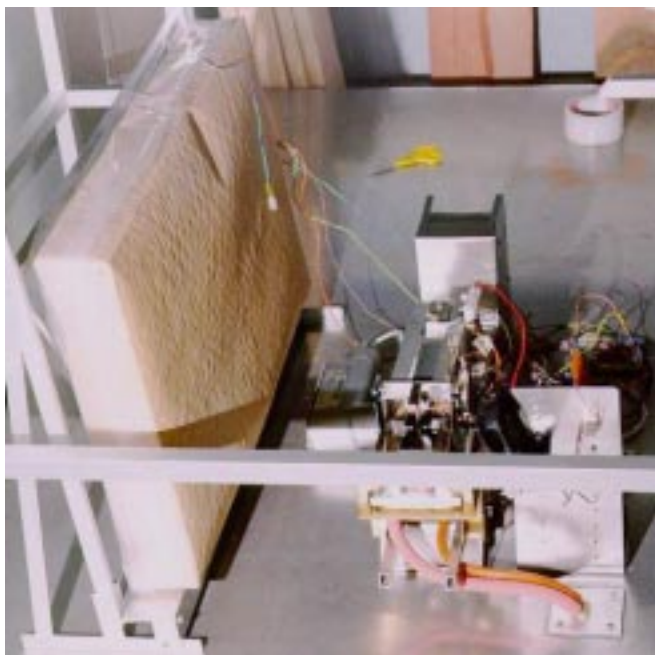


# Humidity buffering of interior spaces by porous, absorbent insulation

Part of Hygrothermal properties  
of alternative insulation materials



TIM PADFIELD

Department of Structural Engineering and Materials  
Technical University of Denmark



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# **Humidity buffering of interior spaces by porous, absorbent insulation**

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## **Summary**

Thermal insulation made from wool will have a detectable, but small, moderating influence on variation in the indoor relative humidity in a house with less than half an air change per hour and with porous wall surfaces, such as paper, limewash or silicate paint.

Water vapour distributes itself fairly evenly through a 160 mm layer of wool insulation during a 24 hour climatic cycle. The RH buffering performance is therefore limited only by its low density and consequent low water capacity by volume. A vapour retarder on the room side of the insulation reduces the buffer action of the insulation to practical insignificance.

Absorbent insulation will only have a useful influence on the indoor climate if the entire wall is redesigned to give a much more porous structure. This development would conflict with the custom of putting a vapour barrier or vapour retarder close to the inside surface of a wall. A more practical way of moderating the indoor relative humidity would be to use an absorbent interior finish instead of the customary gypsum board. The excellent performance of end grain wood as an interior finish is shown for comparison.

The experiments reported here show the influence on the daily variation of indoor humidity of wool, vapour barrier and plasterboard, separately and in combination. Paint is not included in the tests. The response of a wall to a sudden injection of water vapour, as would happen in a kitchen or bathroom, is also studied. In this event the main moderator of the RH is the plaster board, while the wool insulation absorbs water slowly over a period of 60 hours. However, during this time, natural ventilation of a real room would already have moderated the RH. The contribution of the absorbent insulation is therefore only significant if the natural air exchange rate is very low. A low exchange rate is considered desirable to save energy but is also blamed for causing sickness because of the high indoor RH caused by human activities, which encourages microbiological growth. Any beneficial function of organic insulation must therefore lie in its ability to moderate the variation in RH *within the wall* while it releases moisture steadily to the outside to reduce the average indoor RH.

The risk of condensation within a porous wall without a vapour retarder is the subject of two experiments which are in progress. Only when these results are in, will the role of absorbent insulation be clarified sufficiently to justify full scale tests of porous, absorbent walls.

### **What is moisture buffer capacity?**

Porous, absorbent materials release water vapour to the air when its relative humidity (RH) falls, thus acting against the process, usually ventilation, causing the fall in RH. Water is re-absorbed from the air when the RH rises. The process is not exactly reversible, because of hysteresis in the sorption of water by materials.

There is no universally agreed unit for describing the moisture buffering capacity of a material and no international standard for measuring it. The amount of water vapour released from the surface of a material as a consequence of a fall in RH depends on the temperature, the air velocity at the surface, the water capacity of the material (in kg per unit change of RH), the permeability to water vapour and the time scale in which the process takes place. An increase in all these parameters causes an increase in water vapour release.

According to current theory, we need neither a unit nor a standard to define buffer capacity, because the buffer capacity is derivable from the water capacity and the moisture permeability, both of which are easily measured by standardised procedures. The water available for buffering over a specified period can be calculated from the water capacity and the active thickness of the material on this time scale. The active depth is calculated in the same way as the penetration of heat into a material, as described in (1).

The only problem with this procedure is that it predicts a water release that is quite different from the measured release when the material is subjected to a daily cycle of humidity variation, such as would occur in a building. A possible reason for this disagreement between theory and practice is discussed at length in appendix 2. In brief, the theory assumes instantaneous equilibrium between the absorbent material and the air in the pore spaces. It is possible that in a dynamic situation with changing RH across the specimen, the water vapour will not have time to equilibrate with the absorptive material through whose pore spaces it is diffusing. Wadsö and Arfvidsson (2) have shown that the rate of diffusion of water from the pore space into the cell wall of wood is quite slow and cannot be modelled by theories which assume instant equilibrium between the water vapour in the pore air and water in the pore wall.

The consequence of delayed reaction between moisture in the air diffusing through the pores and the material between the pores is that the effective water capacity is less than the value measured according to the standard procedure, in which the specimen is given time to reach equilibrium, often taking several weeks to do so. The depth of penetration during rapid humidity cycles is therefore greater than calculated, because the diffusing moisture is only slowly caught up in the material. Further evidence for a two stage absorption process is provided by experiments where it proved impossible to match the observed RH changes within a porous material subjected to a cyclic RH gradient merely by adjusting the absorption and diffusion constants to achieve a best fit. If the observed amplitude of the RH within the specimen was approximately matched, the phase shift was wrong (3).

