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Measurement of water vapour transport through a porous non-hygroscopic material in a temperature gradient

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SUMMARY:

This was an experiment to identify the driving potential for water vapour diffusion through porous materials in a temperature gradient. The specimen of mineral fibre insulation was placed between a space with controlled temperature and relative humidity and a space with a controlled, higher temperature, and a measured but not controlled relative humidity (RH). This assembly was allowed to reach equilibrium with no vapour movement between the spaces, as tested by a constant RH on each side and by zero flux of water vapour measured in the cold side chamber. The RH and temperature values were converted to partial vapour pressure and to vapour concentration in g/m^3 . The concentrations proved to be more equal on either side of the specimen than the partial vapour pressures. This supports an argument that it is concentration difference that drives diffusion of gases. Isothermal diffusion cannot be tested experimentally in this way, but it is reasonable to assume that concentration is the driving potential. The close equality of the concentrations makes it unnecessary to invoke temperature difference as a third possible potential for driving diffusion.

1. Introduction

The experimental work reported in this paper is an attempt to determine whether partial water vapour pressure or concentration of water vapour molecules in kg/m^3 is the driving force for diffusion through a porous material in a temperature gradient.

There has for some years been a discussion about what is the most significant driving potential for moisture transport through porous materials at moderate relative humidity. The story begins with (Fick, 1855). He stated that the driving force for diffusion is concentration difference. However, he studied primarily diffusion in the liquid phase. In the building physics literature and in several numerical models for heat and vapour transport it is assumed that vapour pressure (usually the partial vapour pressure in a mixture of air and water vapour) is the driving potential. In a system at uniform temperature the vapour pressure is proportional to the concentration. However, if there is a temperature gradient the vapour pressure at the higher temperature is higher, for the same vapour concentration in kg/m^3 . Around room temperature, the divergence between the two measures is about one part in 300 per degree temperature difference.

This divergence is difficult to measure because there is a practical limit to the temperature difference that can be imposed. At the cool side of the porous material the relative humidity (RH) should be held below around 75%, to avoid capillary liquid flow confusing the process. At the warm side there is no

particular limitation to the RH but it is difficult accurately to obtain a reliable concentration or vapour pressure value from measurement of RH below about 20%.

A number of articles have been published on the effect of temperature on moisture transport through a material. Janssen (2011) has recently published a review which compares eight of the most relevant articles. Five of these articles (Kumaran, 1987), (Dahl, et al., 1996), (Galbraith, et al., 1998), (Stephenson, 2003) and (Peuhkuri, et al., 2008) claim that the temperature has or may have an effect on the moisture transport, while four other papers (Galbraith, et al., 1998), (Thomas, 1999), (Glass, 2007) and (Baker, et al., 2009) state that there is no significant effect of temperature on the moisture transport.

The conclusion of Janssen's review was that the papers stating an occurrence of thermal diffusion are flawed, and therefore there is no support for the claim that temperature has an effect on moisture transport.

The purpose of this paper is to test – with a focus on the best possible accuracy of the experimental set-up and method – if either the partial water vapour pressure, or the water vapour content adequately explains the observed diffusion in a temperature gradient, without invoking temperature as a necessary participant in driving the process.

2. Experimental

The principle of the experiment is that a porous specimen is mounted over a cool space with a controlled relative humidity. Above the specimen is a warmed space which is sealed against air flow to the ambient. The RH in this space is measured when the experiment has reached a steady state, when one assumes that there is no net diffusion in either direction. By having the cold climate under the specimen the natural convection within the specimen due to thermal buoyancy is minimised. The specimen is sealed within a cylinder of insulating but impermeable material to ensure a uniform thermal gradient within the specimen. The temperatures and RH measurements are recalculated to partial vapour pressures in pascal and to vapour concentrations in kilograms per cubic metre. The parameter which is closest to being identical above and below the specimen is assumed to be the driving potential. If neither parameter seems to be sufficiently similar above and below the specimen, one must accept the possibility of an entirely different transport mechanism being active. The principle of deciding the driving potential by obtaining the same value on both side of the specimen is also described by (Thomas, 1999).

