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.

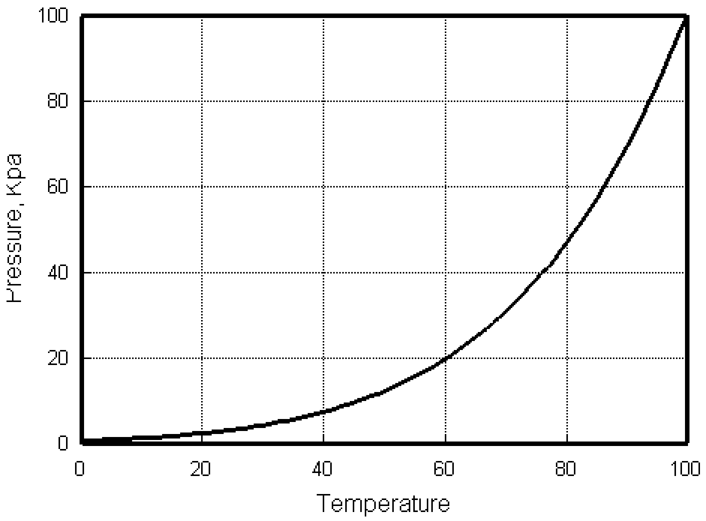


Figure 1.7 The saturation vapour pressure of water.

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.

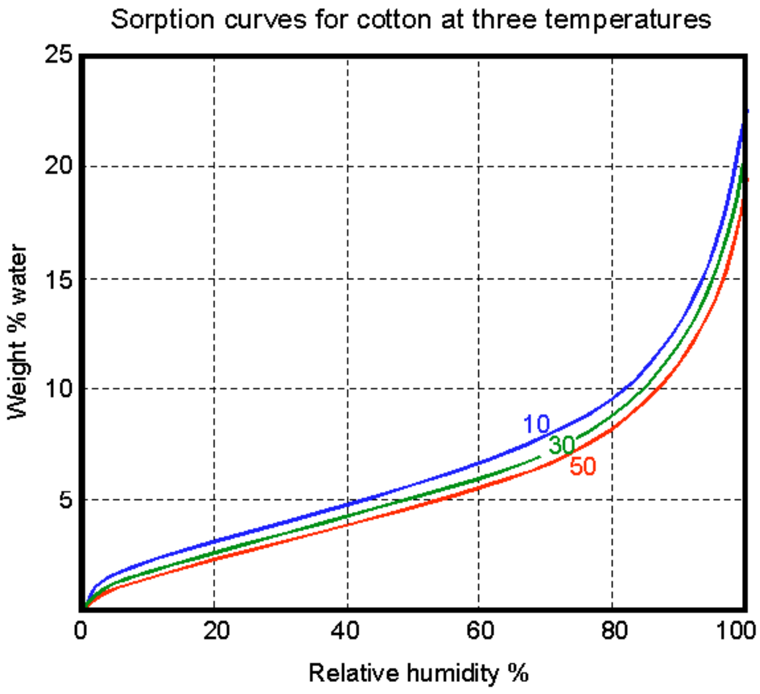


Figure 1.8 The absorption isotherm of cotton at three temperatures

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.

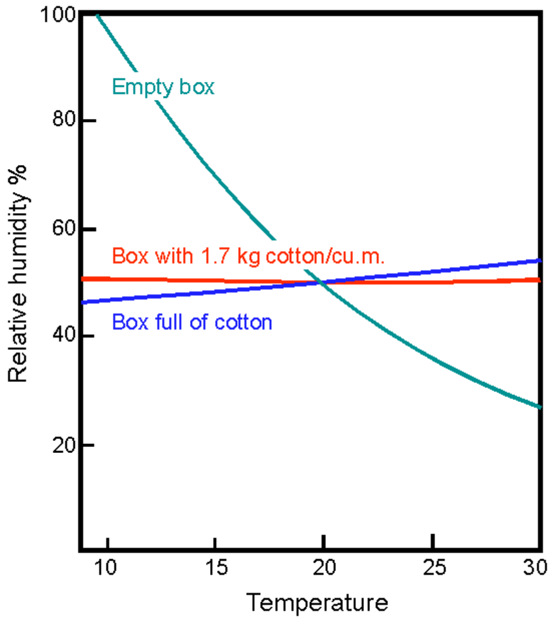


Figure 1.9 The change of relative humidity with temperature in a box with and without cotton as a humidity buffer.

