FROST FORMATION AND CONDENSATION IN STONE-WOOL INSULANTS – THE COURSE OF MOISTURE RESISTANCE FACTOR

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Keywords: stone wool, material properties, frost formation, condensation, moisture resistance factor

Summary

Globally increasing prices of energy have result in raise of thermal qualities of building envelopes. Consequently, these heavy insulated constructions are facing undesirable phenomena – for instance a risk for occurrence of frost formation and condensation together with a changed thermal field in building constructions. Condensed moisture, as well as moisture trapped in thermal insulations during build-up, can also affect an increased dust contamination, algae or mould growth and structural damages.

This contribution reports on a laboratory experiment aimed at growth of frost formation and moisture condensation in stone wool opened to air for specific temperature fields – namely (+20; -20ºC), (+20; -15ºC), (+20; -10ºC), (+20; -5ºC) over fibrous specimens with varying density. Air on warm side of material samples was saturated with moisture. Frost accumulated with time in the part of specimens facing the cold air. In the part facing the warm humid air a condense formation occurred. The wider thermal field and higher density of material samples we used the more distinct border between frost and liquid condensate we observed. Also moisture resistance factor μ, as a basic moisture characteristic of an insulating material, had an upward trend for broader temperature intervals.

Next to the loss of insulating qualities, annual repetition of condensation and frost growth in stone wool can contribute to degradation of the material structure, thermal losses and, in consequence, higher energy consumption.

1. Introduction

Thermal insulation materials are very important to reduce energy load in both existing and newly built constructions. Especially demands on thermal protection of new buildings have become fundamental. Builders are using more and thicker thermal insulations for walls and roofs. A good thermal insulation should perform, among others, low thermal conductivity, durability, dimension stability, resistance to fire and as low negative impact on the environment and human health as possible. Stone wool - thermal insulation made from molten rocks, meets many of the listed features, though it has also negatives. This fibrous building material is one of the most common thermal insulation spread all over the world. Hand in hand with its great potential and expansion, there is a risk for heavy insulated structures. Thanks to insulation thicknesses a moisture capacity in a wall or roof construction is quite big. No doubt, these energy-saving trends in he building industry are right, but new findings and menace resulting from this design should not be omitted.

As we know from the building practice, thermal insulation materials are always exposed to temperature gradient through their thicknesses and to conditions for moistening and desiccation depending on ambient conditions around the layer of thermal insulation. Moisture can enter constructions via leakage in details of window sill, attics, etc. Constructions can also become wet in case of driven rain, heavy rain showers and snowfall during building processes. At the same time, the finished buildings are hardly permeable for inbuilt moisture even this tightness can worsen in time. As a result, moisture content can slightly grow depending upon actual temperature conditions, so condensation and frost formation are annually repeating in certain seasons (above all in late autumn, winter and early spring) of a year.

This contribution describes research project intent on finding possible changes of moisture properties in stone wool that could affect its future degradation. It also aims at better understanding of creation of frost formation and condensation in a limited time interval.

2. Moisture transport in porous materials

Moisture transport in porous materials is represented by vapour diffusion, surface diffusion and capillary conduction. The executed laboratory tests were based on a fundamental moisture transport theory by diffusion represented by Fick's law and its variations. Moisture flow rate *G* was obtained by laboratory measurement and then used for calculation of diffusive flux g. The point of this computational model is specification of moisture resistance factor μ as the key moisture characteristics.

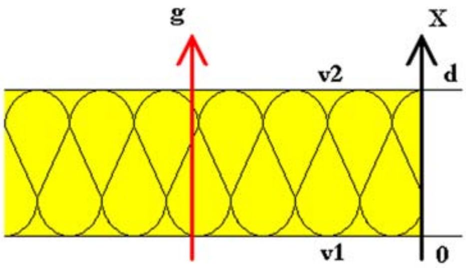

Figure 1 Diffusion of water vapour flux through a layer of stone wool where d is the width of material. Vapour permeability of material is termed δ_v (see Equation 1). Humidity by volume v is kept at v_1 at one side of the layer and at v_2 on the other side. The steady-state diffusive flux is defined as g.