Because of the small difference between these two parameters, the experimental description concentrates on the effort to obtain very accurate RH values.

2.1 The Apparatus

The apparatus is sketched in Figure 1. The specimen is supported over a cylindrical chamber of 791 mm diameter which contains a RH generator. This is basically a water reservoir whose temperature is controlled by a Peltier element. The reservoir is weighed to determine the vapour flux. The chamber air temperature is controlled by an electric heater and a water cooling coil in the annular space around the chamber. The two temperatures, of the water and of the chamber, define the RH but the control system actually uses the signal from a dew point sensor within the chamber and a platinum resistance temperature sensor. The RH on the cool side of the specimen is independently measured by three polymer sensors, which are described in a later section. Above the specimen is a shallow sealed chamber which is heated electrically. This upper chamber also has three RH sensors. The RH sensors incorporate platinum resistance temperature sensors.

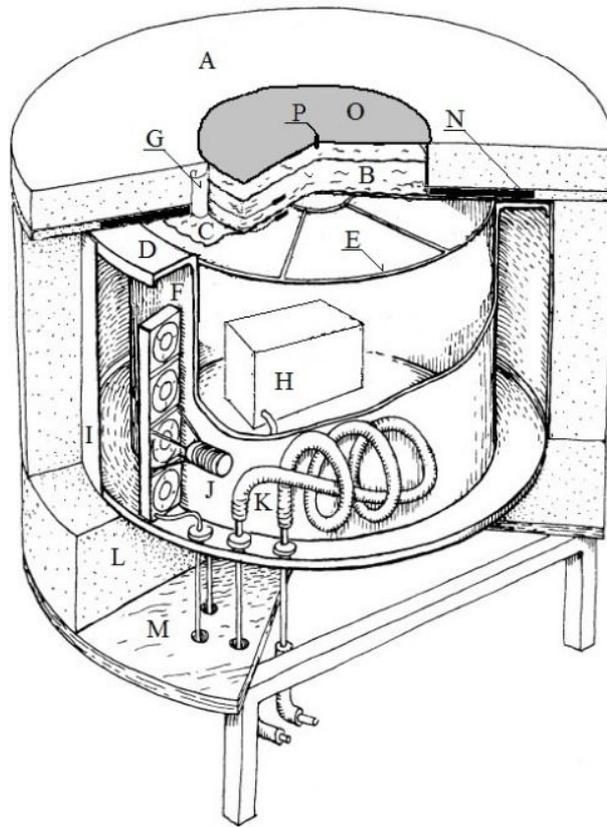


FIG 1. Sketch of the climate chamber. A insulation, B specimen, C Tyvek, D flange over annular space, E open grid, F fans, G polycarbonate foil, H moisture control unit, I stainless steel wall, J heating (electric resistance), K cooling (water circulating in coil), L bottom insulation, M table, N aluminium plate, O Stainless steel plate above sealed airspace, P sensor. [after (Peuhkuri, et al., 2008)].

There is a circular hole 500 mm in diameter in the middle of the aluminium plate, where the specimen is placed, see Figure 2. The specimen is Rockwool, a non-hygroscopic mineral fibre insulation material, with a bulk density of 200 kg/m³, and a dry thermal conductivity of 0.033 W/(m·K). The underside of the specimen is faced with Tyvek (TM) permeable fabric, to reduce disturbance by the fans which stir the air in the cold space below. The side of the cylindrical specimen is enclosed first by impermeable polycarbonate foil then by foam insulation of equal thickness to the specimen. Above the specimen there is a sealed air space which is heated from above. This space has three RH and temperature sensors.

