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MOISTURE DRYING CAPACITY OF MINERAL WOOL INSULATED STEEL-FACED SANDWICH PANELS BY CONVECTION

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Abstract. This study analyses moisture dry-out from a steel-faced insulated sandwich panel by forced convection. Moisture convection performance was studied by laboratory tests and simulation. Two test walls with the lower parts close to the free water level were studied in a laboratory with and without convection. In addition, a real-scale wall was built to south orientate direction. Measurements were also used for simulation model calibration. The hygrothermal simulations were performed with the simulation tool Delphin in stable climatic conditions to determine the magnitude of the convection moisture dry-out capacity. Comparison of the measured and simulated relative humidity showed sufficiently good agreement. The results indicate that convection significantly improves dry-out capacity, especially during summer. However, during autumn and winter their dry-out capacity was smaller. To minimise the wetting of insulation, weather protection during construction and storage is necessary.

Keywords: Drying of structures, sandwich panel, hygrothermal performance, moisture safety.

1. Introduction

The building envelope of nearly Zero Energy Buildings needs to be well insulated [1]. Pihelo [2] showed that the drying-out period is longer in walls with lower thermal transmittance, especially when vapour-tight rigid boards outside the insulation are used [3]. Ojanen [4] studied the hygrothermal performance of mineral wool insulation products in highly insulated structures and showed that the vapour-open thermal insulation, like stone wool, allowed significantly faster drying of the inner concrete layer than the more vapour-tight thermal insulations. Sekki et al. [5] studied external insulated precast concrete wall panels and showed that, for this structure, the drying period was also shortest with a vapour-open insulation material.

Ensuring hygrothermal performance is particularly difficult when the surrounding materials (especially external material – wind barrier) are vapour-tight. Some examples of such structures are the structural insulation panel (SIP) and steel-faced sandwich panel. In SIP, the material which surrounds the insulation is usually oriented strand board (OSB) or plywood, which is slightly vapour permeable. However, in steel faced sandwich panels, the steel sheets are vapour tight. The structural integrity of sandwich panels could be significantly degraded due to the moisture absorbed after long-term exposure to a humid environment [6]. It is thus important to investigate the moisture dry-out methods of the sandwich panels. When water has leaked into the mineral wool sandwich panel, the speed of evaporation is the limiting factor for the increasing vapour pressure compared to the speed of vapour diffusion [7].

Compared to diffusion, the moisture convection allows much larger amounts of moisture to be moved in both the wetting [7] and drying [8] processes. Accidental air leaks can limit the intended drying, as the air does not pass through the entire specified area. The steel-faced mineral wool insulated sandwich panel differs from other structures as it has a very clear structure – airtight external surfaces (exterior and interior steel sheet) and air-permeable internal insulation layer. This makes it possible to form a clearly defined area where air must move to dry the structure. As diffusion drying from a steel-faced mineral wool insulated sandwich panel is limited [9], convection drying is a method to increase the efficiency of moisture dry-out. However, there is still relatively limited research on this field. The current study examines convection drying of a steel-faced mineral wool insulated sandwich panel by small-scale and full-scale laboratory experiments and hygrothermal modelling.

2. Methods

2.1. Laboratory measurements

Moisture drying measurements in laboratory included:

- 3D mock-up test elements to find out convection drying efficiency (Figure 1). Airflow rate per volume 91 l/(min · m^3) (SMC PFM 710), $t_{ambient}$ +23.0 °C, RH 30 % (Hobo UX-100-023);
- Full-scale drying test between indoor and outdoor environment (average airflow rate per volume 23 l/(min · m^3) (SMC PFM 725), t_i +23.0 to +31 °C, measured outdoors data for t_e and RH_e (Humisense A1)) to reveal air pressure distribution and convection drying performance as well to obtain data for the calibration of hygrothermal model.

