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Comparison of fibrous insulations – Cellulose and stone wool in terms of moisture properties resulting from condensation and ice formation

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ABSTRACT

Cellulose fibres are often used as thermal insulation in buildings. The organic nature of cellulose fibres, however, makes the insulation sensitive to high moisture content. This study investigates the moisture performance of cellulose insulation when exposed to a subzero environment. The paper is focused on the condensation and freezing in the material and includes comparison with the authors previous studies on stone-wool insulation. While the used stone-wool samples were water-repellent due to resin binders, cellulose is a typical representative for hydrophilic thermal insulation to which any contact with water condensate can be crucial.

Test specimens of loose-fill cellulose were placed in a special laboratory device providing high moisture load. During a period of 100 h the specimens were subjected to a continuous load of moisture at atmospheric conditions on one side while the other side of the specimen faced a surrounding temperature of 0, −10 and −20 °C and the laboratory tests were repeated three times for each set of the specific thermal conditions (T_i = +20 °C, T_e = 0, −10 and −20 °C). The results indicate that there are minor changes in the water vapour permeability of the specimens. The experimental data from the investigation is compared with a mathematical model that simulates moisture diffusivity of cellulose together with accumulation due to sorption and freezing, using the actual climatic data.

1. Introduction

Generally speaking, thermal insulation prevents heat from escaping from the building. It has been declared many times (by producers, research community) that insulation materials should be stored in dry places and should be installed in such a manner that moisture will not enter into the insulation system [1]. Anyhow, moisture leakages or problems with built-in moisture have been reported too often to be omitted, especially with a trend towards saving energy and higher thermal demands on new and refurbished buildings. These requirements result in a thicker layer of thermal insulation in building envelopes meaning much higher moisture capacity for a number of thermal-insulation materials (e.g. stone wool, cellulose) that can lead to problems with surplus moisture at the time of erection or during the lifetime of a construction.

Fibrous thermal insulations are widely used thanks to their insulating qualities while being environmentally favourable (e.g. cellulose). At the same time, dampness may alter most of their insulating properties. Hence there is need for reliable data about wet fibrous insulations that can be used in calculations concerning imperfect constructions and case studies aiming at most economical solutions for such problems.

The experimental work on cellulose fibre insulation reported in this paper relates to the laboratory measurements that have been conducted on stone-wool specimens with various densities, presented in [2,3]. It focuses on the issue of moisture transport through loose-fill cellulose to provide the real moisture properties in case of condensation and ice formation in the materials. The tests were done for three different temperature gradients and results were compared with those for stone wool. The next objective was to compare the measured moisture balance results with a functional mathematical model, introduced in [3]. The calculation model is based on the monitored indoor and outdoor data from the laboratory tests and it investigates in detail moisture phases (water, ice) during condensation in the cellulose samples and their possible effect on moisture transport properties.

Moisture transport through building materials for both isothermal and non-isothermal conditions has been the subject of many scientific debates (e.g. Galbraith et al.). Data about response of porous light-weight building materials on non-isothermal moisture transport were gathered by Peuhkuri et al. [7]. The role of absorbent building materials in moderating changes of relative humidity

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Nomenclature

A	water sorption coefficient (kg/m^2 $\sqrt{s}$)
b	thermal conductivity supplement (%/M.-%)
c_p	specific heat capacity (J/kg K)
d	width of a layer (m)
D	coefficient of diffusion water vapour in air (m^2/s)
f_u	moisture conversion coefficient, mass by mass (kg/kg)
F_ψ	moisture conversion coefficient, volume by volume (m^3/m^3)
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)
u, U	Moisture content mass by mass (kg/kg)
v	humidity by volume (or water vapour content of air) (kg/m^3)
v_s	humidity by volume at saturation (kg/m^3)
w	moisture content mass by volume (kg/m^3)
$W_{a,Te}$	moisture content that had accumulated in the material sample during the tested period 100 h for the specific exterior temperature (g)
$W_{d,Te}$	moisture content that had passed through the material in the testing period 100 h for the specific exterior temperature (g)
$W_{e,Te}$	water content that had evaporated from the water reservoir into the box during the tested period 100 h (g)

Greek symbols

δ	water vapour permeability (m^2/s)
μ	moisture resistance factor (or water vapour diffusion resistance factor) (−)
λ	thermal conductivity (W/m K)
λ_0	thermal conductivity of dry building material (W/m K)
ρ_d	dry density (kg/m^3)
ψ	moisture content volume by volume (m^3/m^3)

was described by Padfield [13]. Simultaneous heat and moisture transport in building components below the freezing point was presented by Künzel [8]. Marchand and Kumaran (1994) inspected and elaborated moisture diffusivity of cellulose insulation. A study of effects of hydrophilic additives on moisture and heat transport in mineral wool was conducted by Jiřičková and Černý [15]. All these contributions and findings (and others) were used as a source of information for experimental tests and calculations performed in this paper.