Each experiment is allowed to run until equilibrium is attained. This is marked by constancy of RH both above and below the specimen. A further check is provided by the weight of water in the reservoir, whose constancy ensured that there was no significant leakage anywhere in the assembly.

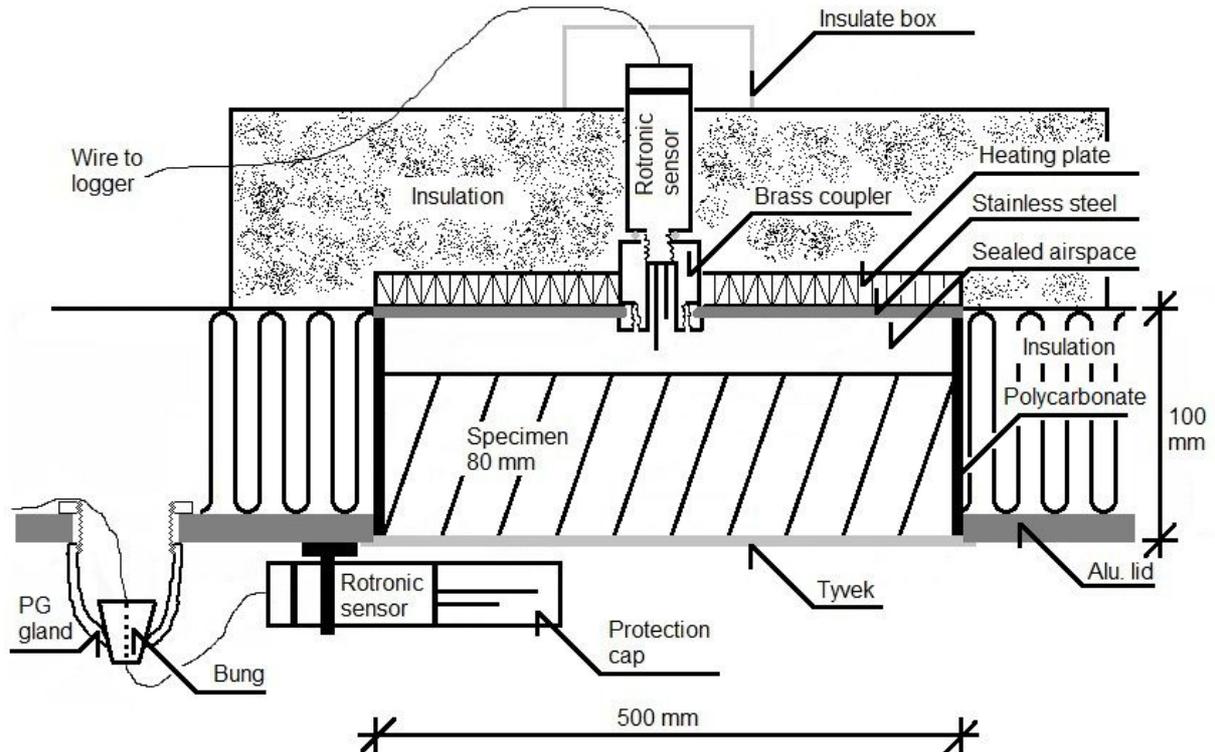


FIG 2. The arrangement of the specimen between the two controlled spaces. A heating plate on top of the sealed airspace creates a temperature of 32°C. Only two of the six temperature and RH sensors are shown.

2.2 Sensor calibration

The temperature and RH sensors were Rotronic HygroClip-S. Three sensors were installed on each side of the specimen. The sensors were calibrated using saturated salt solutions, according to (Greenspan, 1977), and with the manufacturer's ampoules, which are unsaturated salt solutions used just once. The calibration was done by inserting the sensor in a small airtight container containing the saturated salt solution or the ampoule. The calibration temperatures were the same as in the experiment and the same signal processing train was used. Five hours were allowed for equilibration. Calibration was repeated before and after each experimental run. The accuracy of this arrangement was assessed by aggregating the differences between the pairs of calibrations and deriving the standard deviation. For the sensors on the warm side the standard deviation of the RH was 0.9%, and for the cold side it was 0.8%.