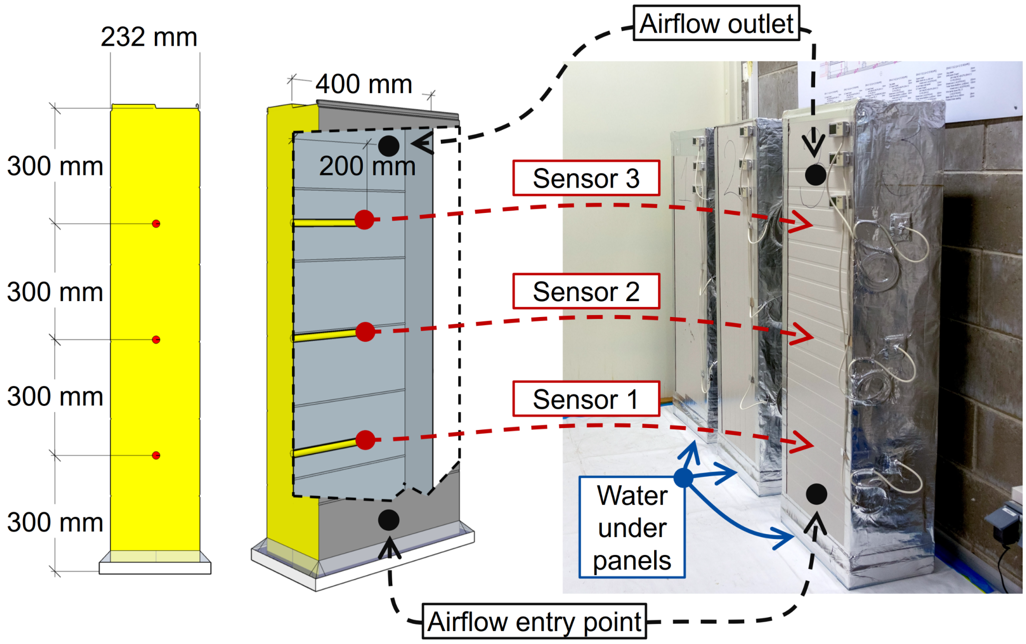


Figure 1. 3D mock-up test elements: (a) with indicated T and RH sensor placement (red dots, Hobo UX-100-023), airflow sensors (black dots SMC PFM 710) and photos of the elements (b).

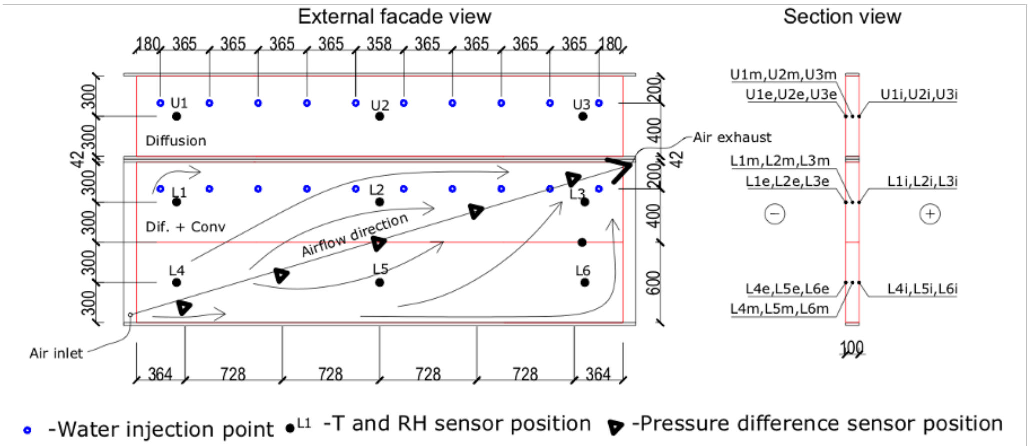


Figure 2. Full scale test walls and sensor positioning (T/RH Humisense A1, airflow SMC PFM 725).

The upper section of the wall, separated from lower parts, was left to dry by diffusion through two open surfaces ($2 \times 600 \times 100$ mm) connected to outside climate conditions while the middle and lower sections were ventilated with air drawn from outside (Figure 2). The test wall had a total of 27 temperature and relative humidity sensors. Additionally, 5 air pressure difference sensors were installed to determine air pressure distribution inside the wall and rule out any possible air leakages that could have a negative effect on the test. Airflow rate was also measured at airflow entry point and airflow outlet. Possible air leakages were tightened until the entering airflow rate reached approximately the same value as the outlet airflow rate. Once the airtightness of wall had been confirmed, water was added through 10 injection points per upper and per lower section and then left to redistribute over the volume for 10 days. Here, 50 ml of water was added through every upper injection point and 100 ml through every lower injection point. After 10 days of redistribution the upper section of the test wall was opened to diffusion and ventilation was started in the lower section. The entire drying period lasted 21 days.