According to Fick's empirical law the steady-state diffusive flux g is:

$$g = \delta_v \cdot \frac{v_1 - v_2}{d} \quad \left[\frac{kg}{m^2 s}\right] \tag{1}$$

Diffusive flux multiplied by cross-section area of the sample gives us moisture flow rate *G*:

$$G = A \cdot g \quad \left[\frac{kg}{s}\right] \tag{2}$$

The rate of diffusion, in the sample can be compared with the one obtained in stagnant air. Introducing the ratio between *D* and δ_v indicates moisture resistance factor μ:

$$\mu = \frac{D}{\delta_v} \quad [-] \tag{3}$$

3. Materials

All material specimens we used for our laboratory measurement were based on stone-wool. They all were commercial products widely used all around the world and taken from a product portfolio of a major producer. Materials with different densities and a varying sphere of use were chosen. Samples were dried and weighed prior to measurements and their dry densities ρ_d were calculated.

The heaviest material sample – SPECIMEN A is primarily used for flat-roof constructions. It is a stiff heavy board of stone wool with integrated double-layer characteristics, which is bonded by organic resin and fully hydrofobised throughout its capacity.

The second fibrous material – SPECIMEN B is a rigid stone-wool board, fully hydrofobised, especially used for flat roofs.

The lightest - SPECIMEN C is a semisoft batt, fully hydrofobised, used for insulating pitched roofs, ventilated facades and sandwich walls.

Table 1 Technical parameters of the used stone wool

Specimen	Declared thermal conductivity λ_D [$Wm^{-1}K^{-1}$]	Dry density ρ_d [kgm^{-3}]
A	0,040	145
B	0,039	112
C	0,035	44

4. Test equipment

At the Department of Civil and Architectural Engineering of the Royal Institute of Technology in Stockholm we designed and built up a special testing device to observe condensation and frost formation in fibrous insulations. The testing set-up consists of a plastic box with open roof, which was replaced by thermal insulation material – stone wool. All specimens were 100mm thick and with surface 300*300mm. Walls and the bottom of the box were insulated with 40 mm thick XPS boards on the outside and coated by an aluminous foil to prevent any weight-gain in surrounding walls caused by moisture uptake from ambient air.

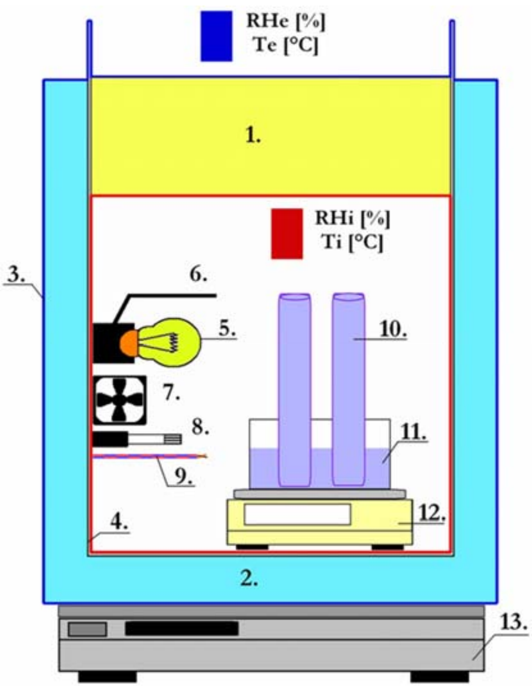

Figure 2 Composition of testing set-up including numbered list of components:

1.material sample (th. 100 mm), 2.XPS insulation of the box-walls (th. 40 mm), 3.aluminium-foil coating, 4.plastic wall of the box, 5.light bulb, 6.cover of the light bulb, 7.ventilation fan providing circulation of air in the testing box, 8.calibrated humidity sensor, 9.temperature sensor, 10.Wettex textile installed to increase evaporation of moisture in the box, 11.water reservoir circa 400 ml, 12.precision laboratory balance registering evaporation of water from the reservoir, 13.precision laboratory balance registering a change of weight of the entire system.

