LABORATORY INVESTIGATION OF TIMBER FRAME WALLS WITH AN EXTERIOR AIR BARRIER IN A TEMPERATE CLIMATE

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ABSTRACT

Recently, the requirements regarding global building airtightness to reduce the exfiltration losses became more severe as result of the trend towards very low energy buildings and Passive Houses. These very strict requirements regarding airtightness are currently achieved with an interior air barrier, which is labour intensive and consequently expensive. At the same time it is observed that new wind barrier solutions - to reduce windwashing of the insulation - can have a major contribution to the global airtightness of timber frame constructions. Consequently, it is questioned whether the labour intensive interior air barrier will still be necessary in practice when the global building airtightness can be guaranteed by an improved wind barrier only.

However, moving the air barrier from the interior to the exterior of the building envelope can imply an increased moisture load, and thus, higher risks for interstitial condensation against the exterior sheathing in cold and moderate climates.

The current paper presents the results of a laboratory experiment to study the hygrothermal behaviour of light weight timber walls with an exterior air barrier only. Four independent test walls (2.3m by 0.5m) are placed between a newly developed hot and cold box, operating at controlled temperatures, humidities and air pressures. All four walls are insulated with 30 cm of standard mineral wool to which OSB is applied as interior sheathing. The test walls differ from each other by the physical properties of applied exterior air barrier; airtightness, moisture buffer capacity, vapour permeability and thermal resistance.

KEYWORDS

Hygrothermal analysis, hotbox-coldbox, exterior air barrier, natural convection, laboratory

INTRODUCTION

The importance of preventing air leakages through building enclosures is well known and documented in literature. Air convection through building envelopes can result in unwanted effects such as draught, interstitial condensation and excessive heat losses.

For timber frame constructions an airtight building envelope is commonly realised by an interior air barrier system. The term ‘air barrier’ refers to the material layer which prevents air leakage between inside and outside through the building envelope. Consequently, the most important property of this layer is the overall continuity, which leads to the requirement of sealing all the joints and intersections in this layer. In cold and moderate climates, such as North-West European areas, the air barrier function is often combined with that of the vapour retarder. Realising a good airtightness with an interior barrier however, is very labour-intensive due to many internal joints, intersections and perforations [2-3].

On the other hand, to protect the insulation layer from unwanted infiltration of outside cold air (so called windwashing), a ‘wind barrier’ is provided at the outside of the insulation. In addition, this exterior layer also serves as drainage plane to prevent water infiltration into the structure. The performance criteria for wind barrier systems regarding air permeance are less severe than for air barriers, and thus, are the joints in the wind barrier usually left unsealed. However, results of field tests [6,8] and numerical investigations [7] emphasise the importance of improving the continuity of the wind barrier layer to reduce heat losses. As a result of these studies, today more and more building companies start to improve the airtightness of the wind barriers by sealing the joints.

In situ measurements [1] show how the air permeance of the wind barriers can be significantly improved with minor modifications. The case study discussed demonstrated that with good workmanship and appropriate materials, an airtightness level lower than 1 ACH at 50 Pa can be reached with the wind barrier only.

Moreover, it is noticed that in Norway the wind barrier evolves more and more towards a secondary air barrier [4,9]. In the Nordic countries it is becoming common practise to measure the global buiding airtightness twice; during the windtight stage and after the building is finished. However, when improving the wind barrier to such levels it becomes impossible to control the continuity of the interior air barrier with pressurisation test, because only the air resistance of the global building envelope is measured. This means that situations can occur where the exterior wind barrier is more airtight than the inner air barrier. In this case the exterior sheathing acts as a wind and air barrier and the inner sheathing only acts as vapour barrier/retarder. Given such a non-continuous interior vapour barrier, concentrated vapour diffusion and moist air by natural convection may enter the building envelope through the gaps in the vapour barrier.

Consequently the question rises to which level this additional moisture load has an impact on the risk for interstitial condensation against the exterior sheathing.