2.2. Modelling

The numerical simulation tool Delphin 5.9 [10] was used for the combined heat, air and moisture (HAM) transport modelling. Delphin is a well-developed, advanced and validated software application suitable for building sciences. The simulation model takes into account measured indoor/outdoor temperature, RH and measured airflow through the length of a wall. In the calculation model heat and moisture can move in 2 directions and airflow in 1 direction. The water injection points were modelled as a raised moisture content within the mineral wool, equally distributed over the height of wall. This caused the calculation model to

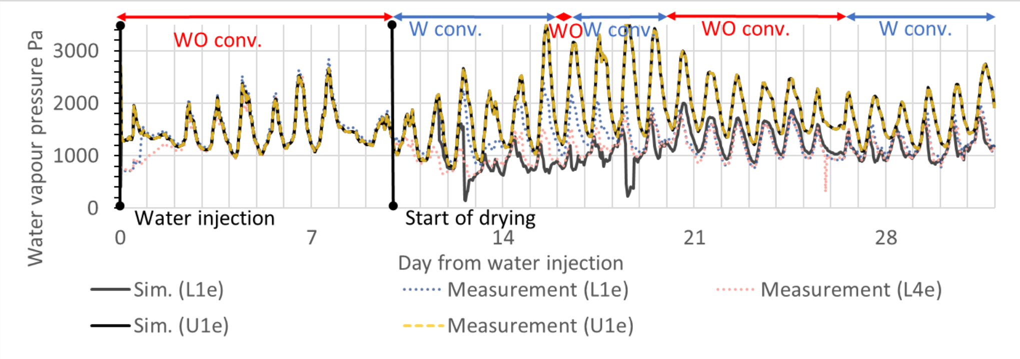


FIGURE 3. Modelled water vapour pressure at sensor positions compared to measured results (Figure 2). W conv. is for time range when lower section of the wall was ventilated and WO conv. when not.

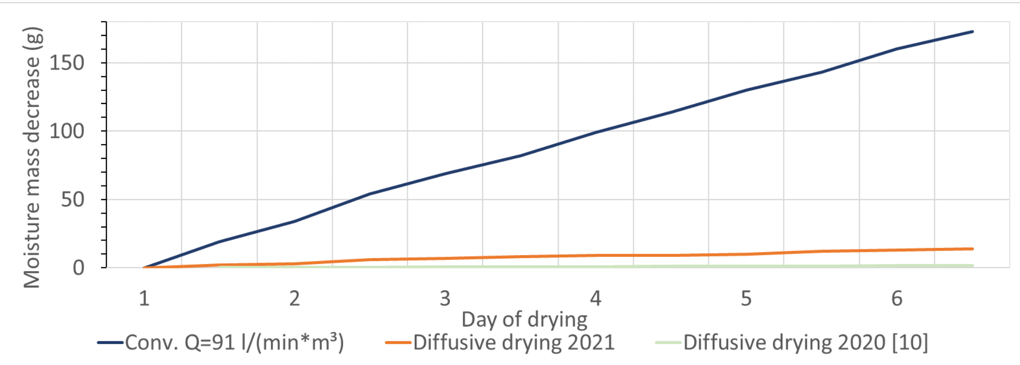


FIGURE 4. Moisture dry-out at stable temperature conditions (Figure 1). Diffusive drying 2020 refers to a previous research on vapour retarding and vapour permeable tape performance [9].

overestimate moisture distribution equality because in reality there was only one injection point per height of the wall. However, the outputs taken from the simulation model showed sufficiently good conformity with the measured results (Figure 3). The calculation model overestimates drying rate near water injection points and underestimates drying rate further away from injection points. More accurate results might have been achieved if the software could have calculated heat/moisture movement in 3 directions and airflow in two directions. The thermal conductivity of mineral wool was determined as 0.04 W/(K · m), bulk density 85 g/m^3, porosity 0.97 m^3/m^3, specific heat capacity 840 J/(kg · K), effective saturation 0.9 m^3/m^3 and water vapour diffusion resistance factor $\mu = 1$. Air permeability of mineral wool is irrelevant in this case because the air flow rate is measured and inserted into the simulation without calculating it by pressure and air permeability.