The sets of three temperature sensors were tested for accuracy at their operating temperatures against a calibrated mercury thermometer.

These uncertainties convert to an uncertainty in the partial vapour pressure of 44, 24 and 11 Pa for the 32, 22 and 12°C temperatures respectively. The concentration values were derived from the partial vapour pressures, so have proportional uncertainty.

The measurement accuracy was sufficient to ensure that all the measured differences between partial vapour pressures made with a 20K temperature span were significant at the 2σ level, while the experiments with the 10K temperature difference showed significant partial vapour pressure differences at the one standard deviation level.

2.3 Temperature and RH stability

The RH and temperature are shown in Figure 3 for a typical period. The data for relatively stable periods were selected for use. Measurements at one minute intervals were averaged over a 10 hour period.

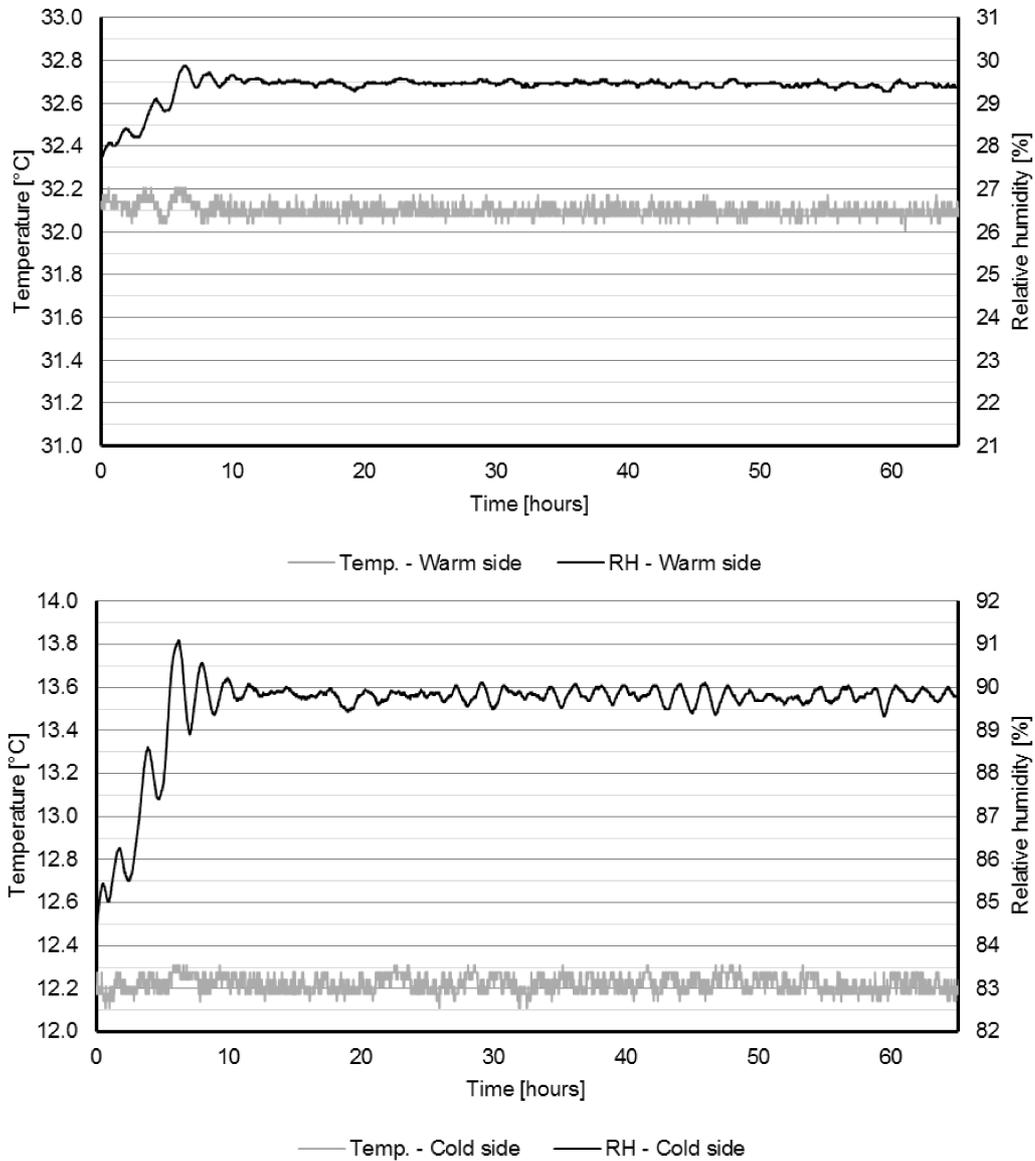


FIG 3. Examples of the measured data above and below the specimen. There was intermittent interference so quiet periods were selected for data processing.

2.4 Calculations