### **How does this argument affect the choice of unit and the measurement method?**

We need a practical standard to define the effectiveness of various materials in buffering the interior RH in a house, which has a daily cycle of water release by people and water loss by ventilation. One important matter is how time should be incorporated in the standard unit. The natural time scale for buffering of the indoor climate, and the climate within a roof structure, is one day. Buffering over longer periods is only effective when the air exchange rate is very slow, as will be shown later.

The standard for buffer performance proposed here is: **the weight of water vapour passing through one square metre of the surface of the test specimen when it is subjected to a 10% peak to peak sinusoidal variation in RH of the adjacent space.** The RH varies around an average that lies between 40% and 60%. In these moderate conditions the water capacity of the material can be assumed to be constant. It is also the RH range in which the water capacity for many materials is at a minimum: most sorption curves are steeper at both low and high RH. The number obtained is slightly temperature dependent, so the temperature must be given together with the weight of water vapour. Notice also that the number is only a property of the material if it is of greater thickness than the reactive depth for the daily cycle. Since there is at present no way of calculating the performance of composite specimens, the number can also usefully be applied to laminates of different materials.

In this article the performance of various materials is first shown graphically, in a way that indicates directly how the materials would moderate the RH in a house with a typical ratio of wall and ceiling to room volume. These data are finally reduced to a single 'figure of merit' for each test wall, according to a calculation described in appendix 3.

### The experimental climate chamber



*Figure 1. The climate chamber. It stands about 1 metre high. The control electronics is in the foreground.*

The test chamber is an airtight box, about a half cubic metre in net air volume, which contains a device that can release measured quantities of water vapour into the air, or condense water vapour from the air, thus imitating the effect of water generated within a house by cooking and bathing, as well as water removal by ventilation to cold outside air. The relative humidity within the chamber is controlled by the interaction of the enclosed absorbent material with the air in the chamber. The design is described in detail in reference 3.

A series of experimental walls was mounted in the chamber, as shown in figure 2. The wall area was about 0.6 square metres per cubic metre of chamber air. This is a typical ratio of wall and ceiling area to volume of a house.

Relative humidity sensors were placed within the walls, as well as in the chamber air space.

The wall shown in figure 2 is made of wool insulation covered with a vapour retarding paper. Various experiments were made with different combinations of gypsum board, vapour barrier or vapour retarding paper and wool insulation. The measured properties of the materials used are given in (3) and are also summarised in the notes to this article.



Figure 2. An experimental wall, 600 mm square, of wool insulation, mounted within the chamber. The wool is covered on the front by vapour retarding paper and sealed on the back with aluminium foil and polyethylene. Wires lead to sensors within the insulation. One of the sensors can be seen dangling in front of the wall. The water vapour flux generator is to the right with the temperature controller in a tower behind it.

The flux generator evaporates, and then condenses, a defined weight of water vapour on a sinusoidal cycle which can be adjusted between 12 hours and 4 days. The water vapour in the chamber air is calculated from the temperature and the relative humidity. The rest of the water vapour passes through the surface of the specimen.

### An experiment which shows how a wall responds to a sudden production of water vapour

Figure 3 shows how an absorbent wall reacts to the sudden production of water vapour indoors, from a kettle boiling dry, for example. This example is presented first, to show qualitatively how the various components of a wall react to this sudden stress. The wall in this case is of normal construction: gypsum board, vapour retarding paper and then the wool insulation. There is no paint on the wall, because plastic paint is impermeable on this time scale.

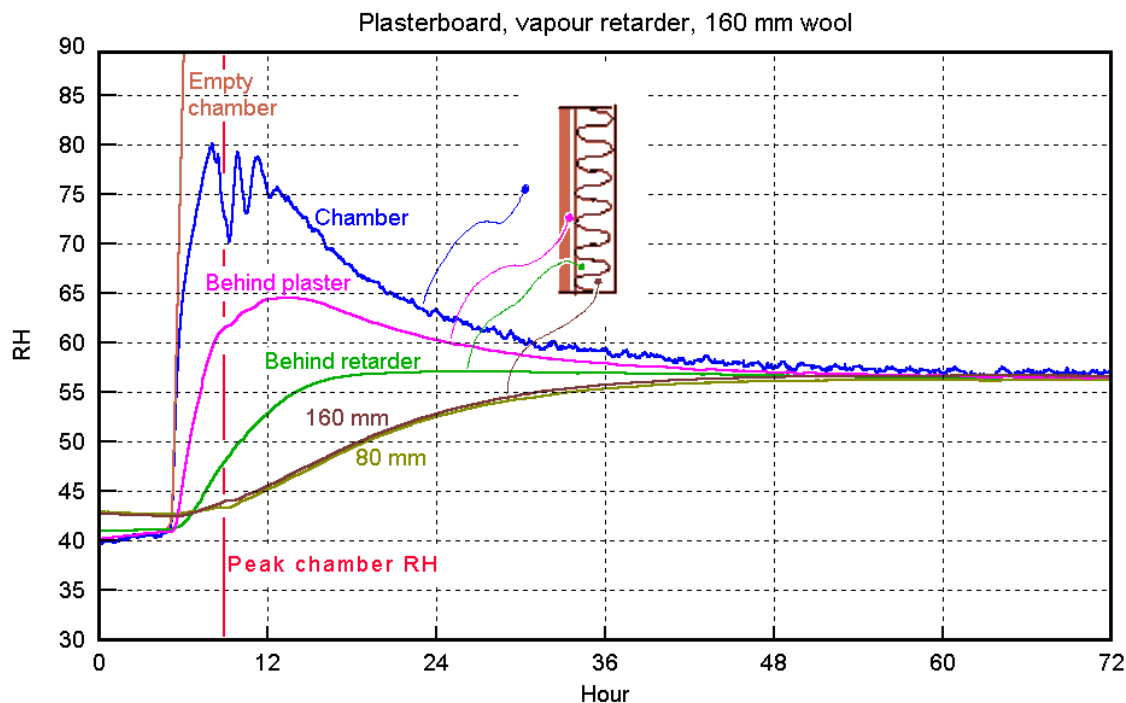


Figure 3. The course of the relative humidity in the chamber and within the experimental wall when water vapour was suddenly added to the air in the chamber. The jagged peaks are caused by instability of the flux controller. The wall surface is 13 mm plasterboard. Behind that is a vapour retarding paper then 160 mm of wool insulation. The back is impermeable. The gypsum board reacts first. The water vapour then diffuses through the vapour retarding paper. The wool insulation reacts quite slowly, over two days.