To study the drying rate of a typical steel-faced sandwich panel wall, the simulation models were updated to represent a typical structure where the panels are 6 m long, 8 m high, 0.23 m thick and have a 30 mm vertical connecting joint at both ends, one for air intake and one for air exhaust. The boundary condition on one of the longer sides was simulated using a stable outdoor climate and on the other side as an indoor climate. Shorter sides were simulated as adiabatic. For the outdoor climate of these simulations, the Finnish moisture reference year, known as Jokioinen 2004, was used. Jokioinen 2004 (average for winter t_e -4.4 °C, RH 93 %, ν 3.3 g/m^3 and for summer t_e +14.5 °C, RH 75 %, ν 9.3 g/m^3) is a critical outdoor climate if the internal part of the structure is protected.

3. RESULTS AND DISCUSSIONS

3.1. STABLE TEMPERATURE CONDITIONS

The temperature and relative humidity indoor remained relatively constant throughout the drying period, respectively ≈ +23 °C and ≈ 30 %. Mineral wool pore air relative humidity at the beginning of the test was 97–100 %. The test piece (Figure 1) which dried by diffusion decreased in mass about 2.5 g/day. Another test piece (Figure 1) dried by convection showed a significantly faster decrease in mass – about 31.5 g/day (Figure 4). The significant impact of airflow gave us the confidence to move forward with the variable temperature conditions test which was carried out on the big test wall (Figure 2).

3.2. VARIABLE TEMPERATURE CONDITIONS

The external temperature throughout the drying period was extremely hot and produced high water vapour pressure levels inside the wall. The drying rate by diffusion depends on the pore air water vapour level in the layer which is near to the open surface compared to the water vapour level in the air which is

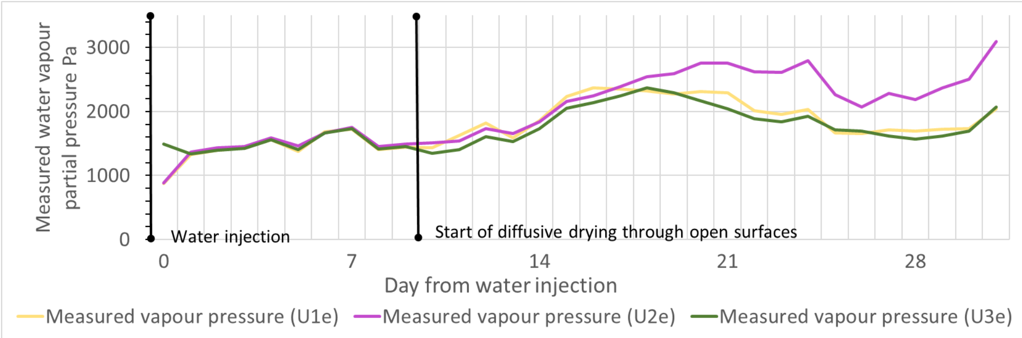


Figure 5. Daily running average of measured water vapour pressures in diffusive drying wall section.

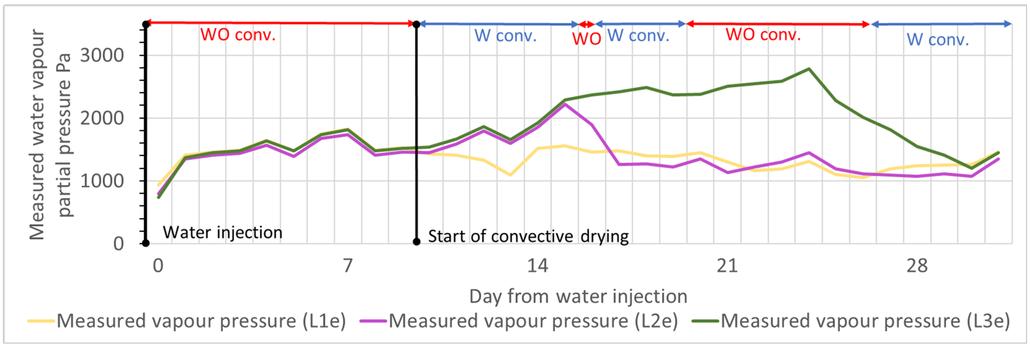


Figure 6. Daily running average of measured water vapour pressures in convective drying wall section.