The current paper presents the results of a comprehensive laboratory investigation in which the hygrothermal response of light weight walls with an exterior air barrier is studied.

Four highly insulated test walls enclosed between two climate chambers to simulate in and outdoor winter conditions in a temperate climate have been analysed. The test walls are based on the configuration currently used in Belgian timber framed Passive houses using Oriented Strand Board (OSB) as interior sheathing and insulated with 30 cm of insulation. The walls differ from each other by the physical properties of the applied exterior air barrier; airtightness, moisture buffer capacity, vapour permeability and thermal resistance. The investigation is performed in five consecutive stages with increasing importance of air transport in the test walls. A detailed description of the test setup and preliminary results, mainly focussing on the thermal behaviour during the first measuring step, were already presented in [10].

EXPERIMENTAL METHOD

Hot box/ cold box equipment

For the current study a new vertical calibrated hot box/ cold box was constructed. Here only the main features are discussed. A more detailed discription can be found in [10].

The test setup consists of three major parts; a test frame to install the studied building component enclosed between two climate chambers to simulate in and outdoor conditions. The warm climate chamber has a cubic inner volume with sides of 2.4 m and is completely insulated with 60cm of PUR insulation panels. The test frame, which was constructed in the same way, has a measuring area of 2.4 m by 2.4 m and a depth of 0.6 m. The cold box on the other hand is only insulated with 0.1 m polyurethane boards.

A controlled IR-bulb in the middle of the warm chamber creates the desired temperature conditions. The cold chamber on the other hand is provided with a convector accompanied with a fan system to control and distribute the temperature. As a consequence of the fan system, a small under pressure in the cold box is unavoidable. The humidity in both the warm and cold chamber is conditioned with free evaporation of salt solutions. To create a total air pressure difference across the test specimen a small ventilator is installed at the back wall of the warm chamber.

Wall configurations and sensor positioning

To investigate the hygrothermal consequences of exterior air barrier systems in timber frame construction, four highly insulated test walls (test area: 2.3m by 0.5m) were tested. All four test walls are insulated with 30 cm of standard mineral wool to which OSB is applied as interior sheathing. The test walls differ from each other by the physical properties of applied exterior air barrier; airtightness, moisture buffer capacity, vapour permeability and thermal resistance. Both the exterior sheathing of the first test wall (further referred to as REFERENCE) and the second test wall (referred to as FIBREBOARD 1) consists of bituminous impregnated soft fibre board with an exterior top layer which increases its airtightness. For the third test wall (FIBREBOARD 2) a similar bituminous impregnated soft fibre board but without top layer is applied. This means that the first three test walls are provided with a hygroscopic and capillary exterior sheathing. Contrary, the fourth wall (FOIL) is executed with a spunbunded foil at the outside. The applied foil is extremely airtight but has no water buffer capacity. The configuration of the test walls studied is shown in Figure 1 and the most important material properties are summarised in the following section.

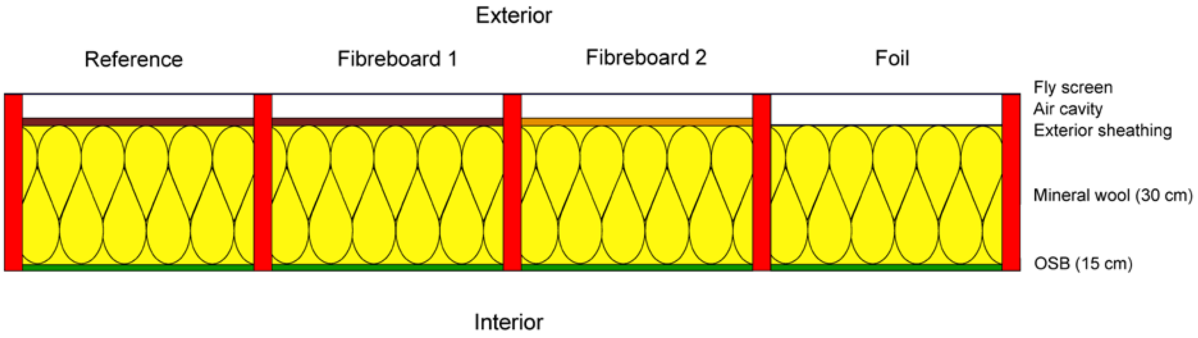

Figure 1. Wall configurations studied.