At the beginning of the test, at hour 5 in the diagram,  $36 \text{ g/m}^3$  of water vapour was suddenly evaporated into the chamber. This would be enough to raise the RH in the empty chamber to 100% and then cause condensation on the chamber walls of 20 g of water per cubic meter of chamber volume.

The test wall absorbed the water so effectively that the actual RH never went above 80% and soon returned to about 57%, not so far above the starting condition at 42%. However, it is not immediately obvious how the absorbed water is distributed between the components of the wall.

The easiest way to explain what happens is to start at hour 60, when the whole assembly has come to equilibrium at 57% RH. At this time one can calculate that the wool has absorbed  $41 \text{ g/m}^2$ , the plaster board has absorbed  $4 \text{ g/m}^2$  and the paper vapour retarder about  $3 \text{ g/m}^2$ . There is  $3.4 \text{ g/m}^3$  remaining in the air. The wall contains about  $50 \text{ g/m}^2$  water. The water injected was  $56 \text{ g/m}^2$  of wall. The agreement is reasonable. At this time the bulk of the water has been collected in the wool. But what was the situation at the peak of the crisis, marked by the vertical red line in figure 3? At this moment the RH in the wool had increased by at most 2.5%, corresponding to about  $7 \text{ g/m}^2$  of water absorbed. About  $8 \text{ g/m}^3$  was in the air and the rest, about  $35 \text{ g/m}^2$ , must have been in the plasterboard and the vapour retarder. The calculation is complicated by the steeply rising absorption curve for plaster and paper at 80% RH, but it is clear that the plasterboard is doing most of the buffering during the acute phase of the event.

It is interesting to note that wool insulation and gypsum board have about the same water absorption per unit of RH change per unit *volume*: approximately  $3 \text{ kg}/(\text{m}^3 \cdot \text{rh})$  (3). The gypsum board is only 14 mm thick (nominally 13 mm) against the wool's 160 mm, but it is closer to the room, so it absorbs the water first and then transfers it slowly through to the wool, so that in the end most of the water is absorbed into the wool.

During this time, in a real house, the air would have changed at least twenty times, securing a moderation of the RH by ventilation alone.

The wool insulation has therefore only a limited influence on the room climate, once it is encapsulated behind plasterboard and vapour retarding paper. If the plaster board had been painted with plastic paint or oil paint the buffer effect of the wall would be negligible, and condensation would drip from all surfaces in the chamber. The buffer performance of this wall therefore depends on the use of a very permeable surface finish, such as water paint, or silicate paint.

This experiment gives an impression of the magnitude of the water movements within the various layers of a wall. The next section gives a more systematic description of the contributions of the components of the wall to the observed humidity buffering in the room, using a more moderate, sinusoidal humidity cycle.



### The contributions to humidity buffering by the various materials in the wall

The series of graphs that follows shows how the various materials in the insulated wall perform alone and in combination.

Instead of being exposed to the vapour from a boiling kettle, the materials in these experiments were exposed to a sine curve of flux into the room, designed to imitate the production of water by human activities and its subsequent release by ventilation. The basic cycle is one day long but one longer cycle is shown to illustrate the endurance of the material to prolonged one way vapour movement.

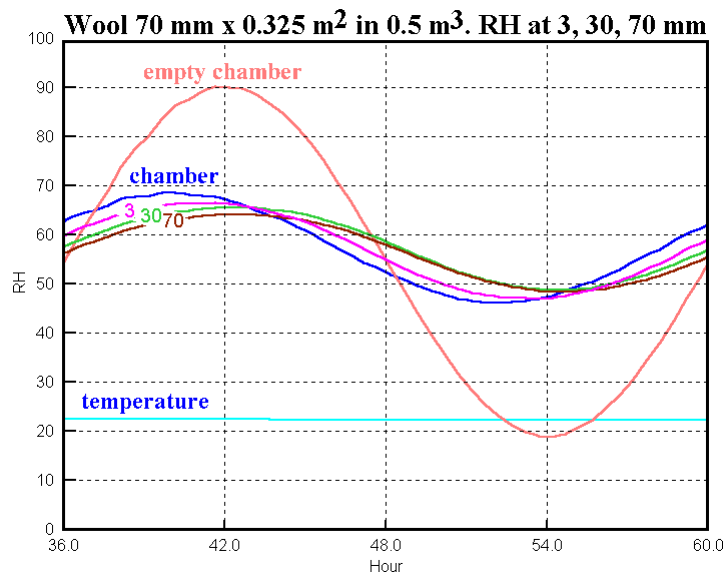


Figure 4. Wool insulation, one day flux cycle. The orange curve (with the widest cycle) is the expected RH if the chamber were empty. The blue line (the second largest amplitude) is the RH observed in the chamber and the other lines are the RH at various depths within the wool, marked in mm. The ratio of area of exposed wool to chamber volume is 0.65, which is a typical ratio of area of wall and ceiling to room volume in an ordinary room.

