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MOISTURE CONVECTION AROUND A CRACK BY PRESSURIZATION

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Abstract. A laboratory test and computer simulation to determine the effect of moisture convection caused by inside overpressure around a leakage in a wooden floor construction was carried out. The purpose of the study was to test the accuracy of modelling the moisture convection with a one-dimensional model. It was assumed that the leakage airflow through a crack with known dimensions and glass fibre insulation is distributed over a certain area of permeable external wood fibreboard. This effective area was determined at the end of the laboratory test by measuring the area of visibly wet surface where condensation took place. By using effective area and airflow through the crack, the simulation was made with a modular simulation environment and a heat and moisture transfer model. The results show that moisture convection was possible to be modelled in one dimension with sufficient accuracy. The limit value of inside overpressure for the tested construction is given as well.

Key words: exfiltration, moisture convection, pressurization, one-dimensional modelling.

1. INTRODUCTION

It is well known that an overpressure inside the building causes exfiltration airflow and possible condensation inside the construction. The moisture convection causes condensation especially in cold climate areas where moisture content of the indoor air is much higher than that of the outdoor. Due to this, overpressure inside the building is usually avoided. However, sometimes pressurization may be profitable. Even slight 1–2 Pa overpressure is very effective to decrease radon concentration in low-rise buildings built in radon areas [1]. In the same way, pressurization may be used for improving indoor air quality – when the building is pressurized with clean supply air, the infiltration of outdoor pollutants (from traffic, etc.) is avoided. In [2] a number of measurements of pressure conditions in typical Finnish detached houses were carried out. It was found that in the case of balanced ventilation, air supply terminals caused in average about 0.7 Pa overpressure in living rooms and bedrooms (in bathrooms and toilets slight underpressure caused by extract terminals was observed). There was no evidence that this small overpressure causes moisture problems. In cold climate the buoyancy will cause significant stack effect in winter. If the temperature difference is 40 °C, pressure gradient in the room is about 2 Pa/m. This leads in a two-storey house to a 5 Pa overpressure on the first floor at the ceiling height. In [3], 2 and 4 Pa are given as design overpressures during winter for one and two storey buildings, respectively. It is recommended to remove this pressure difference by ventilation, but measurements made in [2] have shown that balanced ventilation systems, used in practice, create slight underpressure only in rooms with extract terminals. At the same time, it is evident that a high overpressure, such as 10–20 Pa, might cause remarkable damages. Thus it is important to know the limit values for acceptable slight overpressure. These values depend on the air-tightness and type of the construction. In this paper, a wooden floor structure used in detached houses with crawl space is studied. A laboratory test was carried out and special attention was paid to how the moisture convection can be calculated with a one-dimensional model.

2. THE LABORATORY TEST

The tested construction was a wooden floor with chipboard on the warm side, glass fibre insulation, and wood fibreboard on the cold side (Fig. 1). The construction was in vertical position during the test. No vapour barrier was used and a crack of 200 mm length and 0.7 mm width was sawed into the chipboard. The dimensions of the tested construction were 1.2×1.2 m, but moisture convection took place through much smaller area around the crack. Since wood fibreboard has higher moisture permeability than glass fibre insulation, the condensation took place on the internal surface of the wood fibreboard. To follow moisture content in different parts of the wood fibreboard, the specimens shown and numbered in Fig. 1 were used. The specimens were made by cutting the wood fibreboard and located on both sides of a joist; specimen No. 2 was behind the crack. It was possible to take these specimens away for weighing and to put them tightly back as wood fibreboard swelled during the test. Wood specimens were placed in the glass fibre insulation. Detailed description of the laboratory arrangement is given in [4].

In the beginning of the pressurization test all the materials were dry and the moisture content of the wood fibreboard was about 12 kg/m^3. On the warm surface, the temperature was 23 °C and relative humidity 47%, and on the cold surface 1 °C and 81%, respectively. These conditions were kept constant during the test. Moisture content of the wood fibreboard specimens was weighed once a day and is shown in Fig. 2. At $t = 0$ overpressure 20 Pa (in the room) was switched on. After that, the moisture content of the wood fibreboard increased quickly and the condensation on the surface of the fibreboard specimen No. 2 became visible. At $t = 252$ h, overpressure was reduced from 20 to 10 Pa. Now moisture content in the wood fibreboard decreased slowly, but on the surface no changes were observed whereas water droplets were still visible on the surface of the specimen No. 2. This demonstrates that wood fibreboard was not notably capillary-active, the droplets remained on the surface and the surface darkened only slightly. A photo of condensation is shown in Fig. 3. The test was finished at $t = 315$ h.