Each test wall is provided with 18 thermocouples placed at three heights: (1) 20 cm from the bottom, (2) middle height and (3) 20 cm from the top, at every material interface, in the ventilation cavity and the middle of the insulation layer. Also 15 relative humidity sensors were installed at the same positions except from the interface OSB-mineral wool (warm side). Additionally, the heat fluxes were measured at this interface at the three heights. For each wall also a pressure gauge was installed at the middle height.

Besides this continuous logging system, the wind barrier layer was constructed in such a way that each part of the wall contained three removable specimens (12cm by 12cm). The specimens are used to quantify the moisture evolution of the fibreboard on a two-weekly basis. Special care was given to the airtightness of the perimeter of each specimen. After every measurment the joinst were sealed with airtight tape.

Boundary conditions and test sequence

The experiment, which lasted for about four months, was subdivided in five main consecutive measuring steps. In the first four steps the test walls were exposed to typical winter conditions with increasing importance of natural and forced air convection.

During the first step both the interior and exterior sheathing is airtight. In the second step, gaps are introduced in the interior barrier of all walls except for the REFERENCE section. The gaps correspond with slits of 1 cm at 20 cm from the top and bottom of the OSB and cover the full width of each test wall to maintain the two dimensional situation. In step 3 and 4 an increasing overpressure was created in the hotbox.

Finally, in the last step the conditions in the cold box were adapted to create drying conditions inside the walls. Table 1 summarises the boundary conditions in both the warm and cold chamber.

Steps	**Days**	**T_{HB} (°C)**	**$P_{v,HB}$ (Pa)**	**T_{CB} (°C)**	**$P_{v,CB}$ (Pa)**	**P_a (Pa)**
1	35	20.1	1180	3.0	652	1.4 - 2.7
2	28	20.1	1185	3.4	684	0.6 - 1.6
3	24	20.1	1228	3.2	687	5.4 - 6.6
4	11	20.2	1292	3.3	698	10.1 - 12.5
5	32	24.2	1618	22.5	2007	1.6 - 1.8

[1] Overpressure depends on the position of the test wall an varies between these values

Table 1. Boundary condition in hotbox (HB) and coldbox (CB) during the consecutive measuring steps

It should be noted that the current climate conditions represent an averaged typical winter month in a temperate climate, such as Belgium.

Material properties

Most important material properties are summarized in Table 1 and Figure 2. Apart from the heat capacity all material properties were measured at the laboratory. Special care was given to the air permeability and in particular to the mineral wool. For the permeability perpendicular to the fibres ($K^{\perp}$) and parallel to the fibres ($K^{\parallel}$) seven specimen were tested. The results found are in agreement with Økland (1998) who lists an overview of measured air permeability of mineral wool from literature. However, it was observed that $K^{\parallel}$ was very sensitive to the installation of the specimen in the test setup.

Material	**d (mm)**	**ρ (kg/m³)**	**c_p (J/(kgK))**	**λ^1 (W/m/K)**	**$K^{\perp}$ (m²)**	**$K^{\parallel}$(m²)**
Fibreboard 1	18	285	2068	0.045	4.65E-14	-
Fibreboard 2	18	274	2068	0.047	1.37E-12	-
Foil	0.2	-	-	-	airtight	-
OSB	15	630	1880	0.06	8.20E-15	-
Mineral Wool	300	21.3	840	0.033	1.7E-09	6E-09[2]

[1] heat conductivity at measured 0°C

[2] large variation depending on specimen positiong (2 - 10 E-09 m²)

Table 2. Boundary condition in hotbox (HB) and coldbox (CB) during the consecutive measuring steps