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. The buffer capacity *per unit of wall area* is small. It is very porous, so the entire thickness of the wool is brought into play, even during a daily flux cycle.

Figure 4 is interpreted in this way: The water vapour cycle within the chamber had a peak to peak amplitude of 18.2 g/m<sup>3</sup>. At 23°C this amount of water would increase the chamber RH by about 90%. There is, however, some residual water absorption by the chamber and the equipment within it, so the experimental performance of the chamber is shown by the orange line, which swings about 72% in RH.

When the wool is placed in the chamber the RH cycles through about 22% RH. The RH cycle has been reduced to about a third of its normal range, which means that two thirds of the injected water vapour has been absorbed by the wool, which occupies 5% of the volume of the chamber. The traces for the RH measured at several depths within the wool shows that the water has diffused right through it.

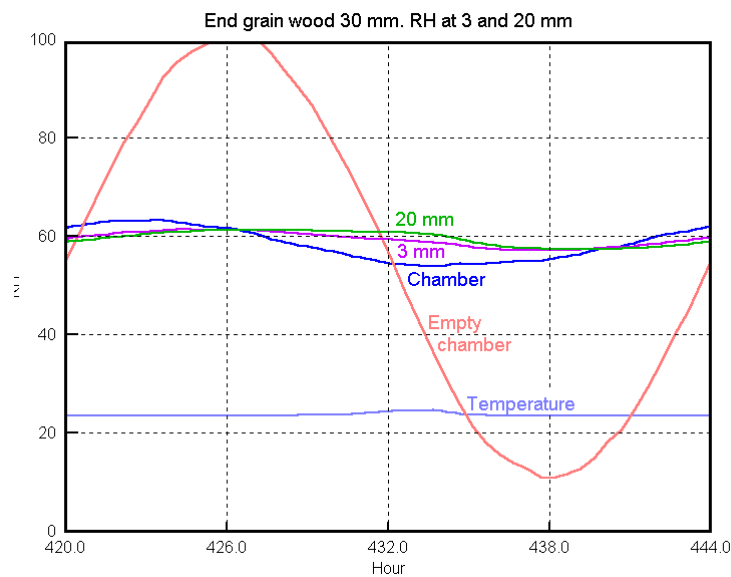


Figure 5 A one day cycle for wood cut across the cell direction. It buffers much better than wool, in spite of the only 30 mm depth of the wooden blocks, compared with 70 mm of the wool in figure 4.

Figure 5 shows, for comparison, the performance of end grain wood under similar experimental conditions. The RH swing is now only 10%, so only about 15% of the water released into the chamber air remains in the air. Furthermore, the shallow curves for the RH deeper within the wood show that the moisture has not completely reached equilibrium at the back of the 30 mm wooden slab during this 24 hour cycle. (The irregular course of the RH within the wood is an experimental error caused by the unsteady temperature during this experiment.)

Wood is the best humidity buffer of the common building materials, but only when used in this unusual orientation. It does, however, illustrate an important point: a relatively thin layer of a good buffer on the wall surface will outperform wool insulation, even when the insulation is exposed to the room.

The next graph, figure 6, shows a two day cycle for wool. The maximum flux is the same, so the RH calculated for the empty chamber now goes to 100% early in the cycle and would, without the wool, cause condensation of 20g water per cubic metre of air. The wool still buffers the chamber RH reasonably well. An even greater vapour flux would be met with a stronger buffer performance, because the sorption isotherm of wool rises steeply with increasing RH, so a steadily greater proportion of the injected water will be absorbed into the wool. There are limits to the usefulness of this property, however, because above about 65% RH wool is vulnerable to biological attack.

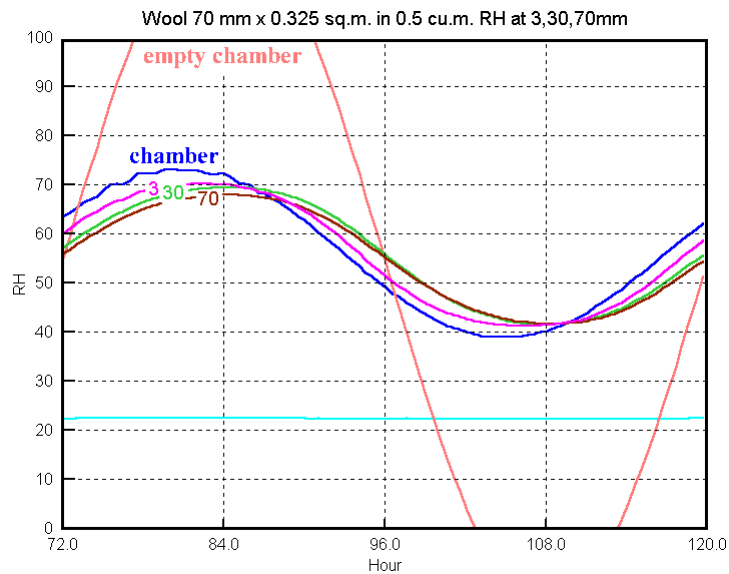


Figure 6 A two day cycle for wool exposed in the chamber. The entire thickness of the wool is reacting, which compensates to some extent for the low density of the insulation. The maximum flux is the same as in the one day cycle, so the amount of water released into the chamber is twice as much.

A four day cycle for wool insulation shows an greater RH 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 massive materials such as wood or clay.

### Wool insulation encapsulated

A typical wall construction would be gypsum board as the interior finish, then a vapour retarding paper and wool insulation with some permeable outer sheathing to allow ventilation of moisture to the outside. In this experiment, however, the wool is sealed on the outside surface.

These materials are examined one by one in reference 3. The following graphs, taken from that publication, show the effect of the addition of a vapour retarding paper and then gypsum board over the wool.