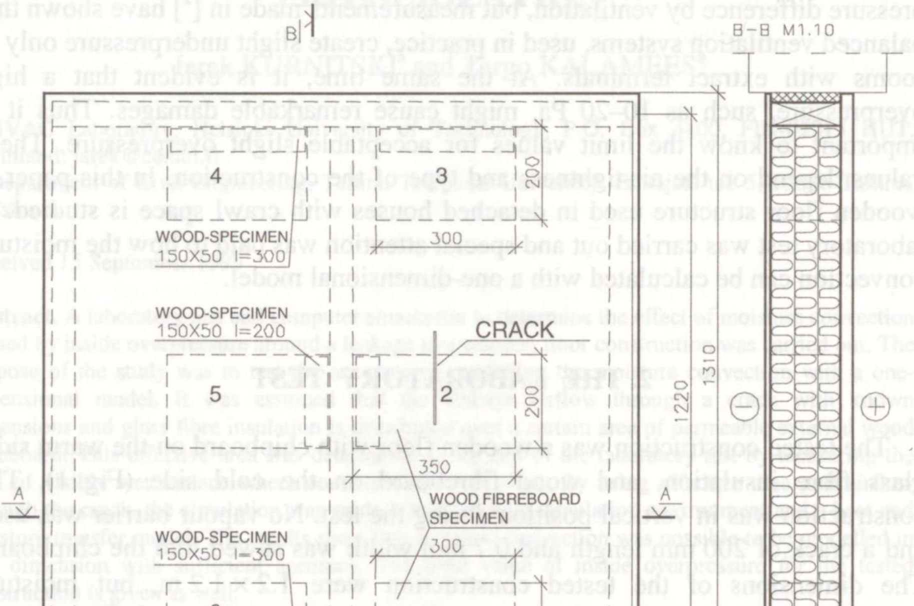

Fig. 1. Dimensions of the construction and location of the wood specimens and of the wood fibreboard specimens (numbered from 1 to 6).

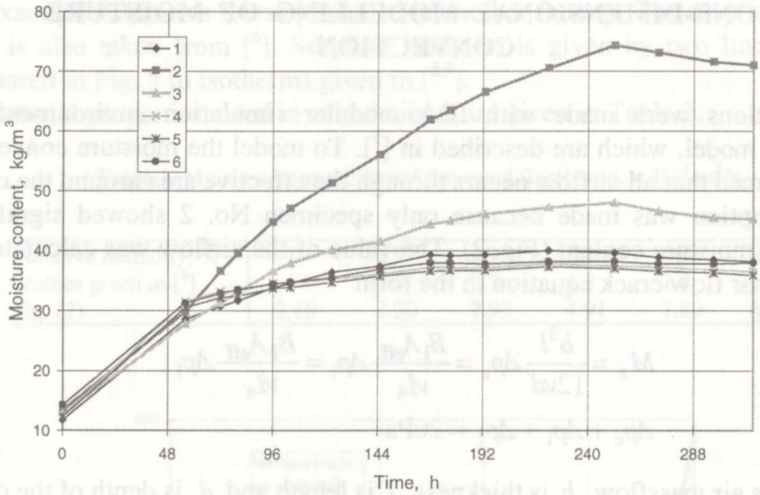

Fig. 2. Moisture content of wood fibreboard specimens during the test.

After the test, the wood fibreboard was removed and the area of the wet surface (Fig. 4), where condensation had taken place, was measured. This area was $0.40 \times 0.28 = 0.112$ m^2 and it is used in the next section as effective area A_{eff} for modelling.

Fig. 3. Photo of condensation on the internal surface of the wood fibreboard specimen No. 2 at $t = 276$ h.