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.

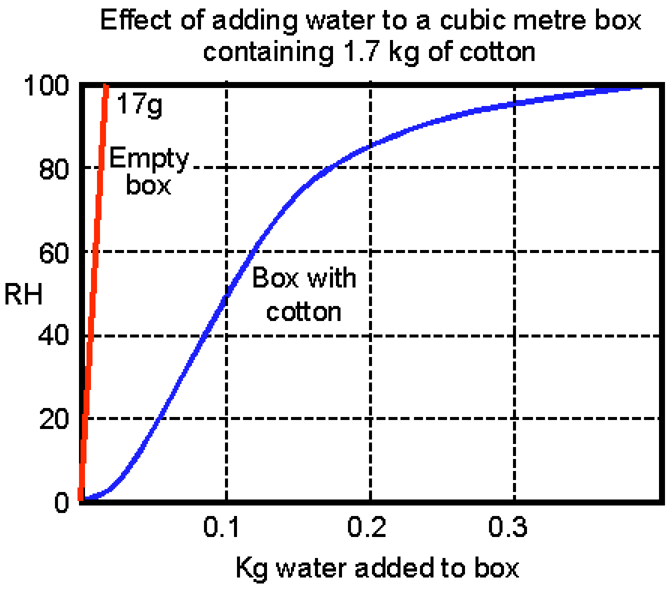


Figure 1.10 Buffering the relative humidity of a box against the effect of adding water: 17 g of water added to the dry empty box will raise the RH to nearly 100%. If there is 1.7 kg of cotton in the box over 200 g of water must be added to give the same RH increase

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.

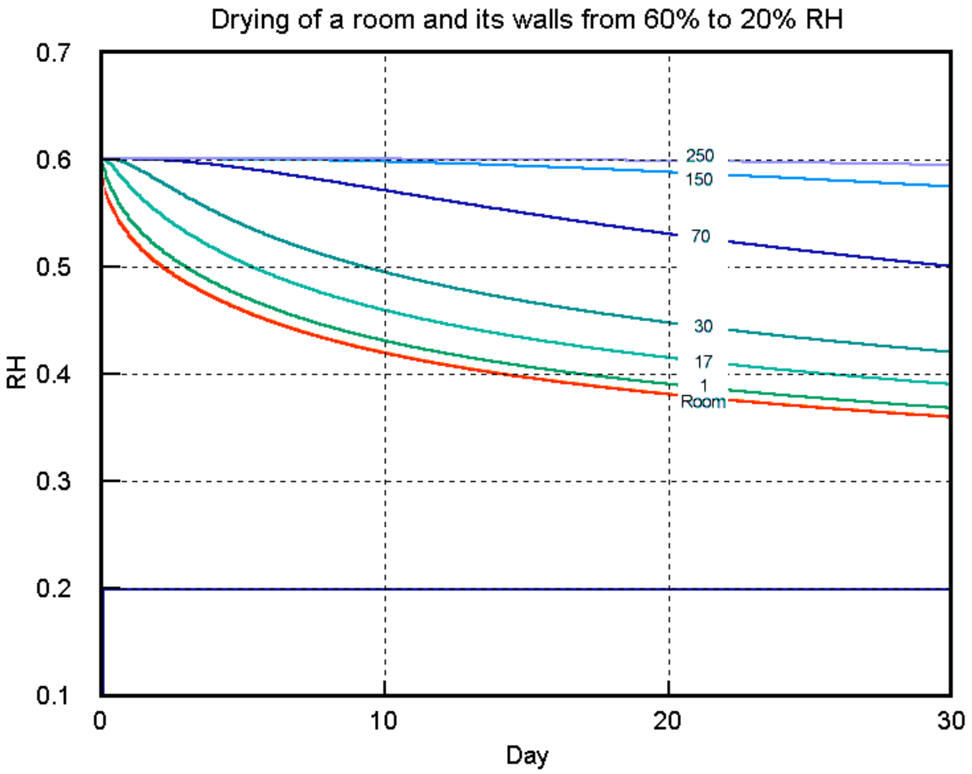


Figure 1.11 Fick's law applied to the drying of a room bounded by porous, absorbent walls, all initially at equilibrium with 60% RH. The room has half an air change per hour. The outside air is at 20% RH and at the same 20 degree temperature as the room.

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.