in contact with the open surface. Further away from the open surface diffusion also takes place inside the mineral wool but the difference in water vapour pressure between mineral wool layers becomes lower when moving further inside the wall, away from the open surface. This limits the moisture movement rate from the centre of wall span to the open surface. However, the water vapour pressure levels remained relatively high in the diffusive drying section (Figure 5) compared to the section which was ventilated by airflow (Figure 6). Water vapour partial pressure in the figures below is a daily running average created with 24 data points.

The water vapour levels inside the ventilated test wall section become largely homogeneous at the end of the drying period (Figure 6). This indicates that all the moisture inside the wall has moved towards the exhaust of the airflow and exited the wall. The nearer the layer is to the airflow input, the faster it dries because outside air displaces this area faster. The layer near to the airflow exhaust is the last one to dry because all the moisture gets sucked there before exiting the wall.

3.3. Drying strategies for summer and winter

The updated calculation model simulated drying at various airflow rates. Relative humidity of summer outdoor air was reduced to 10 %, which takes into account the assumption that air is processed through an air compressor and excessive moisture is extruded from the air. Variable air inflow temperatures were tested to find out the optimal temperature for winter climate conditions (Figure 7). It is important to maintain relatively high airflow rates in winter to ensure that the air has not cooled down too much before reaching the outlet, otherwise it would limit the moisture content in air exiting the wall (Figure 8). The drying was simulated until air in mineral wool pores reached the water vapour content of outside air. The drying process might be faster if there is a known performance criterion and appropriate maximum humidity content.

3.4. Applying drying on a real scale wall

Sandwich walls in a real-life situation might be more complicated than the test wall built for this research. It is common that sandwich panels have additional holes for fastening secondary constructions which makes the wall more air permeable and increases leakages. A sandwich wall might also have non-perpendicular angles which could make proper tightening even more challenging. Proper tightening should make the wall impermeable for air on pressure difference. To apply convective drying on a multi-span wall with many vertical joints it is recommended to place ventilated joints with negative air pressure drop and free joints for compensation air over one so that the air moves from adjacent joints towards the ventilated joint (Figure 9 and Figure 10). The key to this airflow trajectory is properly tightened possible air leakages (horizontal joints between panels, screw holes, etc.). It is also important to protect the vertical joints against

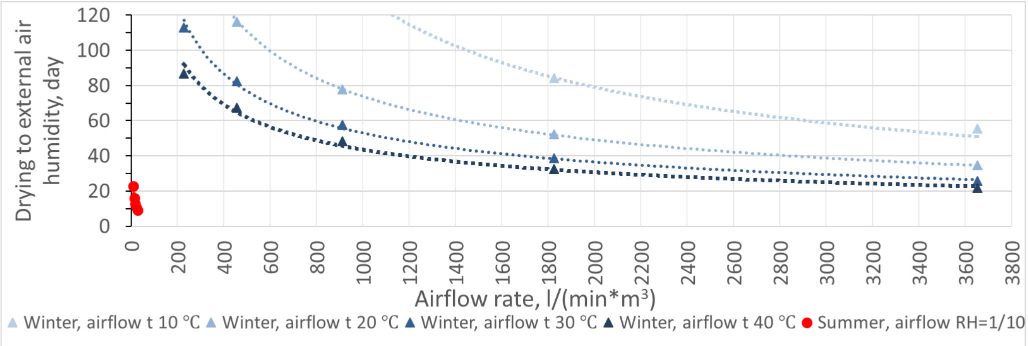
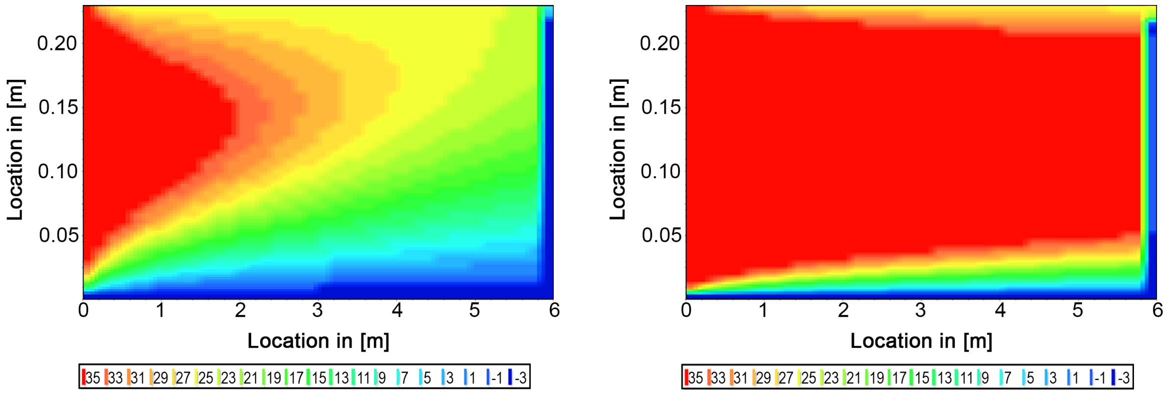