When a vapour retarding paper is placed in front of the wool the performance is drastically reduced. The RH swing is 34% in the chamber, so the water is distributed almost evenly between the chamber air and the experimental wall. The identical RH curves for the middle and the back of the wool indicate that diffusion through the 160 mm of wool is evenly distributing the vapour that gets through the vapour retarder. The line marked 2 (mm), which is just behind the vapour barrier has a markedly greater RH swing. This is difficult to interpret. The RH sensor inhibits free air movement: it is a plastic rectangle, about 5 x 10 x 1 mm thick, with the active surface facing the vapour barrier. It should have been placed edge on to the vapour barrier. The vapour retarder alone, without wool, has a significant buffer effect, giving a 42% RH amplitude in the chamber.

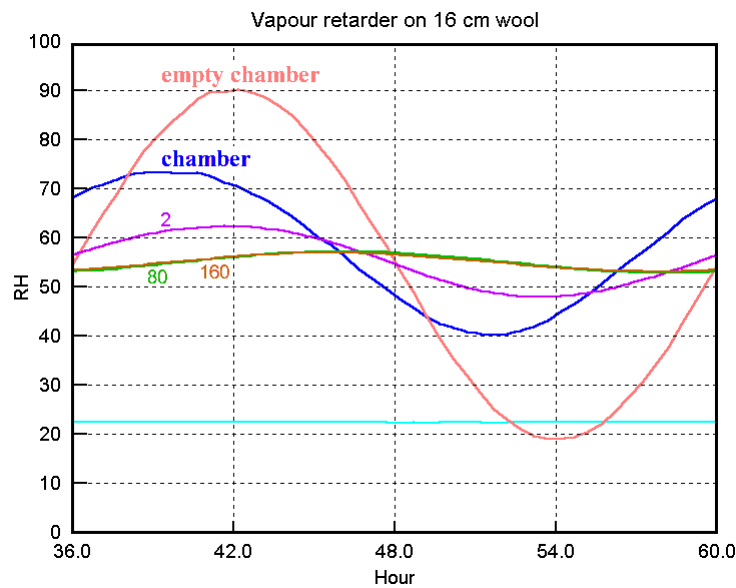


Figure 7. When a vapour retarding paper is put in front of the wool the buffer performance is greatly reduced. In this figure the wool thickness has been approximately doubled to 160 mm. The RH is shown at 2 mm, just behind the vapour retarding paper, and at 80 and 160 mm from the surface. The back is impermeable.

The wool reacts with a delay, but uniformly throughout its depth, indicating that the rate determining step is the passage of vapour through the retarding paper. The RH variation within the wool has dropped from about 20% in figure 4 to about 5%, in spite of the greater amplitude of the RH variation in the chamber in figure 7.

The next graph in the series shows the performance of a wall of unpainted plasterboard, then vapour retarding paper and 160 mm of wool insulation over an impermeable back.

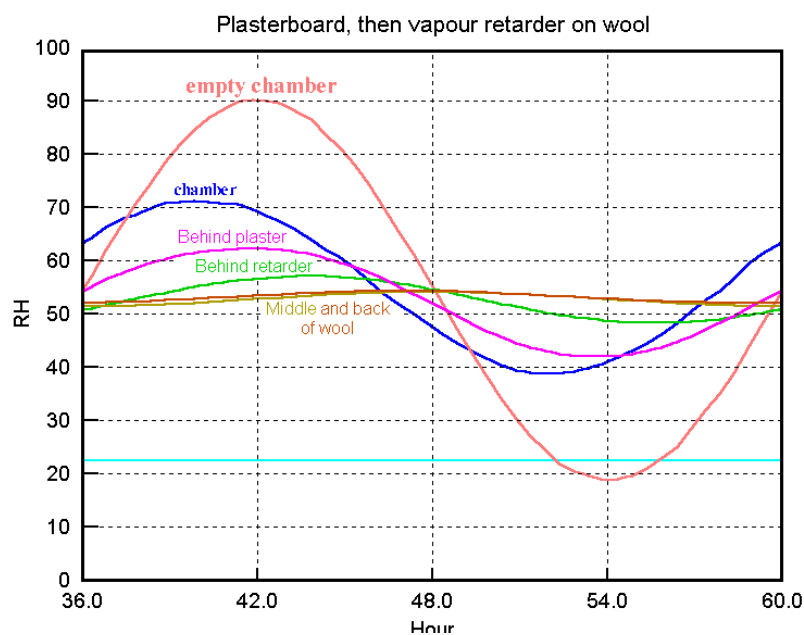


Figure 8 Buffer performance of a wall of plasterboard, vapour retarding paper and wool insulation. The performance is very similar to that of vapour retarding paper over wool. This is because the plaster board has a buffer performance of its own, mainly provided by the two layers of paper enclosing the almost unabsorbent gypsum.

The permeability is so reduced that the wool hardly reacts at all. The RH variation within it has been reduced to 2%, indicating a very small exchange of water vapour with the chamber. The moderate buffering performance is mostly due to the plaster board alone, as comparison with the next figure shows.