In the box was placed a vessel with water. Volume of water was 400ml. For faster spread of moisture in the box, the water reservoir was settled with two tubes of Wettex textile – a piece of non-woven material based on cellulose with high water retention and water sorption. Evaporating water from the inner reservoir was registered by a precision laboratory balance under the vessel. The box was also equipped with moisture and temperature sensors collecting data about inner conditions (Ti, Rhi). Stable indoor temperature in the box was provided by a light bulb connected to a voltage transformer. Bulb shielding protected specimens from heat radiation. To keep circulation of warm air in the inner space, we used a tiny ventilation fan.

Any weight change of the entire system was registered by another precision balance placed under the testing box. Thanks to both inner and outer balances, it was possible to observe the amount of moisture evaporating in the system and the amount that truly left the system. To control temperature gradient and relative humidity in material specimens, extra three moisture and temperature sensors were installed into outer sides and centre of each material sample, see Figure 3. That gave us a complex view of moisture processes in different altitudes. Moisture leakages in joint around the material sample were denied by sealing with non-absorbent polypropylene tube and silicon bonding agent.

Figure 3 Temperature and humidity sensors placed in material specimen.

The entire testing set-up was placed in a climate chamber with regulated temperature (Te). Conditions in the climate chamber were recorded by another couple of temperature and humidity sensors. Thanks to two pieces of Wettex (mentioned above) the inner volume of the plastic box (30 litres) became saturated by water flux within few minutes. After reaching the saturated state, relative humidity in the box (RHi) remained stable for the rest of the testing interval.

5. Results and discussion

Specimens were tested for four different outdoor temperatures (Te=-20°C, Te=-15°C, Te=-10°C, Te= -5°C), while the indoor temperature was always the same, Ti=+20°C. Each measurement lasted 100 hours. Material samples were cut into pieces in two altitudinal levels just after the testing period and each piece was weighed before drying. This helped us to map an extent of moisture throughout the material.

Water in the upper part of specimens was in form of frost (see Figure 4), while in the lower part it was in form of condensation. Both zones accumulated in time. The frost was equally spread over the depth of tested materials. Growth of frost formation in specimens was clearly visible in cross-sections of material samples A and B (materials with higher densities). There was no visible zone of frost formation and condensation for the specimen C (material with the lowest density) even it occurred.

The collected data were analyzed and charted into figures. Moisture characteristics like moisture flow rate *G* (kg/s), diffusive flux *g* (kg/m^{2}s) and, consequently, moisture resistance factor *μ* (-) were calculated.

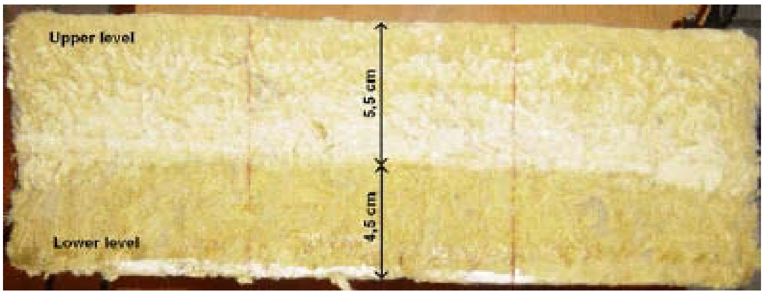

Figure 4 Specimen A - zones of frost formation (upper part) and condensation (lower part).

Measured and calculated data are summarized in Table 2 below. Moisture resistance factors *μ* for all tested materials were highest for outdoor temperature Te=– 20ºC and also the frost formation was most widespread in this case. The frost was stationary, as it is in practical cases, where it does not melt and evaporate until outdoor conditions turn.

