Construction and Building Materials 23 (2009) 1775–1787

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Frost formation and condensation in stone–wool insulations

Tomáš Vrána *, Folke Björk [1]

Department of Civil and Architectural Engineering, Division of Building Materials, KTH Royal Institute of Technology in Stockholm, Brinellvägen 34, 100 44 Stockholm, Sweden

ARTICLE INFO

Article history:
Received 3 September 2007
Received in revised form 14 October 2008
Accepted 24 October 2008
Available online 27 December 2008

Keywords:
Stone–wool
Material properties
Frost formation
Condensation
Moisture transport
Moisture capacity

ABSTRACT

This paper reports on a laboratory experiment concerning frost formation and moisture condensation in fibrous insulation based on stone–wool. Frost formation in samples of stone–wool open to air was noted in cases when temperature field over the specimen was between +20 and −20 °C and air on the warm side was saturated with moisture.

Frost accumulated with time in the part of the specimen facing the cold air. In the part of the specimen facing the warm humid air condense formation occurred. In this part the material had moisture content considerably higher than what could be anticipated from data such as moisture isotherms.

Border between frost and liquid condensate was quite sharp in the specimens of higher density. Moisture content mass by mass has an upward trend with decreasing density of the material sample. Moisture resistance factor was found to be quite high at these circumstances. Reason for this is not clear.

1. Introduction

As the experience from building practice shows, condensation in insulating materials can result in serious reduction of thermal properties and, in consequence, systemic upset of living qualities in dwellings. Moisture in building insulants can also affect an increased dust contamination, algae or mold growth as well as damages due to the frost formation occurring in winter periods.

Aim of this study was to investigate the process of condensation and frost formation in stone–wool materials. Deeper knowledge of this phenomenon is good for insight of processes when high thicknesses of thermal insulation are used in cold climates and moisture might become trapped in the building envelope. The materials studied are insulants with varying densities and intended for particular spheres of use – flat-roof boards, pitched-roof boards and wall boards. Knowing more about water transport and travel of condensate throughout the insulation layer, as well as, formation of frost from inbuilt moisture in stone–wool based products can contribute to sort out what kind of damages mineral–wool may undergo and how moisture may impact durability of a building structure.

The moisture resistance factor, which is indicating how much greater the resistance of a material is compared to an equally thick layer of stationary air at the same temperature [1] as defined below, is detected for tested samples. When temperatures on both sides of a material differ in tens of degrees Celsius, this can result in formation of frost in the material and, in consequence, in discrepancies of moisture properties.

The heat and moisture transport processes in buildings are usually strongly connected to each other. The influence of moisture on thermal conductivity is formalized in the standard ISO 10051.

Studies of moisture transport and absorbent properties of mineral–wool insulants are not as frequent as scientific papers concerning thermal properties. Useful information about moisture dynamics in building envelopes was presented by Peuhkuri [2]. The role of absorbent building materials in moderating changes of relative humidity is described by Padfield [3].

A contribution about coupled heat and moisture transfer through fibrous insulation, which (for the first time) takes into account evaporation and mobile condensates, was elaborated by Fan and Wen [4]. The same authors (et al.) came two years later with an improved model of heat and moisture transfer and its comparison with experimental results [5].

2. Moisture transfer in porous material [6]

Moisture transport in porous materials is represented by vapour diffusion, surface diffusion and capillary conduction. Performed laboratory measurements are based on fundamental moisture transport theory by diffusion. A computational model concerns about the moisture resistance factor μ as a key moisture characteristics (see Fig. 1).

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

$$g = \delta_v \times \frac{v_1 - v_2}{d} \ (\mathrm{kg/(m^2 s)}) \quad (1)$$

* Corresponding author. Tel.: +46 8 790 8721; fax: +46 8 411 8432.
E-mail addresses: tomas.vrana@byv.kth.se (T. Vrána), folke.bjork@byv.kth.se (F. Björk).
[1] Tel.: +46 8 790 8663; fax: +46 8 411 8432.