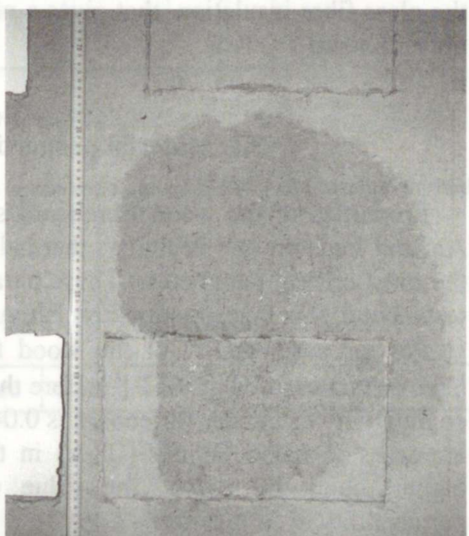

Fig. 4. Photo of the wet area of the wood fibreboard. Lower specimen inside the wet area is No. 2.

3. ONE-DIMENSIONAL MODELLING OF MOISTURE CONVECTION

Calculations were made with IDA modular simulation environment and HAMWall model, which are described in [5]. To model the moisture convection it was assumed that all airflow occurs through the effective area around the crack. This assumption was made because only specimen No. 2 showed significant increase in moisture content (Fig. 2). The value of the airflow was calculated by using laminar flow crack equation in the form

$$M_{\mathrm{a}} = \frac{b^3 l}{12 \nu d} \Delta p_{\mathrm{c}} = \frac{B_{\mathrm{i}} A_{\mathrm{eff}}}{\nu L_{\mathrm{i}}} \Delta p_{\mathrm{i}} = \frac{B_{\mathrm{f}} A_{\mathrm{eff}}}{\nu L_{\mathrm{f}}} \Delta p_{\mathrm{f}}, \qquad (1)$$

$$\Delta p_{\mathrm{c}} + \Delta p_{\mathrm{i}} + \Delta p_{\mathrm{f}} = 20\mathrm{Pa}.$$

Here M_{a} is air massflow, b is thickness, l is length and d is depth of the crack, B is air permeability, ν is the cinematic viscosity of air, and L is thickness of the material layer; index "f" is for fibreboard, "i" for insulation, and "c" for crack.

Since chipboard is an airtight material, all airflow caused by pressure difference took place through the crack. This was modelled by neglecting moisture capacity of the chipboard, i.e., it was considered that air flows directly through the crack to glass fibre insulation. In the model the sorption isotherm of the glass fibre insulation, that gives a negligible moisture capacity, was used for the chipboard.

3.1. Material properties used in calculations

Properties of the wood fibreboard strongly influence the calculated results. Air and moisture permeability, thermal conductivity, and sorption isotherm are the most critical parameters. These parameters can be determined by laboratory tests, but in this investigation Finnish material data was used.

For air permeability of the wood fibreboard the values $3.2\text{–}4.7 \times 10^{-12}$ m^2 have been measured at VTT [6]. Here the value 4.5×10^{-12} m^2 was used. Thermal conductivity of the dry fibreboard is 0.045 W/m/K and at 10% moisture content it increases to 0.055 W/m/K [7]. As in the test the moisture content was twice higher, about 60 kg/m^3, the value of 0.065 W/m/K was used. Moisture permeability δ is given as

$$\delta = 2.1 \times 10^{-6} + 6.65 \times 10^{-6} \varphi^3, \qquad (2)$$

where φ is relative humidity. This equation is compared in Table 1 to values measured by VTT and published in [8]. Hedenblad [9] gives for moisture permeability lower, constant value 4×10^{-6} m^2/s, but the measured fibreboard is not exactly the same as it was produced in another factory. The sorption isotherm used is also taken from [8]. Sorption isotherm is given by two line fit that is compared in Fig. 5 to isotherms given in [8,9].

Material properties, used in calculations, are given in Table 2.