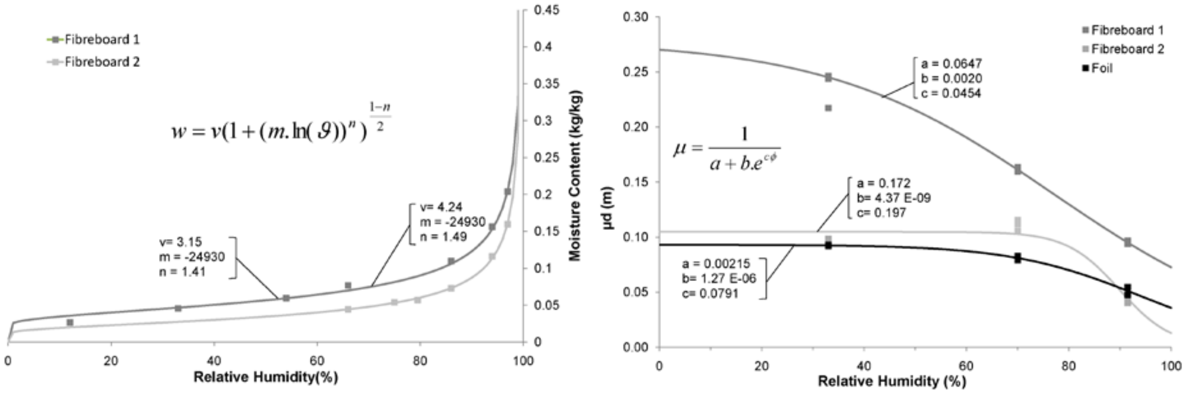

Figure 2. Sorption isotherm (left) and vapour diffusion resistance (right) of the different wind barriers as function of relative humidity.

TEST RESULTS

Thermal response

As a first step in analysing the results we focus on the thermal distribution in the test walls. Figure 3 shows the dimensionless temperature profiles of the four walls at the top and bottom row for measuring stage 1, 2 and 4. This corresponds with the situations where (1) the interior OSB sheathing is intact, (2) top and bottom gaps in the interior sheathing are introduced and (3) an overpressure of 10 Pa is realised in the warm chamber.

This figure clearly shows that during the first step (blue triangles) the temperature distribution bends upwards at the top (filled markers) and downwards at the bottom (open markers) which indicated the existence of natural convection within the walls. This was studied more in depth with additional numerical simulation in [13]. This study shows that the existance of very small vertical gaps between the mineral wool and the sheathing material combined with the (local) increase of the air permeability of the installed mineral wool has a great influence on the magnitude of natural convection inside the walls. During the second measuring step (red squares) this effect increases as a result of the introduction of the gaps in the interior sheathing. At this stage it was also noticed that the temperature profile for the least airtight wall (FIBREBOARD 2) bends also upwards at the bottom row. This means that the exterior sheathing is even so air permeable that as a result of the 1.6 Pa overpressure across this wall (introduced by the ventilators in the cold chamber) forced exfiltration already dominates the air flow in this section. When finally an overpressure of 10 Pa (green dots) is realised in the fourth step this effect becomes of course much more dominant in the ‘FIBREBOARD 2’ section. Also for FIBREBOARD 1 this effect is (to a minor degree) observed. For the most airtight wall (FOIL) this remains negligible.