0950-0618/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conbuildmat.2008.10.014

Nomenclature

A	area (m^2)
c_p	specific heat capacity (J/kg K)
D	coefficient of diffusion water vapour in air (m^2/s)
d	width of a layer (m)
G	moisture flow rate (kg/s)
g	steady-state diffusive flux (kg/m^2 s)
RH_i	relative humidity (%)
RH_e	relative humidity (%)
T	temperature (°C)
T_e	exterior temperature (°C)
T_i	interior temperature (°C)
v	humidity by volume (or water vapour content of air) (kg/m^3)
v_s	humidity by volume at saturation (kg/m^3)
Z	water vapour resistance (s/m)
Greek symbols	
δ_v	vapour permeability (m^2/s)
θ	temperature (°C)
μ	moisture resistance factor (or water vapour diffusion resistance factor) (–)
λ	thermal conductivity (W/mK)
Φ	relative humidity (%)
ρ_d	dry density (kg/m^3)

Diffusive flux multiplied by cross-section surface of a sample gives us moisture flow rate G

$$G = A \times g \text{ (kg/s)} \tag{2}$$

Since moisture flow rate G in our case was obtained by laboratory measurement (see Section 5), we can rearrange Eq. (1) and use it for calculation of g

$$g = \frac{G}{A} \text{ (kg/(m}^2\text{s))} \tag{3}$$

Courses of outdoor temperatures (T_e) and outdoor relative humidity (RH_e), as well as, indoor conditions (T_i, RH_i) were registered by sensors during all measurements and used in particular calculation – for instance in the Ideal gas law, which gives the relation between the vapour content and the partial pressure

$$p_v = 461.4 \times (T + 273.15) \times v \text{ (Pa)} \tag{4}$$

The water vapour content of air, or humidity by volume, is denoted by v (see Eq. (4)). At the same time, relative humidity Φ (RH_i, RH_e were registered during each laboratory measurement) is defined as proportion between humidity by volume and water vapour content in air at saturation v_s

$$\Phi = \frac{v}{v_s}(-) \rightarrow v = \frac{\Phi}{v_s} \text{ (kg/m}^3\text{)} \tag{5}$$

whereas v_s is

$$v_s = \frac{a \times (b + \frac{T}{100})^n}{461.4 \times (T + 273.15)} \text{ (kg/m}^3\text{)} \tag{6}$$

And can be calculated with the appropriate coefficients a, b, n for both outdoor and indoor temperatures (T_e, T_i)

$$\begin{aligned} &0 \leqslant T \leqslant 30\,^\circ\text{C} \quad a = 288.68 \text{ Pa } b = 1.098 \; n = 8.02 \\ &-20 \leqslant T \leqslant 0\,^\circ\text{C} \; a = 4.689 \text{ Pa } b = 1.486 \; n = 12.3 \end{aligned} \tag{7}$$

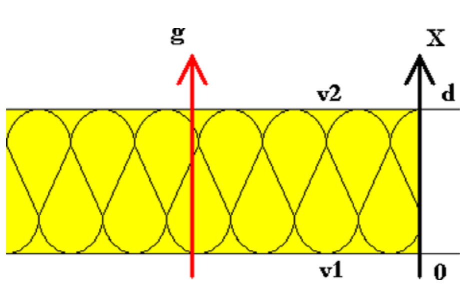

Fig. 1. Diffusion of water vapour flux through a porous material.

Finally, moisture resistance factor μ is defined as

$$\mu = \frac{D}{\delta_v}(-) \tag{8}$$

where vapour permeability δ_v is known from Eq. (1) and coefficient of diffusion water vapour in air D is generally expressed [7]:

$$D = (22.2 + 0.14 \times \theta) \times 10^{-6} \text{ (m}^2\text{/s)} \tag{9}$$

θ is temperature in °C.

The moisture resistance factor μ is defined for an isothermal case. In this study it is a thermal field over the stone–wool specimens. The μ value is here calculated using the value for the coefficient of diffusion D that is valid at the mean temperature of the tested sample.

3. Materials

Material specimens analyzed in this paper are fibrous insulations based on stone–wool. They all are widely used commercial products taken from portfolio of a major producer of thermal-insulation materials. Stone–wool samples of varying densities and specific sphere of use were chosen. Specimens were cut to blocks with following dimensions – 300 mm (length) × 300 mm (width) × 100 mm (thickness). 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 upper highly stiff layer is up to 20 mm thick and provides sturdiness against mechanical stress; $\rho_d = 45$ kg/m^3 (material with the highest content of binders used in the measurement).

The second fibrous material – Specimen B is a rigid stone–wool board, fully hydrofobised, especially used for flat roofs; $\rho_d = 112$ kg/m^3.

The lightest insulant in the laboratory measurement – Specimen C is a semisoft batt, fully hydrofobised, used for insulating pitched roofs, ventilated facades and sandwich walls; $\rho_d = 44$ kg/m^3 (material with the lowest content of binders used in the measurement) (Table 1).

Material specimens were pre-conditioned prior to measurements. They were installed to the testing set-up without moisture load and in advance (12 h) exposed to the set outdoor and indoor conditions. Initial data – e.g. T_e, RH_e, T_i, RH_i, were registered. This was effective and desired material adaptation for the successive laboratory measurement. Detailed description of the experimental part, as well as, extended information on specimen treatment will follow in the next section.