Table 1. Moisture permeability of the wood fibreboard, $\times 10^{-6}$ m²/s

Relative humidity, %	0	25	50	75	95	100
Values given in [8]		2.2	2.7	4.9	7.8	
Eq. (2)	2.10	2.20	2.93	4.91	7.80	8.75

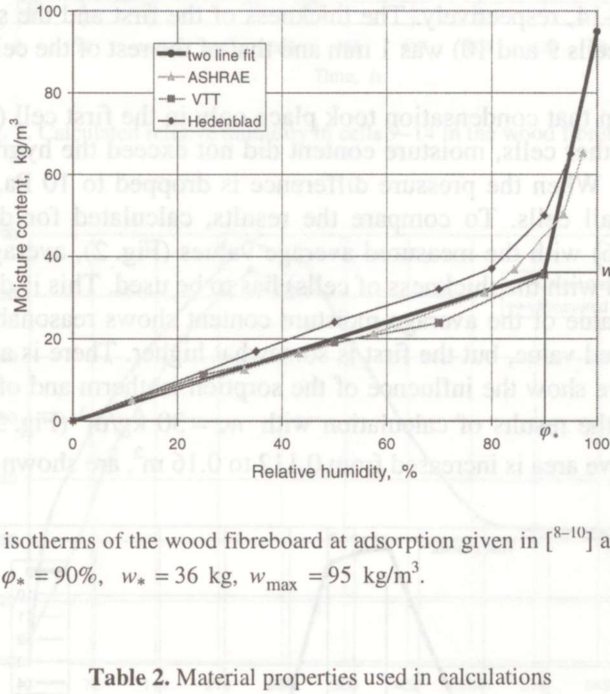

Fig. 5. Sorption isotherms of the wood fibreboard at adsorption given in [8–10] and two line fit used in calculations: $\varphi_* = 90\%$, $w_* = 36$ kg, $w_{\max} = 95$ kg/m³.

Table 2. Material properties used in calculations

Property	Chipboard	Glass fibre insulation	Wood fibreboard
Thickness, mm	25	150	12
Thermal conductivity, W/m/K	0.13	0.045	0.065
Density, kg/m³	600	17	285
Specific heat capacity, J/kg/K	1400	750	1350
Moisture permeability, m²/s	2×10^{-7}	18×10^{-6}	Eq. (2)
Sorption isotherm, given by two lines:			
φ_*, w_*		25%, 0.2 kg/m³	90%, 36 kg/m³
$w_{\max}$		0.35 kg/m³	95 kg/m³
Air permeability, m²		2×10^{-9}	4.5×10^{-12}

3.2. Results

When material properties given in Table 1 are used, one obtains for air mass flow 4.6×10^{-5} kg/s. Pressure drop in the crack is 3.03 Pa, in the glass fibre insulation 0.46 Pa, and in the wood fibreboard 16.5 Pa.

The moisture content and the relative humidity of the wood fibreboard, calculated with material properties given in Table 2, are shown in Figs. 6 and 7. Here at $t = 315$ h, when the test was finished, the pressure difference Δp is set to 0 and calculations are continued up to 720 h to show the drying of the construction. In calculations every material layer has been modelled by a certain number of calculation points or cells [5]. Here in the total 14 cells were used. Chipboard was modelled by 2 cells (cells 1 and 2), glass fibre insulation and wood fibreboard by cells 3–8 and 9–14, respectively. The thickness of the first and the second cell of the fibreboard (cells 9 and 10) was 1 mm and that of the rest of the cells 11–14 was 2.5 mm.

It can be seen that condensation took place only in the first cell (cell 9) of the fibreboard. In other cells, moisture content did not exceed the hygroscopic limit value 95 kg/m^3. When the pressure difference is dropped to 10 Pa, slow drying takes place in all cells. To compare the results, calculated for different cells (shown in Fig. 6) with the measured average values (Fig. 2), average of the cell values (weighed with the thickness of cells) has to be used. This is done in Fig. 8.

Calculated value of the average moisture content shows reasonable agreement with the measured value, but the first is somewhat higher. There is an explanation for this. First, we show the influence of the sorption isotherm and of the effective area. In Fig. 9, the results of calculation with $w_* = 30$ kg/m^3 (Fig. 5) in the case when the effective area is increased from 0.112 to 0.16 m^2, are shown.

