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Heat and moisture transfer in fibrous thermal insulation with tight boundaries and a dynamical boundary temperature

Uroš Leskovšek [a,*], Sašo Medved [b]

[a] TRIMO d.d., Prijatljeva 12, 8210 Trebnje, Slovenia
[b] Faculty of Mechanical Engineering, University of Ljubljana, Askerceva 6, 1000 Ljubljana, Slovenia

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ABSTRACT

Prefabricated, lightweight building elements are widely used in the building construction sector. Such elements consist of fibrous thermal insulation encapsulated between two metal sheets. Under various circumstances, moisture can appear in the insulation matrix. Since the temperature of the boundary metal sheets changes dynamically with meteorological conditions, heat and mass transfer between boundaries appear in this case. This paper presents a transient model of the heat and mass transfer, including the sorption and condensation processes. A numerical model considers the dynamical changing of the boundary temperatures. A parametric study considering different amplitudes of temperature change, different moisture masses and different thicknesses of the insulation matrix was made. It was found that a relatively small mass of water in the insulation matrix can result in a significantly increased average heat flux during a periodic cycle. The numerical code was verified with experiments, which showed good agreement with the numerics.

1. Introduction

The envelopes of modern, non-residential buildings, like shopping centers, sport halls and schools are frequently made of façade panels, consisting of two steel facings and a fibrous insulation core. Although the steel facings are impermeable, due to the cracks and flaws in these steel facings, the untight junctions between the façade panels and the inappropriate storage of panels, moisture can appear in the insulation matrix. Furthermore, because of the steel facings' high tightness, the drying of such façade panels is usually not possible. The presence of this moisture in the panel can then result in a physical and chemical deterioration of the insulation matrix and the steel facings, which reduces the life time of the insulation panels. In addition, the insulating properties of the façade panels tend to deteriorate.

Due to the dynamical changing of the meteorological parameters, the temperature of the insulation panels' outer steel facing changes significantly over the period of a day. During the night the outer steel facings' temperature is, due to the lower temperature of the surroundings and the long-wave sky radiation, usually lower than the temperature of the inner steel facing. During the day it is, due to the higher air temperature and the solar radiation, usually higher than the temperature of the inner steel facing. This causes a diffusion mass transfer, accompanied by a latent heat flux in the direction of the outer steel facing during the night and in the direction of the inner steel facing during the day.

Early studies of the coupled heat and mass transfer in porous materials were made by DeVries [1], Luikov [2] and Whitaker [3]. Ogniewicz and Tien [4] determined the importance of latent-heat release during condensation for the overall heat transfer in thermal insulation. Developing their own model, Motakef and El-Masri [5] and Shapiro and Motakef [6] studied condensate accumulation and its movement inside the thermal insulation. A major discrepancy in the temperature profile for their modeling and measurements occurred in the condensation zone. Wijeysundera et al. [7,8] modeled and measuring the quasi-steady heat flux experimentally determined vapor diffusion through fibrous thermal insulation. The warm boundary of the insulation slab was exposed to a flow of moist air and at the cold, impermeable boundary the condensate accumulated. Wijeysundera et al. [9] later upgraded the study by developing a non-stationary numerical model for a determination of the condensate accumulation in the specimen. The model corresponds well with the measured data for the first 70 h of the coupled heat and mass transfer process. Fan et al. [10–14] studied the coupled heat and mass transfer through fibrous textiles. They developed a non-stationary numerical model, which considered the sorption on the fibers and the mobility of the condensate as well. A comparison between the calculation results and the experiments showed a good agreement. Choudhary [15] numerically studied the 2D condensation around a cold pipe and the removal of the condensate by a wick (gravity, capillary action). Olutimayin

* Corresponding author.
E-mail address: uros.leskovsek@fs.uni-lj.si (U. Leskovšek).