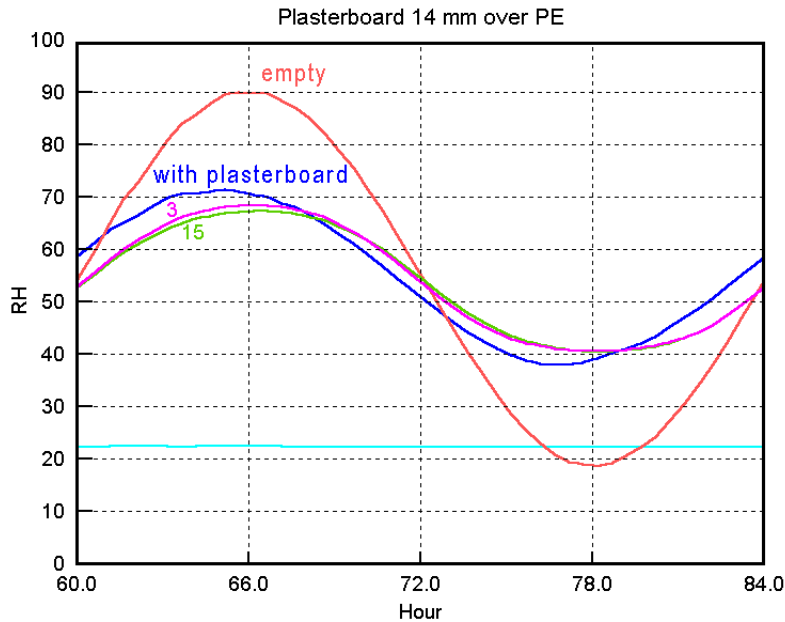


Figure 9. The buffer effect of plasterboard alone. The RH variation is scarcely different from that of the composite wall with wool insulation behind a vapour retarder.

A layer of paint on the wall would further reduce the influence of the wool. One must infer from this series of experiments that the best way to buffer with wool is to hang a tapestry in the room. The insulating value is much less but the moisture exchange is much greater.

### Discussion of experimental results and suggestions for further research

The graphical results give an impression of the buffering effect of the materials on the climate in a room. Table 1 shows the same data reduced to a single number for each graph. This number is the water vapour passing through one square metre of surface as a result of a 10% peak to peak cyclic variation of RH over one day.

Table 1. Grams of water vapour passing, one way, through one square metre of surface as a result of a 10% peak to peak cyclic variation of RH over one day.

Wool, 70 mm thick	10.3
End grain wood 30 mm thick	21.8
Wool, 160 mm behind vapour retarder	5.5
Plaster board, 13mm (nominal), vapour retarder, 160 mm wool	5.8
Plaster board alone	5.5

These results show that wool insulation, even without any screening from the room, is not as good a humidity buffer as 30 mm of end grain wood panelling - an unusual surface finish, but effective.

Wool concealed behind plaster board and vapour retarder has scarcely any effect at this cycle time: it is little better than the plaster board alone (compare the last two lines in the table).

One must conclude that wool insulation contributes very little buffering to the indoor climate when it is used in the conventional house wall, screened from the interior by painted plasterboard and vapour retarder. The only way to include the insulation as a significant influence on the interior climate is to use a porous paint on the plaster board and to move the vapour retarder towards the middle of the insulation. This idea is controversial, because there is a risk of condensation within the wall in cold weather. The constant temperature experiments reported here can shed no light on this matter.

The performance of absorbent insulation in a wall exposed to both a vapour pressure gradient and a temperature gradient is not well understood. Some experiments by Siau and coworkers (4), and by Krus (5) suggest that the conventional models used as the basis for calculating the probability of condensation are not quite right.

There are good theoretical reasons to believe that the main benefit from absorbent insulation is buffering of the climate *within the wall structure*. These ideas are now being tested by two experiments under way in the Institute of Building and Energy at the Technical University of Denmark. These experiments are expected to give a reliable prediction of the usefulness of absorbent insulation in moderating the climate within walls, and particularly within roofs. Our hope is that absorbent insulation will prevent condensation on a daily cycle, as long as air flow is limited. In sunny weather the cooler side of the insulation will see a high RH and will absorb water accordingly. On a cold night the cold upper layer of insulation will intercept moisture from below. Even the low density wool fibre mat may have enough capacity to deal with the moisture bouncing back and forth in the roof space as hot days follow cold nights.

Further experiments could reveal the performance of semi-insulating, highly porous, water absorbent materials within a wall, such as cellular concrete or cement wood composites. These materials theoretically make the risk of condensation worse. When they become hot they will release large amounts of water vapour which can overwhelm the capacity of the absorbent insulation. In such cases it should be an advantage to have absorbent materials on the inner side of the insulation. One would expect the ideal construction to consist of an outer skin with weak absorption, so that the large temperature reversals will not mobilise too much water vapour, with an inner skin that is highly absorbent and almost at constant temperature, to absorb the water vapour that inevitably circulates under the shifting temperature gradient. Another subject for experiments would be the alternative strategy of combining the insulating and the structural components of a wall in massive semi-insulating materials such as cellular concrete or light clay mixtures.

## **Conclusions**

The experimental results show that wool insulation concealed behind a vapour retarding paper and gypsum board has no significant influence on the room climate, if the house is ventilated at the recommended half an air change per hour. Absorbent insulation has, even when directly exposed to the interior, a limited buffer capacity because of its low density. An equivalent stabilising influence can be obtained with a much thinner layer of materials such as end-grain wood, or clay plaster. On the other hand there is reason to believe that absorbent insulation provides a margin of safety over mineral fibres, particularly in roof construction, because it buffers the migration of water vapour caused by the large temperature gradient induced by solar radiation. Further investigation should therefore be directed towards understanding, and quantifying, the role of absorbent insulation in protecting the building structure from condensation damage, leaving the control of the indoor climate to materials with a higher density.

## References and notes

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4. Siau, J.F. and Babiak, M., 'Experiments on nonisothermal moisture movement in wood.' *Wood and Fibre Science* 1983 v.15 pp40-46.
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5. Martin Krus, 'Moisture Transport and Storage Coefficients of Porous Mineral Building Materials', Fraunhofer Verlag, Stuttgart 1996, ISBN 3-8167-4535-0.

Other contributions to the discussion on the real driving force for moisture movement in absorbent materials are summarised in an appendix to: Kumaran, M. Kumar, 'Material Properties' International Energy Agency, 1996. ISBN 90-75741-01-4.

### Material properties:

Details of the measurement of the material properties are given in reference 3. The essential values are given in the table below. The sorption curve is simplified to a constant, which is adequate for the moderate RH variation in the graphs shown in this article.