The following equation was used for calculating the saturation partial water vapour pressure and was taken from (Danvak, 1988).

$$p_{v,sat} = \exp\left(23.5771 - \frac{4042.9}{T - 37.58}\right)$$

(1)

Where $p_{v,sat}$ saturation partial water vapour pressure (Pa)
 T temperature (K)

The concentration in kg/m^3 was derived from the partial vapour pressure using the gas law.

3. Results

3.1 The sequence of experiments

Several combinations of temperature difference and cold side RH were used. The results are summarised in Table 1.

TABLE 1. The experimental results for the seven independent experiments. The per mil differences are calculated from the hot side value minus the cold, divided by the cold side value. Note that runs 5 and 6 are duplicates, but give very different results.

Run	Warm side				Cold side				Difference	
	T °C	RH %	Pressure Pa	Conc. g/m ³	T °C	RH %	Pressure Pa	Conc. g/m ³	Pressure ‰	Conc. ‰
1	31.3	20.2	922	6.56	12.3	60.8	873	6.63	54.2	-9.9
2	32.1	27.7	1325	9.40	12.2	83.8	1191	9.04	106.9	39.6
3	32.1	29.4	1408	9.99	12.2	89.8	1279	9.71	96.0	28.8
4	21.5	36.1	928	6.82	12.3	61.3	876	6.65	58.1	26.1
5	21.6	45.8	1183	8.69	11.9	84.5	1178	8.95	4.3	-29.2
6	21.2	48.5	1225	9.01	12.1	84.0	1189	9.02	30.3	-1.1
7	21.3	51.9	1312	9.65	12.2	90.0	1278	9.70	26.2	-5.2