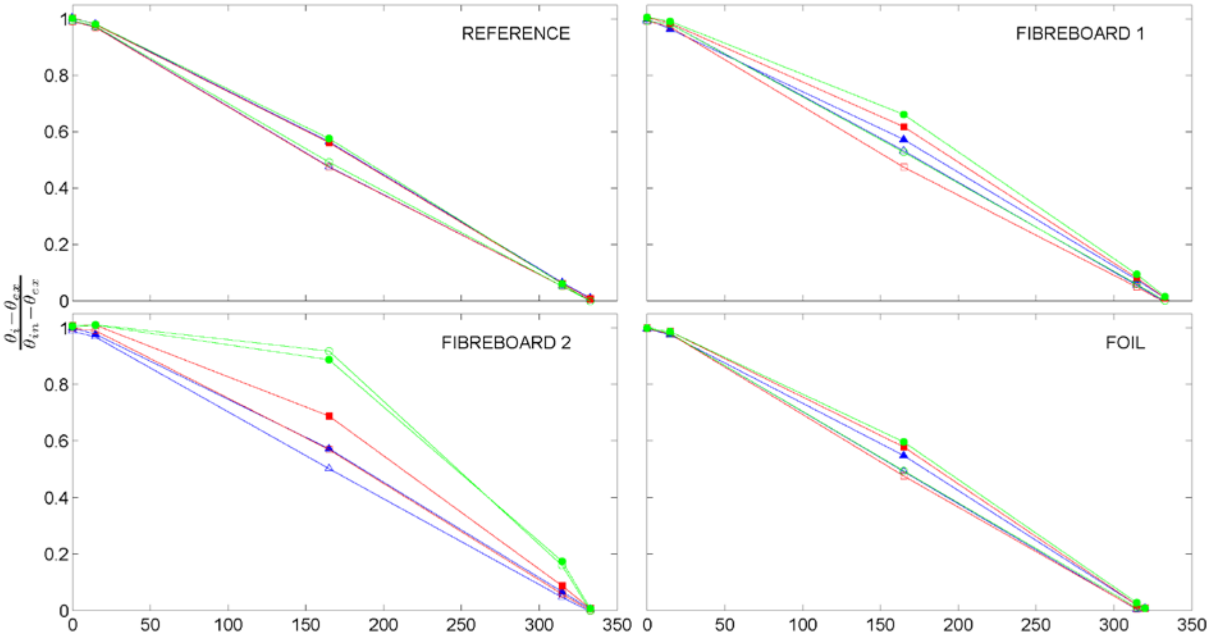

Figure 3. Dimensionless temperature profile of four test walls at top row (filled markers) and bottom row (open markers) during measuring step 1 (blue triangle), step 2 (red square) and step 4 (green dot).

Hygrothermal response

The same method and notation is used to present the dimensionless vapour pressure profiles across the test walls in Figure 4. During the first step all four walls show a similar vapour pressure profile: steep drop behind the vapour retarder (OSB) followed by a slight decrease towards the outer side. Only for FIBREBOARD 1 the vapour pressure at the top row is somewhat deviating from the expected values. At this row the vapour pressure is slightly higher than in the other walls. This cannot be the result of air exfiltration since this should also be noticed in the temperature distribution as well. A more plausible explanation might be found in a local decrease of the vapour resistance in the interior sheathing material or the sealed gap.

In the subsequent step, when the gaps in the interior sheathing are opened, the influence of natural convection on the moisture load becomes very pronounced. For all walls with interior gaps the vapour pressure at the top row increases while the vapour pressure at the bottom row remains the same. Only for FIBREBOARD 2 also the vapour pressure at the bottom row increases since forced exfiltration is then already dominant as a result of the high air permeance of the exterior sheathing as discussed in the previous section.

When an overpressure of 10 Pa is realised the vapour pressure profiles confirms the observation of the temperature profiles. For FIBREBOARD 1 a slight increase in vapour pressure is noticed as a result of forced exfiltration while this effect is much stronger in FIBREBOARD 2. For the wall with the exterior foil this influence is hardly noticed.