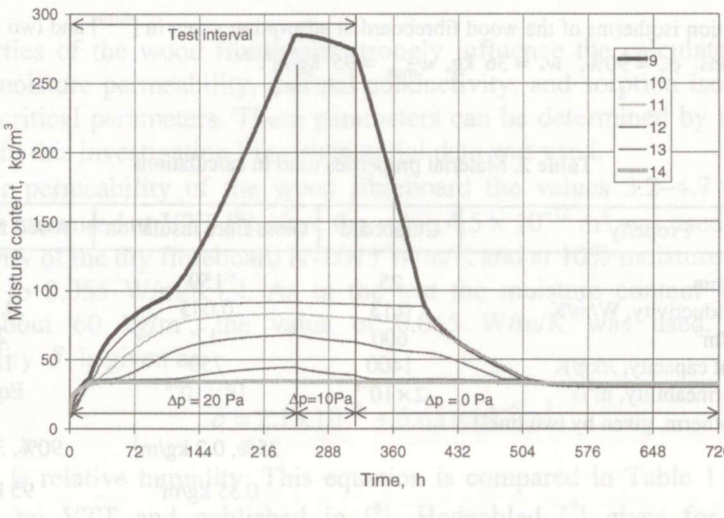

Fig. 6. Calculated moisture content in cells 9–14 of the wood fibreboard; cell 9 is the first cell of the fibreboard, in contact with glass fibre insulation.

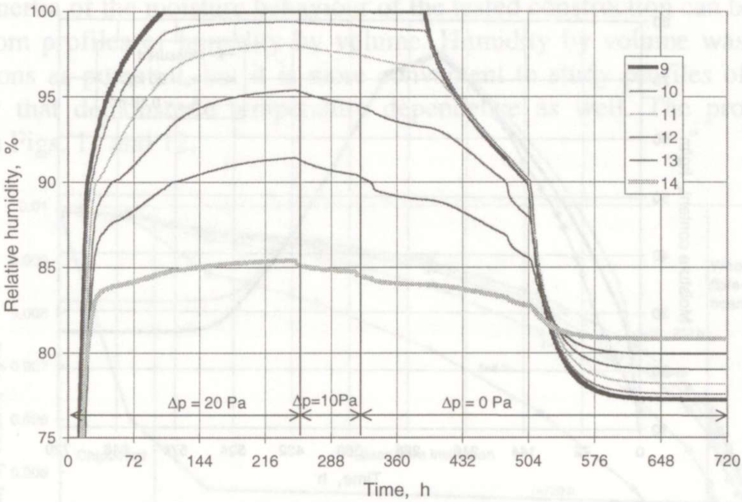

Fig. 7. Calculated relative humidity in cells 9–14 in the wood fibreboard.

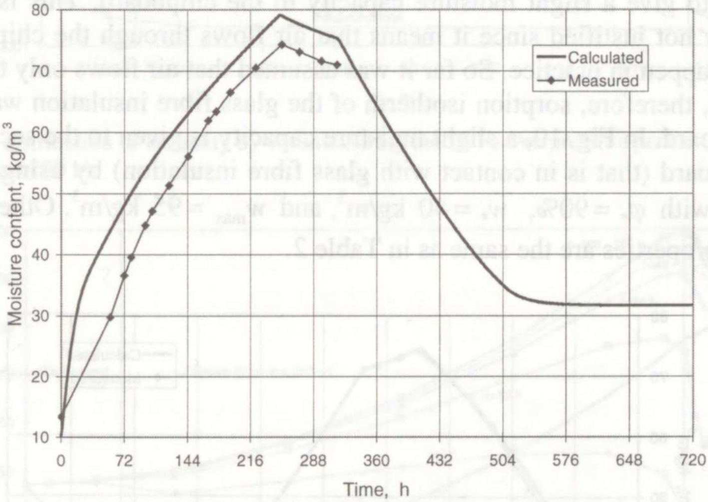

Fig. 8. Calculated and measured average moisture content in the wood fibreboard.