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Nomenclature

C	water vapor concentration (kg/m^3)
C_1	mass of liquid water per unit volume (kg/m^3)
C_s	saturation concentration of water–vapor (kg/m^3)
C_{so}	mass of sorbed moisture per unit volume (kg/m^3)
c_p	specific heat capacity at constant pressure (J/kgK)
D_e	effective diffusion coefficient of water–vapor in insulation matrix (m^2/s)
D_{12}	binary diffusion coefficient of water–vapor in air (m^2/s)
h	latent heat (J/kg)
k	thermal conductivity (W/mK)
L	thickness of thermal insulation matrix (m)
m	mass of water per unit area of thermal insulation (g/m^2)
m_w	total mass of water in insulation matrix per unit area of thermal insulation (g/m^2)
$m_{w,cc}$	total mass of water which enables development of the complete evaporation cycle per unit area of thermal insulation (g/m^2)
Q	heat transfer per unit area of thermal insulation (J/m^2)
q	heat flux (W/m^2)
$\dot{q}$	rate of heat generation per unit volume (W/m^3)
T	temperature (°C)
T_0	temperature at the boundary $x = 0$ (°C)
$\overline{T}_0$	average temperature at the boundary $x = 0$ (°C)
T_A	temperature amplitude at the boundary $x = 0$ (°C)
T_L	temperature at the boundary $x = L$ (°C)
t	time (s)
u	moisture content (kg/kg)
x	length scale, coordinate (m)

Greek symbols

Γ	rate of sorption/desorption, condensation/evaporation (kg/m^{3}s)
ε	volume fraction (m^3/m^3)
ρ	density (kg/m^{3}s)
τ	effective tortuosity of the insulation matrix (–)
φ	relative humidity (–)
ω	angular frequency (1/s)

Subscripts

a	air
e	effective
f	dry fibrous thermal insulation
fg	phase change
g	gas
l	liquid
s	solid
so	sorption
v	vapor

and Simonson [16] studied the vapor boundary layer growth in the cellulose insulation. They realized that the moisture transfer and the vapor boundary layer thickness are very sensitive to the sorption curve.

Kumaran [17,18] measured the heat flux through a sealed, moistened specimen of glass-fiber insulation at different constant boundary temperatures. The scheme of a typically determined heat flux history is shown in the Fig. 1. The initial steady state (AB) corresponds to a steady, simultaneous transport of heat and moisture, where the water evaporates at the boundary surface with a higher temperature. The final steady state (CD) corresponds to the heat conduction through a dry specimen. It appears when all the water has condensed at the boundary with a lower temperature. The transition between both states (BC) corresponds to a gradual moving of the drying front in the direction of the boundary with the lower temperature. Hakoi and Kumaran [19] modeled the described process. The modeling and the measurement results corresponded well, except for the transition period between both steady states (BC), where a major discrepancy occurred.

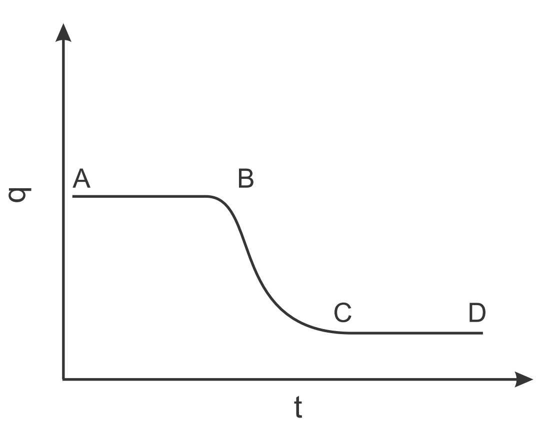

Fig. 1. Heat flux through the specimen as a function of time. Boundary temperatures were constant [18].

Wijeysundera [20] performed similar measurements to those made by Kumaran [17,18] and developed a numerical model. He studied the influence of the initial moisture distribution on the heat flux dynamics after a step change of the boundary temperature. The difference between the heat fluxes he measured and calculated was significant especially in the transition period (Fig. 1 BC). We suppose that one of the reasons for this discrepancy is the neglecting of the sorption process.

Despite the wide use of prefabricated lightweight building elements and the common problem of moisture being present in such elements, we found that the unsteady heat and mass transfer caused by dynamical thermal boundary conditions has not yet been studied in detail, although the dynamical thermal boundary conditions are common for in situ conditions. In our previous research [21] we found that even in the case of a local moisture source, after a few periodic cycles the moisture spreads approximately equal all over the fibrous insulation matrix. Due to that we assume, the mass transfer can be studied one dimensionally. Investigated insulation matrix is made of rock wool.

2. Problem formulation

A one-dimensional, transient model of the coupled heat and mass transfer in a fibrous thermal insulation with impermeable boundaries was developed. Using the model, the heat and moisture transfer as well as temperature and moisture concentration fields in an insulation matrix can be determined for an arbitrary dynamical changing of the boundary temperatures. For the development of the model the assumptions listed below were taken into account.

(1) The insulation matrix is homogenous.
(2) The conduction and water–vapor diffusion are the only transport mechanisms within the fibrous insulation matrix.