2. Methodology

This study is engaged in the measurements of moisture transport through fibrous thermal insulations when subject to extreme moisture loads. This includes the investigation of the accumulated moisture content and the influences on the water vapour permeability of the materials. The scheduled programme combined laboratory measurements and computer simulations. In this way, it was expected to receive a more complex results seeing that the practical tests can be conducted for a finite time interval. The experimental part was done using a special testing set-up (see Section 2.2) where the material samples were exposed to moisture transport via diffusion. Cellulose samples were tested at three different temperature fields:

(a) $T_e = -20\,^\circ\text{C}, T_i = +20\,^\circ\text{C}$ (b) $T_e = -10\,^\circ\text{C}, T_i = +20\,^\circ\text{C}$ (c) $T_e = -0\,^\circ\text{C}, T_i = +20\,^\circ\text{C}$

For each test conditions, three measurements were applied to provide adequate information for data analysis.

As was stated above, the testing set-up worked with extreme moisture load when the saturated state was reached. Massive liquid condensation in the samples was followed by formation of ice, which was created in time in the upper part of specimens heading exterior temperatures under the freezing point. The interior and exterior conditions (T_i, Rh_i, T_e, Rh_e) as well as moisture balance in the entire testing set-up were registered. In consequence, they were used for calculation of moisture resistance factor, μ. The μ-factor is a basic moisture characteristic indicating permeability of building materials (cellulose and stone wool in this case) in comparison to the diffusion of water vapour in air. The measured outdoor and indoor temperatures and relative humidity were also used as input data for the mathematical model (described in Section 2.3) that aimed at finding possible effect of ice formation on diffuse moisture transport and sorption curves of the listed materials. Please, observe that more attention is paid to results for cellulose insulation and the results for stone wool have just comparative and illustrative function, since they have been presented in the authors' recent contributions, [2,3].

It was presumed that condensation and formation of ice can notably slow down diffusion transport through the cellulose samples for extreme exterior temperatures. At the same time, the next assumption was that most moisture will accumulate in the samples for such conditions. In addition, it was expected that μ-value will increase with the ice formation dominated regime. These hypotheses are discussed later in the paper.

2.1. Material specimens

In the building industry the term 'cellulose' is used for insulation backfilling material. It is a fibre produced from recycled paper. It is treated by boron compounds (borax, boric acid) to make it less flammable and resistant towards microbes, insect and animal pests. Generally, it is delivered loose-filled or pressed in 15 kg bags. Cellulose is mostly used for gap insulations in roofs, walls and floors. They can also be spattered together with water or bonding agent. Typical bulk density of cellulose fibres as thermal insulation varies from 30 kg/m^3 (for loose-fill application) to 90 kg/m^3 (for maximum compaction or application with binders) [4]. In our case we used the bulk density of 32 kg/m^3 according to producer's recommendations for the chosen testing material.

Our previous laboratory tests have inspected stone-wool specimens of various density, [2,3,5]. Stone wool is also a type of fibrous insulation used to prevent heat losses in buildings. In contrast to cellulose, which is organic matter, the stone wool is inorganic material with partial organic content represented by resin binders providing water-repellent function. Thanks to wooden origin the cellulose is a hydrophilic material. In an effort to bring a more complex view on thermal insulations with fibre-like structure and their behaviour under extreme moisture load both data for mineral wool and cellulose are referred-to Table 2.

Samples with the dimensions 300 mm (length) × 300 mm (width) × 100 mm (thickness) were preconditioned. They were weighed prior to measurements and the dry density, ρ_d, was calculated.

There were three moisture and temperature sensors installed directly into outer surfaces and the centre of each material sample. They registered temperature gradient and relative humidity in adjusted intervals (120 s). That gave us a better view of thermal and humid conditions throughout the specimens. Detailed results from the measurement for cellulose, and in consequence, a comparison of moisture balance in both materials respectively is presented later in the paper. And now we put readers' attention to a brief description of the testing set-up.

2.2. Testing set-up

The used testing set-up comprises of a plastic box, two balances, a water reservoir and a material specimen, see Fig. 2 below. The box is insulated by extruded-polystyrene boards on outside to prevent from wall condensation in the box due to temperature gradient. A stable inner temperature T_i = +20 °C is provided by a light bulb attached to one vertical side of the box. The entire set-up was placed in the climate chamber with a preset temperature, T_e.

Measurements were done for three different temperatures of the ambient air in the climate chamber, T_e = −20 °C, T_e = −10 °C, T_e = 0 °C. Water was added to the system via an opening in one wall of the box just before the beginning of the testing period, which lasted for 100 h. The opening for water feed and cabling, as well as, the joint around the tested specimen were sealed and tight. Amount of water that evaporated from the water reservoir $W_{e,Te}$ and amount of moisture that truly left the system were registered $W_{d,Te}$. Accumulated volume of water and ice in the samples, $W_{a,Te}$,was detected via weighing-desiccation-weighing process.

A more detailed description of the testing set-up is given in [5].