Figure 7. Moisture dry-out duration at stable temperature conditions to outside air humidity (pore air vapour content in summer $9.3/10 = 0.93$ (g/m^3) and in winter 3.3 (g/m^3). Blue lines indicate drying in winter at different air inflow temperatures, red line shows drying in summer with reduced moisture content in the air.



(a). (b).

Figure 8. Temperature distribution on top view of the wall (vertical length 0.23 m and horizontal length 6 m), winter period, air inflow temperature +40 °C (A) airflow rate 228 l/(min · m^3) (B) airflow rate 3 650 l/(min · m^3). Red area shows temperature over +35 °C and navy blue is for areas under -3 °C.

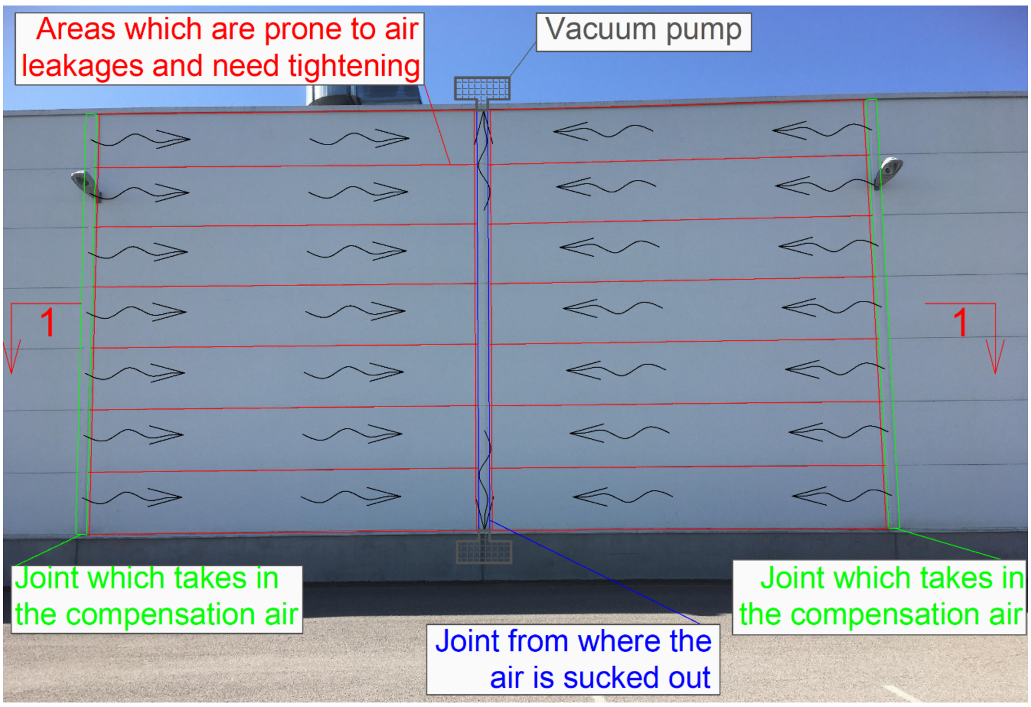


Figure 9. Scheme on facade for ventilated vertical joints and compensation air joints.