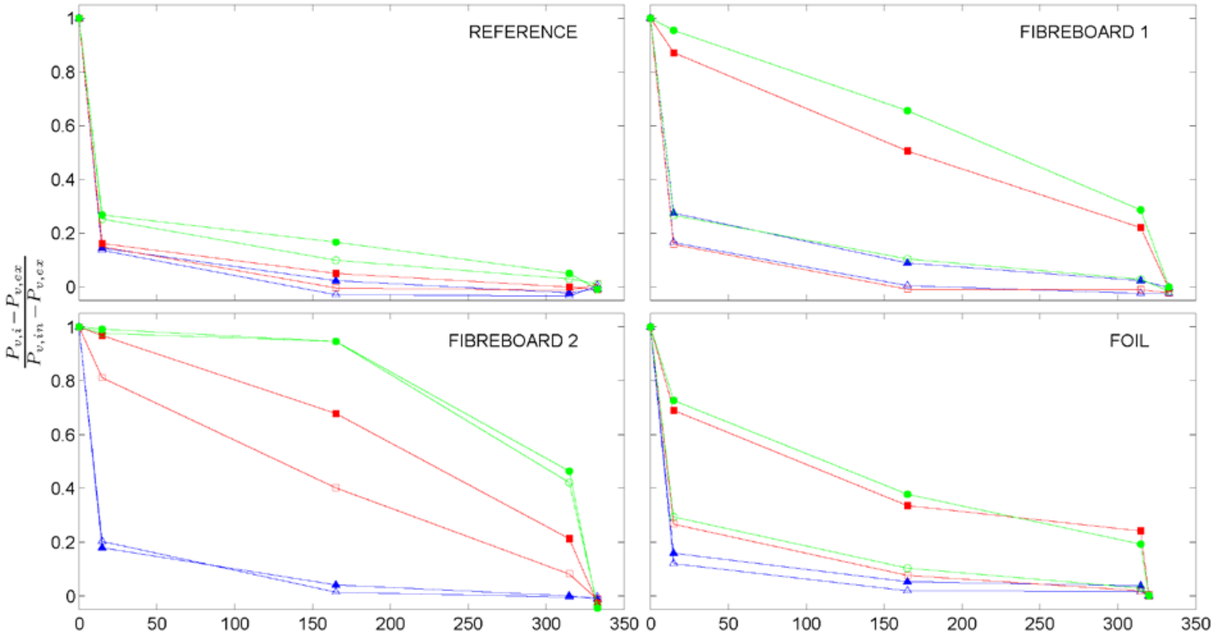

Figure 4. Dimensionless vapour pressure profile of four test walls at top row (filled markers) and bottom row (open markers) during measuring step 1 (blue triangle), step 2 (red square) and step 4 (green dot).

In addition to the vapour pressure profiles the evolution of the moisture content in the exterior sheathing material (Figure 5) gives valuable information about the continious increased moisture load introduced by natural convection.

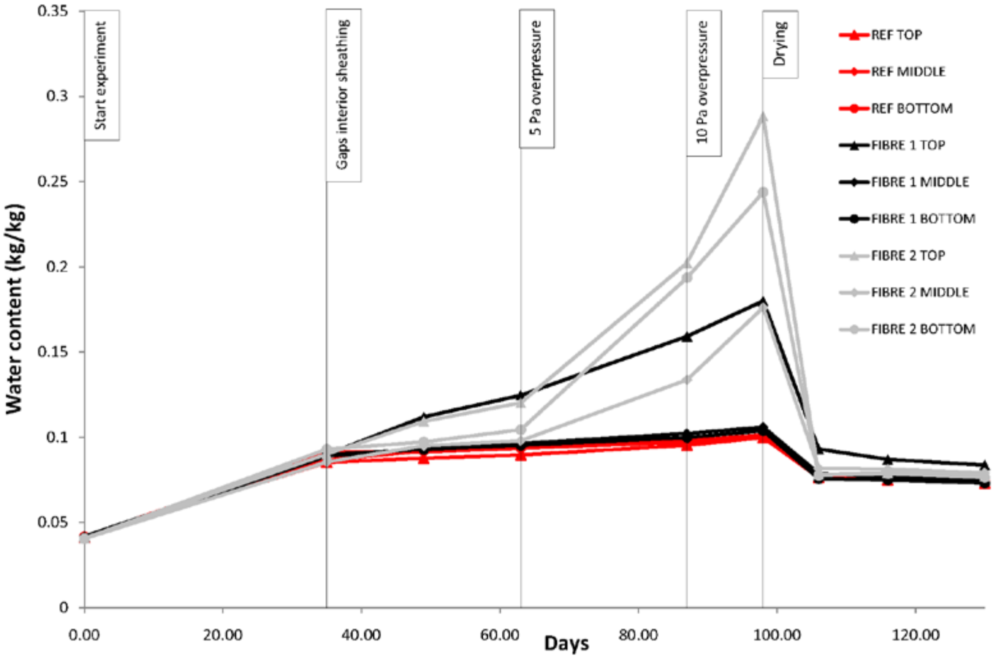

Figure 5. Moisture content evolution of the weight sample in the exterior sheathing. (top: triangle, middle: diamond, bottom: dot)