Material	Water capacity	Diffusion coefficient	Density kg/m <sup>3</sup>
Wool insulation	152	140	19
Wood, longitudinal	98	88	384
Gypsum board 13 mm	5	25	685
Vapour retarding paper	120	0.03	400

Water capacity is in  $\text{kg}/(\text{kg} \cdot 100\%RH) \times 10^3$  measured at 45 - 60% RH

Water vapour diffusion coefficient is in  $\text{kg}/(\text{Pa} \cdot \text{m} \cdot \text{s}) \times 10^{12}$  measured at 50% - 76% RH

The vapour retarding paper is ØKO Dampbremse B2 (Miljø Isolering).

The wood is *Picea abies*, Norway Spruce

The wool insulation is from Scandan. The fibres are felted together but have a definite orientation parallel to the exposed surface.

## Appendices

### 1. The practical limits to passive buffering of the indoor climate

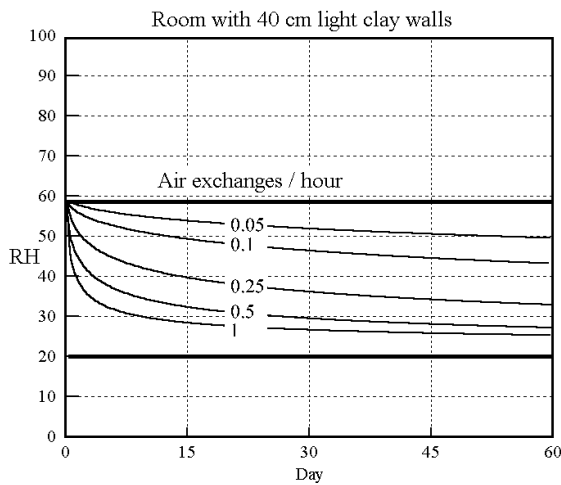


Figure 10. The effect of air exchange rate on moisture buffering. The curves show the rate of descent of the room RH from 58% towards the 20% RH of air leaking in. The room has thick clay walls of surface area  $1 \text{ m}^2$  per  $\text{m}^3$  of room air. The temperature is  $20^\circ\text{C}$ .

The existing mathematical treatment of moisture movement is used here to predict the practical limits to the use of buffer materials.

The calculation of the movement of moisture through porous, absorbent materials is treated very much like the movement of heat through materials (as long as the RH is moderate). The analogy is, however, not really very close. One important difference is that the amount of water vapour in air at a given relative humidity is strongly dependent on temperature, while the moisture content of materials is mainly dependent on the prevailing RH, regardless of temperature. This means that the buffer capacity of materials falls very rapidly with increasing temperature, because more water must be exchanged to change the RH by one unit. This effect hardly exists in heat exchange, where the heat capacity of both air and material is nearly independent of temperature. The calculations shown in this section are for systems at  $20^\circ\text{C}$ .

### The influence of air exchange rate on the buffering of the indoor climate

Notice, in figure 10, the enormous influence of air exchange rate on the buffer performance of an absorbent wall. At one air change per hour, the RH has already fallen half way to the final 30% after barely a day. A house with only about one change of air per day, however, holds a high RH for several months.

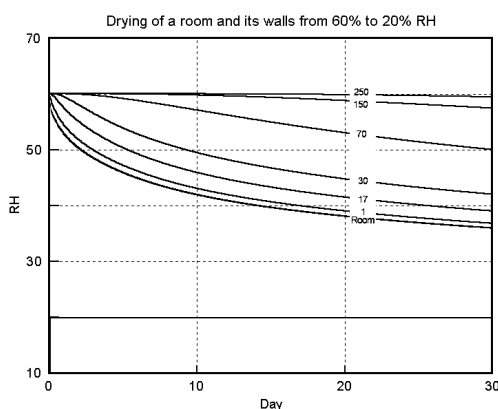


Figure 11. The calculated RH within a wall as it releases water vapour to the room. The final RH is 20%.

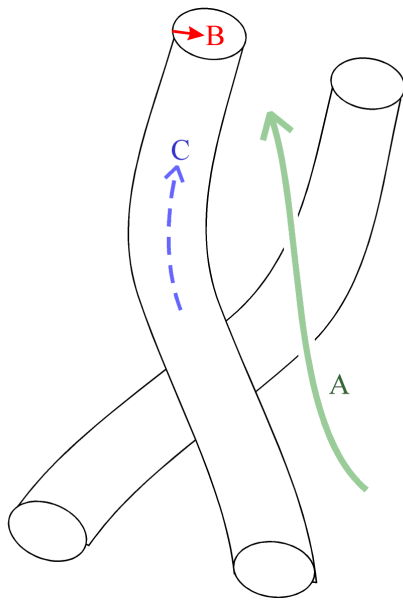
The influence of the thickness of the wall is shown in figure 11. The wall in this example is 300 mm thick and the room has half an air change per hour. The half time to equilibrium of the room air is about 13 days. At this time the back of the wall has hardly reacted to the loss of water from the surface. Only the first 30 mm of the wall is contributing usefully to moderating the loss of water from the room. (The difference between the half time to equilibrium in this graph and in figure 10 is that the wall is made of a different material.)

These two graphs show that the usefulness of absorbent walls depends very much on the room ventilation rate and to a lesser extent on the wall thickness. The useful thickness of a material to buffer the indoor climate depends on its permeability but is of the order of a few centimetres, up to 20 cm for porous insulating materials. Water from greater depth cannot escape quickly enough to compete with the loss of water through ventilation.



**Appendix 2. The limitations of the standard measurements in describing dynamic processes**

In the cup method for measuring water vapour permeability, the test specimen forms the lid of a container nearly filled with a saturated salt solution. This solution maintains a constant RH in the air above it, even when some water has evaporated. The assembly is placed in an environment of lower RH. The container is weighed at intervals. When the rate of loss of weight has become constant, the permeability of the material is calculated from the water partial vapour pressure difference across it, the weight loss of water per second, the thickness of the specimen and its area.