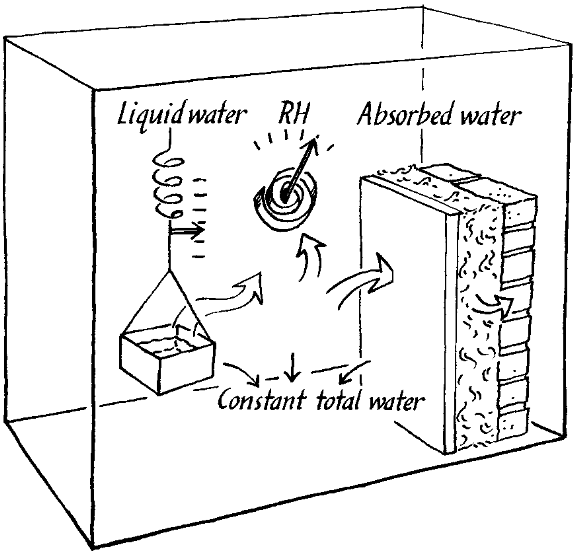


Figure 1.12 Principle of operation of the water vapour flux chamber. The airtight chamber contains a fixed quantity of water which is distributed between three components: a water tank, which is weighed, the air in the chamber, whose RH is measured and the experimental wall, whose change in water content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

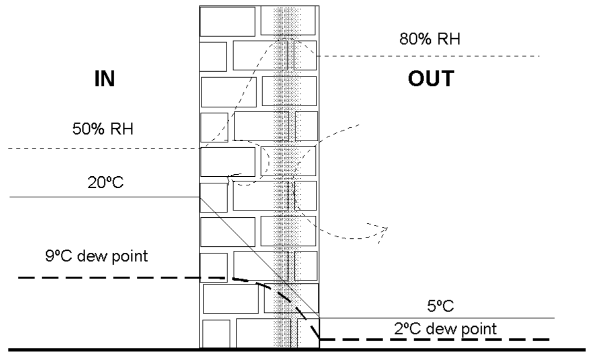
If the vapour pressure gradient is the effective influence, the outside wall will function as a slow dehydrater of the indoor climate, because the inside water vapour concentration is generally higher than that outside, so there will be a slow diffusion of water vapour outwards. The importance of this 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.

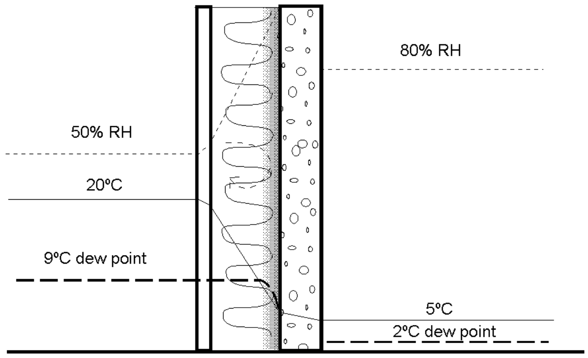
The doubtful practical value of vapour barriers, particularly in non-absorbent walls

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.

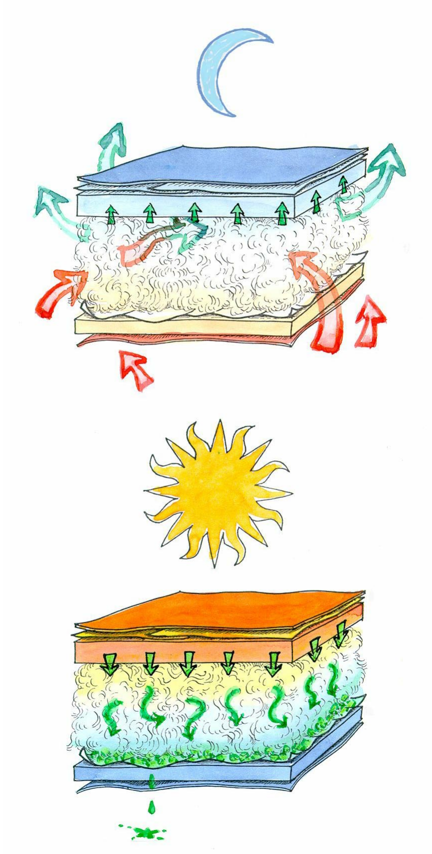


Figure 1.14 Distillation of water from a roof deck moistened by water condensed during the winter (top). On a sunny spring day (bottom diagram) the water will be distilled over to the relatively cool ceiling. The process can be reduced by absorbent insulation, or by impermeable insulation.

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.