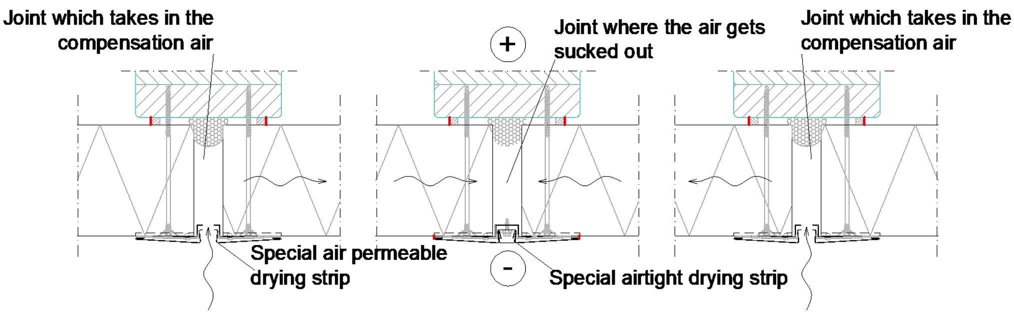


Figure 10. Scheme on top view of facade for ventilated vertical joints and compensation air joints.

diagonal rain with a temporary drying strip on the joint. The drying strip on the ventilated joint has to be airtight in order to avoid air leakages near the pressure drop.

Our research confirmed the proof of concept, but future studies should analyse cost efficiency and feasibility. It is up to discussion whether the method should be used if its cost exceeds the cost of replacing the panels or the energy demand becomes unacceptably high. A method to reduce energy consumption of the drying method in winter would be adding temporary extra thermal insulation on the outer face of the sandwich panel wall. This would rise the temperature of the external face and therefore increase the evaporation of moisture adsorbed on mineral wool fibres near the cold surface. However, arguably the best option would be to implement proper moisture management during both the construction phase and service life.

4. Conclusions

The following conclusions can be offered for drying a wall of steel-faced mineral wool insulated sandwich panels:

- Stable temperature conditions test indicated that convective drying has the potential to lower moisture mass dozens of times faster than drying by diffusion.
- Even very small air leakages can cause uncontrollable airflow, hence taking compensation air from somewhere else reduces drying in areas that are located further away from pressure drop.
- The drying of a sandwich wall is modellable in the case of a 2-dimensional heat/moisture transport and 1-dimensional airflow if there are no significant air leakages.
- Drying in winter requires heating the air that gets sucked into the wall and it is important to maintain relatively high airflow rates in order to avoid air cooling down too much before exiting the wall at the other end. Airflow temperature and airflow rate significantly affect drying speed and final moisture content.
- Air flow rate of the winter drying method which no longer increases the rate of drying significantly is 3 650 l/(min · m^3). If the air inflow temperature is +40 °C then it would take 21 days to dry for an 8 m long, 6 m high and 0.23 m thick wall at the air flow rate 3 650 l/(min · m^3) to dry to humidity content of outside air (t_e -4.4 °C, RH 93 %, ν 3.3 g/m^3) which resulted total moisture content 21.3 g/m^3 per wall volume.
- To achieve the lowest moisture content in the wall it is recommended to reduce the air water vapour content by processing it in an air compressor.
- Air flow rate of the summer drying method which no longer increases the rate of drying significantly is 27 l/(min · m^3). It would take 9 days for an 8 m by 6 m and 0.23 m thick wall at air flow rate 27 l/(min · m^3) to dry to humidity content of compressed outside air (t_e +14.5 °C, RH 7.5 %, ν 0.93 g/m^3) which resulted total moisture content 9.1 g/m^3 per wall volume.
- To increase the rate of drying in summer it would be necessary to develop a device between the air compressor and the wall which acts as an hydrophore meant for air and maintains the pressure and flow of dried air into the wall.

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