*Figure 12. Water vapour mainly diffuses through the air spaces, process A. Movement into the fibre, B, does not occur during the measuring period of the cup method for determining permeability. Water movement through the material itself, process C, is a minor contributor to the diffusion in a fibrous insulator, but becomes dominant in gels, such as cement and plastic wrapping material.*

The process of diffusion through a very porous material, such as fibrous insulation, is sketched in figure 12. The arrow marked **A** represents the diffusive movement of water vapour through the air channels. This is the dominant mechanism transferring water out of the container. Initially, there will also be absorption into the fibres, mechanism **B**. This only occurs in the very beginning of the experiment when the initially dry material (we suppose) comes to equilibrium with the RH gradient that establishes itself through the test specimen. All evidence for this process is discarded, because the permeability is based on the weight loss after a steady state has been reached.

Process **C** is the relatively trivial movement of water through the material itself: water molecules hopping from one loosely formed molecular alliance to another down the water concentration gradient within the fibre.

The observed weight loss and the calculated diffusion coefficient include only processes **A** and **C**. Furthermore, there is no way of separating the contributions of **A** and **C**. In the material sketched in figure 12 one can guess that **C** is trivial, but in a denser material, such as American Style high pressure paper fibre insulation, wood shavings or cellular cement, **C** could be quite a significant contribution to the total water flux.

A consequence of the dominance of water transport by route **A** is that the nature of the material becomes immaterial! Glass wool will give the same water vapour permeability as sheep's wool, as long as the fibre mats have a similar physical structure. One is really measuring the permeability to any gas, not particularly water.

Does the exclusion of mechanism **B** matter, and does the lack of knowledge of the partitioning between **A** and **C** matter?

It probably damages our understanding of the reaction of absorbent insulation to the daily atmospheric cycle of RH change and to the dispersion of "crisis water" generated within a house. This

dramatic term refers to water released in large quantity for a short time: by showering and cooking and partying. There are also non-human sources of "crisis water", such as the melting of condensed ice under roof surfaces in the morning sun.

Why should we doubt the adequacy of the two classical moisture parameters used in all models of heat and moisture transfer: the sorption curve and the diffusion constant?

The first, and most easily explained, problem is that diffusion into, and through the material increases greatly with temperature. This is because water hopping between weak molecular bonds requires activation energy, which becomes available at a rate that increases exponentially with temperature. Diffusion through the air, however, increases roughly proportionally with the absolute temperature. The relative magnitudes of diffusion through the air spaces and through the material will therefore change with temperature. There are

also other reasons for dramatic changes in the balance between the two processes, such as polymers passing through their glass transition temperature.

The other reason to doubt the adequacy of the current theory is its neglect of the kinetics of the diffusion of water into the fibre from the air in the pores (process **B**). The assumption is that it reaches equilibrium very fast compared to all the other processes going on. That is measurably true for water absorption into a sheet of paper or a thin silk fabric, but it is certainly not true for more complex structures which contain clots of quite dense material as islands in a more porous structure. Close up pictures of paper insulation shows a considerable inhomogeneity. One can make an analogy with Amsterdam and Venice: the fine network of channels inhibits the movement of sewage into the more spacious adjacent lagoon, which enjoys a faster exchange with the great sea beyond. (One can continue with the analogy: In the case of Amsterdam the flow is deliberately improved by water flow supplementing diffusion. Even a small total pressure difference across the wall of a house is so potent a cause of water vapour transport that it completely dominates the process. We don't encourage use of this flushing mechanism because a lot of heat accompanies the water vapour.)

The evidence for slow absorption as a major unappreciated factor in the processes moving water through walls comes from Padfield's experiments, reported in (3). These experiments show an unexpectedly deep penetration into the material of a daily RH cycle. This can be explained by assuming slow absorption into the material, meaning that the effective sorption curve of the material is shallower than the official equilibrium curve: the water molecules can wander deeper without being grabbed by the material. Hysteresis is another factor contributing to a shallower sorption curve, but not enough to account for the discrepancy.

Padfield's experimental results have not been analysed with full mathematical rigour. It should be possible to tease out the magnitude of process **B** in figure 12 from the observed dynamic behaviour shown in Padfield's graphs. This could lead to an experimental method for separating the diffusion processes through very porous materials, which the cup method cannot do.

Other researchers have used a simpler experimental system, weighing cubes of wood, for example, exposed to a step change in RH (2). They have compensated for the relative lack of experimental detail with a more ambitious program of mathematical analysis. I suggest that a combination of these two approaches would be fruitful.

For the moment one must accept that the current standards for measuring material properties do not provide enough information to predict reliably the response of absorbent building materials to the daily moisture cycle which dominates the microclimate of houses.

### **Appendix 3: Calculation of the buffer capacity**

The flux generator blows 9.6 g of water vapour into the chamber during the upward going half cycle. This causes the RH to rise by an amount that depends on the ability of the test specimen to absorb water vapour. Let us suppose that the RH rises 15%, from 45% to 60%. The air volume of the chamber is about 0.5 m<sup>3</sup>, depending a little on the volume of the test specimen. A rise of 15% RH corresponds, at 23°C, to 1.5 g more water vapour in the air. The remaining 8.1 g has been absorbed by the test material.

In practice it is the absorption per unit area that is the interesting quantity. The specimen area in most of the experiments reported here is 0.325 m<sup>2</sup>. The water absorbed by the material is therefore  $8.1/0.325 = 25$  g. To allow easy comparison between materials this value is reduced to the absorption with a 10% rise in RH:  $25/1.5 = 16.6$  g.

Notice that this number is not a characteristic of the material but of the construction. It also depends on the RH, because all materials have a steeply rising absorption at high RH, so the buffer capacity between 80% and 90% may well be ten times greater than the number obtained at moderate RH.