During the first stage all weight monster show the same moisture content evolution. However, from the moment the gaps are introduced a significant moisture increase is noticed at the top position. For FIBREBOARD 2 also the moisture content at the bottom and middle position slightly increases indicating the existence of forced convection. Creating in the next two steps an overpressure across the walls does not seems to influence the moisture content of

FIBREBOARD 1. For FIBREBOARD 2 on the other hand – of which the exterior sheathing is twenty time more air open – we can see a clear correlation between the magnitude of the overpressure and the moisture content of the weight samples at the three heights.
As a result of the high vapour permeance of the exterior sheathing an instant steep decrease of the moisture content is observed when drying condition are created in the final step.

DISCUSION

The current paper studies the hygrothermal impact of light weight highly insulated walls with an exterior air barrier. Three different potential exterior air barrier materials were tested. The results show that a sufficiently airtight material is a prerequisite in obtaining a safe building envelope. To this respect FIBREBOARD 2 (0.1 m³/m²/h/Pa) obviously fails, resulting in a forced exfiltration flow through the wall, and thus, increased heat losses and very high moisture contents of the exterior sheathing. For FIBREBOARD 2 (0.005 m³/m²/h/Pa) this effect was limited to a very minimum from which we can conclude that such levels of air permeance are sufficiently low to prevent harmful amounts of forced exfiltration.
On the other hand, the result show that even if forced convection is limited (FIBREBOARD 2 and FOIL), an increased moisture load is introduced into the structure by moving the air barrier to the exterior of the building envelope. For both tests sections the results show that water vapour driven by natural convection enters through the upper gap and deposits at the cold side of the insulation layer (Figure 6). The danger of this process is its continuity. Driven by the temperature difference across the wall, this convection loop provides a constant moisture flow towards the upper cold side of the structure.

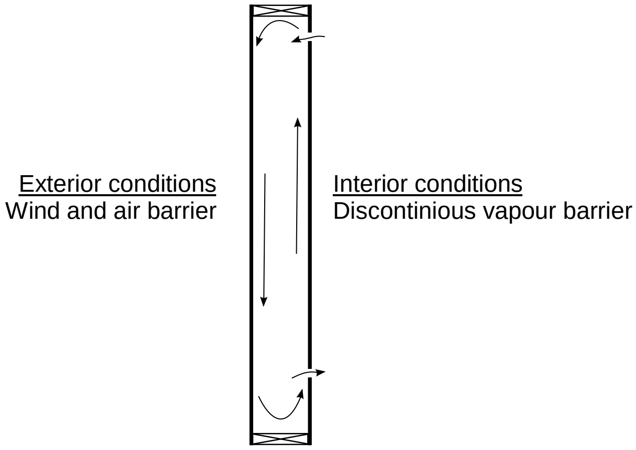

Figure 6. Air flow pattern as a result of natural convection inside a vertical wall with exterior air barrier.

CONCLUSION

The current paper presents the results of a laboratory experiment to study the hygrothermal behaviour of highly insulated walls with an exterior air barrier. The results show an increased moisture flow at the upper part of the walls driven by buoyancy forces. The magnitude of this flow is, apart from the position and size of the gaps, highly depending on the air permeability and the accuracy of the installation of the insulation layer. For the current study (very carefully installed) mineral wool is used which leads to a significant moisture increase. Further tests to investigate the importance of this effect for other insulation materials, such as cellulose or studying the influence of bad workmanship of the insulation layer would be an added value to this research.

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