In Fig. 9, the maximum values show good agreement, but near $t = 0$ the calculated adsorption is much more rapid than the measured one. The same phenomenon can be seen in Fig. 8. This can be explained by the moisture capacity of the timber frame and of the chipboard, which are not taken into account in calculations. It is obvious that in the beginning of the test, the dry timber frame and chipboard adsorb significant amount of moisture until equilibrium is achieved. The only way to add this moisture capacity to the current

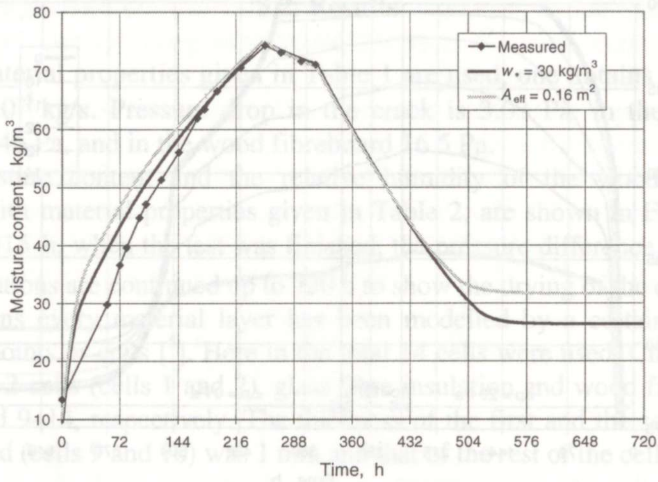

Fig. 9. Average moisture content in the wood fibreboard when sorption isotherm or effective area are changed.

model is to give a slight moisture capacity to the chipboard. This is, however, physically not justified since it means that air flows through the chipboard that will not happen in practice. So far it was assumed that air flows only through the crack and, therefore, sorption isotherm of the glass fibre insulation was used for the chipboard. In Fig. 10, a slight moisture capacity is given to the second cell of the chipboard (that is in contact with glass fibre insulation) by using a sorption isotherm with $\varphi_* = 90\%$, $w_* = 40$ kg/m^3, and $w_{max} = 95$ kg/m^3. Other values of material properties are the same as in Table 2.

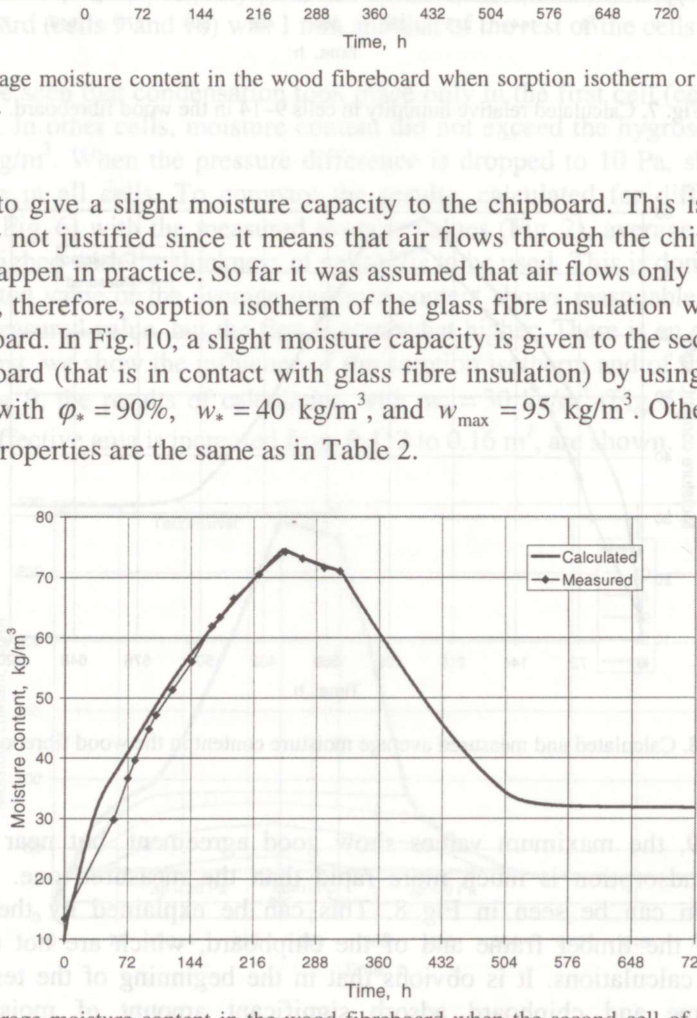

Fig. 10. Average moisture content in the wood fibreboard when the second cell of the chipboard has moisture capacity.

