format):

Electrical circuit diagrams

Data logger program

Java code for the modelling program