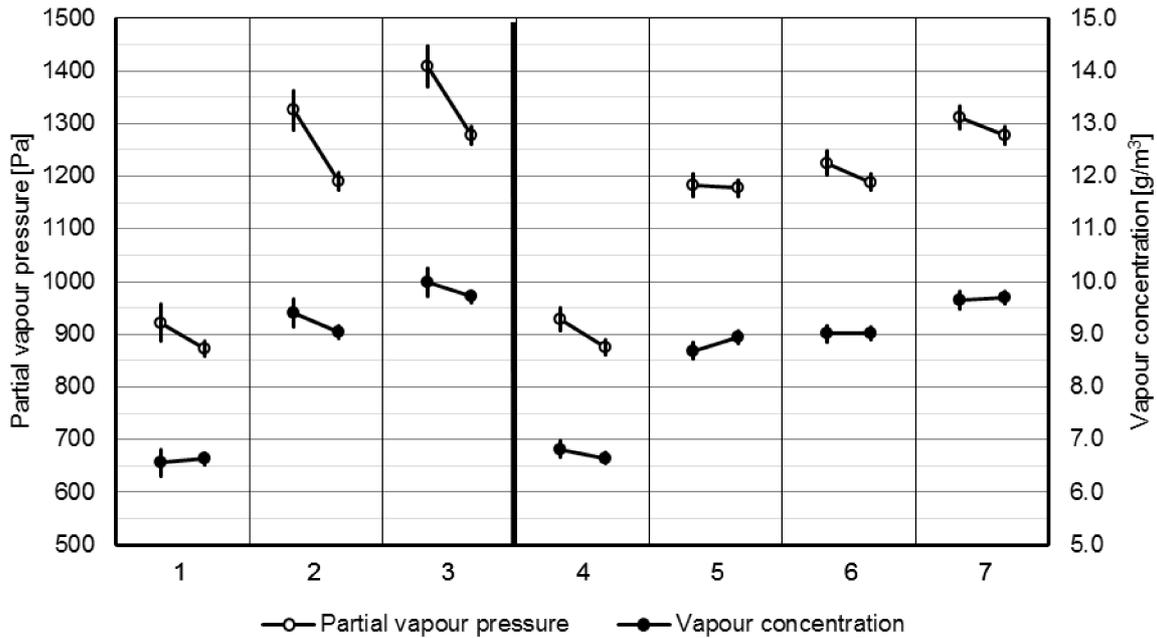


FIG 4. The absolute values of vapour pressures and water vapour concentrations for each experimental run, with σ error bars. The values for hot and cold sides are linked. The flatter links for the pairs of concentration values indicate that this is the potential driving diffusion. The warm side is shown to the left in the illustration of each experimental run.

4. Discussion

All but run 5 show a greater proportional difference in partial vapour pressure across the specimen, and with the higher pressure on the warm side, which would be expected if the concentration were the same on both sides. If one discounts run 5, which was actually the first of the series of experiments, later duplicated as run 6, there is a consistent pattern of vapour pressure excess on the warm side.

The concentration results are more puzzling. Run 1, with relatively low cold side RH and high temperature difference should give the purest result, with little interference from capillary condensation within the porous specimen. It is quite convincing in showing that the concentration above and below is almost equal, while the vapour pressure is higher above, as must then be the case. Runs 2 and 3, with high cold side RH, show the concentration higher at the warm side, and the vapour pressure correspondingly even higher. This sequence of three runs suggests the possibility that at high RH there is condensation at the cold side with liquid flow towards the high temperature side enhancing the concentration above the specimen. However, the experimental runs with the lower temperature difference show an entirely different pattern, with reduced warm side concentration associated with high RH on the cold side.

5. Conclusion

We present strong evidence for concentration rather than vapour pressure being the driving force for vapour diffusion through a porous material. After reaching a steady state with no vapour flow through the specimen, all but one of the seven experiments showed a smaller relative difference in concentration than in vapour pressure across the specimen.

Every experiment showed the vapour pressure higher on the warm side. The concentration differences were more evenly balanced, with three runs showing a higher concentration on the warm side, three runs showing a slightly lower concentration on the warm side and one anomalous run showing considerably

lower concentration on the warm side. The experiments performed with the higher temperature gradient, from 12°C to 32°C, and a high cold side RH at 83% showed both vapour pressure and concentration higher on the warm side, hinting at some residual flow process pumping water molecules towards the warm side.

The measurements were at the limit of precision attainable by RH sensors. The temperature difference across the specimen cannot be increased over about 20K without the cold side RH becoming so high that liquid water begins to play a role in the process, or the warm side RH becomes too low to measure with high precision. Absolute certainty is just beyond our grasp but it seems that the unquestioning acceptance of vapour pressure as the driving force for vapour diffusion is not justified. It must also be said that there is no practical significance to this uncertainty because the choice of driving force has scarcely any effect on calculations of the performance of buildings.

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