The inertia of the moisture behaviour of the tested construction can be seen in detail from profiles of humidity by volume. Humidity by volume was used in calculations as potential, but it is more convenient to study profiles of relative humidity that demonstrate temperature dependence as well. The profiles are shown in Figs. 11 and 12.

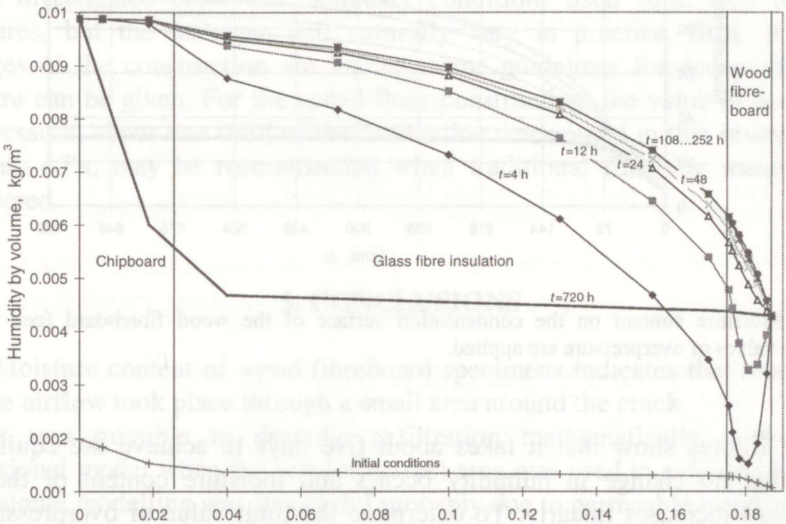

Fig. 11. The distribution of humidity by volume during the 20 Pa overpressure period (t = 0–252 h) and at 0 Pa (t = 720 h).

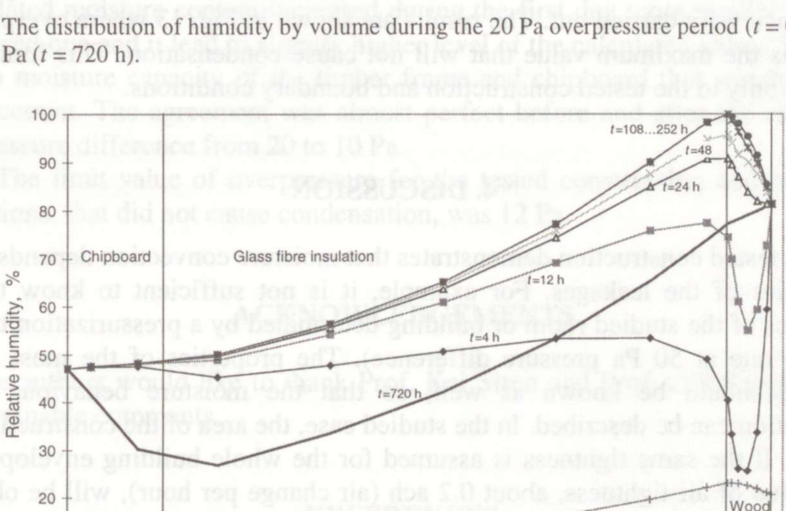

Fig. 12. Distribution of the relative humidity during the 20 Pa overpressure period (t = 0–252 h) and at 0 Pa (t = 720 h).

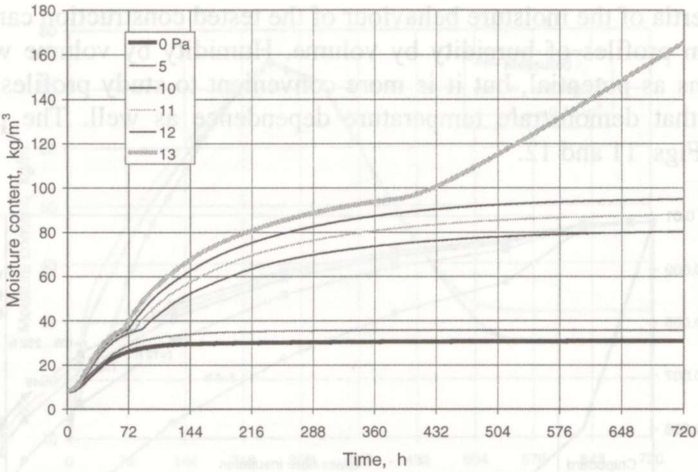

Fig. 13. Moisture content on the condensation surface of the wood fibreboard (cell 9) when different values of overpressure are applied.