Mi factors were compared with standards. They were found 2 times or 2,5 times higher than standard values, that are equal to 1 for both dry or wet mineral wool with density between 10-200 kg/m^3, for the highest temperature gradient through the material (Te=-20°C; Ti=+20°C). Consequently, EN 13162 says:" In the absence of measurements, the moisture resistance factor, *μ*, of mineral wool products, either unfaced or faced with a fabric with an open structure, may be assumed to be equal to 1." Remaining *μ* values for the temperature gradients (Te=-15°C; Ti=+20°C), (Te=-10°C; Ti=+20°C), (Te=-5°C; Ti=+20°C) had a downward trend (see Table 2) towards the tabulated values.

Our previous laboratory measurements for outdoor temperature Te within an interval (+20°C to +5°C) detected *μ* values in the interval <1,13-1,18> for the stone-wool specimen A. We used the same testing set-up, as well as, the same dimensions of material samples. In this case, results coincide with tabulated values introduced in EN standards mentioned above.

Table 2 Experimentally measured moisture resistance factors μ for the specified indoor and outdoor conditions within time interval 100 hours.

SPECIMEN A				
External conditions		Internal conditions		μ [-]
T_e=-20°C	Rh_e=63%	T_i=+20°C	Rh_i=72%	3,05
T_e=-15°C	Rh_e=66%	T_i=+20°C	Rh_i=75%	2,03
T_e=-10°C	Rh_e=72%	T_i=+20°C	Rh_i=78%	1,94
T_e= -5°C	Rh_e=75%	T_i=+20°C	Rh_i=79%	1,46

SPECIMEN B				
External conditions		Internal conditions		μ [-]
T_e=-20°C	Rh_e=66%	T_i=+20°C	Rh_i=72%	2,44
T_e=-15°C	Rh_e=67%	T_i=+20°C	Rh_i=75%	1,82
T_e=-10°C	Rh_e=73%	T_i=+20°C	Rh_i=77%	1,81
T_e= -5°C	Rh_e=75%	T_i=+20°C	Rh_i=80%	1,55

SPECIMEN C				
External conditions		Internal conditions		μ [-]
T_e=-20°C	Rh_e=63%	T_i=+20°C	Rh_i=72%	2,85
T_e=-15°C	Rh_e=68%	T_i=+20°C	Rh_i=75%	1,92
T_e=-10°C	Rh_e=72%	T_i=+20°C	Rh_i=76%	1,65
T_e= -5°C	Rh_e=74%	T_i=+20°C	Rh_i=78%	1,42

Taking into account results from others´ research, water vapour transport properties of stone wool are also influenced by fiber orientation and bulk densities of used specimens.

6. Conclusions

The constructed testing set-up, as well as, the chosen research approach was found effective in the studies of moisture processes in stone-wool based insulating materials. It also proved that the phenomenon of frost formation in the stone wool can exist for specific temperature gradient and moisture load - input conditions we often meet in practice.

Frost formation in the stone-wool samples opened to air was noted in all cases when the temperature field was between (+20 and –20ºC), (+20 and –15ºC), (+20 and –10ºC) and (+20 and -5°C). Air on the warm side was saturated with moisture. In the part of the specimen facing the warm humid air a condense formation occurred. Samples with higher densities (specimen A - ρ_d=145kg/m^3, specimen B - ρ_d=112kg/m^3) were visibly divided into the zone of frost formation and the zone of condensation in the cut. Also in the lightest stone-wool sample (C - ρ_d=44kg/m^3) the frost formation and condensation occurred, but no sharp borderline was observed.

Further studies are relevant in finding why moisture resistance factor (*μ*) in stone wool is comparatively high under circumstances of frost formation and if this can deteriorate in time. Last but not least, consequential degradation of the material structure together with loss of insulating qualities is paramount from the view of new trends in building industry, energy costs and sustainable development.

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