The figures show that it takes about five days to achieve the equilibrium. After that no change in humidity occurs and moisture content of the wood fibreboard increases linearly. To determine the limit value of overpressure that will not cause condensation, simulations with various values of the pressure difference were carried out. The results are shown in Fig. 13 where overpressure 12 Pa is the maximum value that will not cause condensation. This limit value applies only to the tested construction and boundary conditions.

4. DISCUSSION

The tested construction demonstrates that moisture convection depends on the properties of the leakages. For example, it is not sufficient to know the air-tightness of the studied room or building determined by a pressurization test (air change rate at 50 Pa pressure difference). The properties of the most critical leakage should be known as well, so that the moisture behaviour during exfiltration can be described. In the studied case, the area of the construction was 1.4 m^2. If the same tightness is assumed for the whole building envelope, very low value of air-tightness, about 0.2 ach (air change per hour), will be obtained for a typical detached house. During the test, most of the leakage airflow occurred through an 0.11 m^2 area. When air-tightness is calculated by using this effective area, a completely different value, 3 ach, is obtained. Thus, overall value of air-tightness does not tell much about moisture convection.

The results of the computer simulation show that at least in the studied case, it was possible to describe moisture convection with a one-dimensional model. It is obvious that exfiltration will cause a complicated three-dimensional airflow pattern. However, in the case of permeable materials, such as glass fibre insulation and wood fibreboard, the assumption that airflow is divided over a certain area around the leakage, was justified. Even more, the moisture content was slightly overestimated due to moisture capacity of the timber frame that was not taken into account. Generalizing the results is problematic as these apply only to the investigated case. The boundary conditions used suite well for floor structures, but the leakages will naturally vary in practice. Still, if typical leakages of the construction are known, some guidelines for acceptable overpressure can be given. For the tested floor construction, the value of acceptable overpressure, about one third of the limit value determined in this investigation, i.e., max 4 Pa, may be recommended when traditional finishing materials are considered.

5. CONCLUSIONS

1. Moisture content of wood fibreboard specimens indicates that most of the leakage airflow took place through a small area around the crack.

2. It was possible to describe exfiltration mathematically with a one-dimensional model when the wet (effective) area was used in calculations. One-dimensional modelling was successful probably due to permeable materials.

3. Calculated results show reasonable agreement with the laboratory test. Calculated moisture content increased during the first day more rapidly than the measured one and it lead to slightly higher level of the calculated value. This was due to moisture capacity of the timber frame and chipboard that was not taken into account. The agreement was almost perfect before and after the change of the pressure difference from 20 to 10 Pa.

4. The limit value of overpressure for the tested construction and boundary conditions, that did not cause condensation, was 12 Pa.

ACKNOWLEDGEMENTS

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NIISKUSKONVEKTSIOON PRAO ÜMBRUSES ÜLERÕHUL

Jarek KURNITSKI ja Targo KALAMEES

Ruumisisese ülerõhu põhjustatud niiskuskonvektsiooni efekti määramiseks puitpõrandas õhulekke (prao) ümbruses on tehtud laboratoorne katse ja arvutisimulatsioon. Töö eesmärk oli määrata, missuguse täpsusega on võimalik modelleerida niiskuskonvektsiooni konstruktsioonis ühedimensioonilise mudeli abil. Modelleerimisel oletati, et läbi prao ja klaasvati voolav õhuhulk jaotub ühtlaselt poorse puitkiudplaadi teatud pindalale. See, nn. efektiivne pindala määrati katse lõpus visuaalselt. Teades läbi efektiivse pindala ja prao voolavat õhuhulka teostati arvutisimulatsioon soojus- ja niiskusülekande mudeliga. Tulemused näitavad, et niiskuskonvektsiooni saab piisava täpsusega modelleerida ühedimensiooniliselt. On leitud ka katsetatud konstruktsiooni seesmise ülerõhu piirväärtus.