International Journal of Heat and Mass Transfer 117 (2018) 273–279

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Transient simulation of coupled heat and moisture flow through a multi-layer porous solid exposed to solar heat flux

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ARTICLE INFO

Article history:
Received 9 August 2017
Received in revised form 2 October 2017
Accepted 2 October 2017

ABSTRACT

The present paper reports the simulation of unsteady coupled moisture and heat transport through a multi-layer porous solid. The governing partial-differential transport equations are written and solved simultaneously for the continuous driving potentials, i.e. relative humidity and temperature. The coupled equations are solved numerically using a singular boundary integral representation of the governing equations. The multi-layer porous solid building elements under study are submitted to convective heat and mass exchange with the surrounding environment and exposed to solar heat flux.

The integral equations are discretized using mixed-boundary elements and a multidomain method also known as the macro-elements technique (Brebbia, 1984 [1], Popov et al., 2007 [2]). The numerical model uses quadratic approximation over space and linear approximation over time for all field functions, which provides highly accurate numerical results.

1. Introduction

Building envelopes are exposed simultaneously to environmental conditions that vary inside and outside. It is known that changes in temperature, moisture and air pressure have a major impact on the sustainability of building components. It is thus important to develop reliable numerical simulation tools that can handle the coupling of heat, air and moisture (HAM) phenomena, and that can accurately capture the hygrothermal behaviour of building components and their influence on both the indoor environment and a building's energy consumption [3–5]. It should be noted that moisture transport through the multi-layer solid walls is a complex phenomenon that involves the coupled transport of liquid, vapour and heat.

It is also known that condensation can damage materials and may have a negative impact on human health [6]. This has motivated the modelling of the hygrothermal and energy performance of buildings, which depends on the very complex interactions between a building and its inside and outside environments. Of those interactions, solar radiation is the main contributor to heat gains in buildings, especially in residential buildings.

A number of calculation methods have been proposed for evaluating the effects of solar radiation when simulating heat transfer through building elements.

Francisco Flor et al. [7] proposed a technique to evaluate the direct, diffused and reflected incident solar radiation for all type of surfaces. This method splits the calculation process into two main steps: a preliminary process to calculate the direct, diffuse and reflected radiation ratios based on different known solar positions and on the characterization of surfaces and volumes, and a post-process to calculate the ratio for each solar radiation component, corresponding to a certain hour, day and month. The proposed methodology was analytically verified and experimentally validated. The results demonstrated the accuracy of the proposed model.

Tamene et al. [8] used a finite difference approach to study heat transfer through a wall with three layers exposed to variable solar flux on the outside, taking into account heat exchanges by convection on both sides.

Shi et al. [9] used the climate data of 35 cities around the world to study the impact of changing the longwave emissivity and solar reflectance of building envelopes on annual air-conditioning energy loads in order to find the most suitable exterior building coating/finishing systems for the various climatic conditions. The results show that the longwave emissivity and solar reflectance of building envelopes both play a significant role in energy-savings in buildings, especially in tropical and in mountain plateau climates.

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https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.010
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Vorre et al. [10] presented a method for calculating the thermal radiant impact on a person for better simulation of thermal comfort in building energy modelling tools. The method is based on a view factor calculation method, using a numerical integration of projected area factor.

Evins et al. [11] implemented some improvements to the longwave exchange processes in the EnergyPlus simulation software that enable a better calculation of the surface temperature. These improvements include assumptions regarding ground temperature and the coupling of other building surfaces. The authors showed that, failure to consider the longwave radiation exchange in sufficient detail can lead to inaccurate temperature predictions.

Since sky radiation models play an important role in the long wave radiation exchange between the opaque surfaces of buildings and their surroundings, Cekon et al. [12] analysed the accuracy level of longwave sky radiation models in the MZELWE simulation module of the ESP-r program. The degree of applicable conformity for the radiation models was determined by comparing the results with real outdoor experimental measurements. The authors concluded that the external surface temperature of the building envelope at night, when there is no solar radiation, could be underestimated if the ESP-r default model is used.

Daouas [13] proposed a dynamic analytical model based on a complex finite Fourier transform technique to simulate the transient heat transfer through multi-layer roofs. In this model, the incident solar radiation, the convection exchange with ambient air, and the longwave radiation exchange with the sky were considered separately. The model was validated using numerical simulations from EnergyPlus software and experimental measurements taken from the literature. The impact of the outside longwave radiation exchange on both the energy requirements and the optimum insulation thickness was evaluated. The results of this study showed that if the longwave radiation is neglected the cooling loads can significantly increase. Based on these results, the author concluded that the energy cost for a building lifetime of 30 years could be overestimated if longwave radiation is not considered in the dynamic simulations, leading to higher values of optimum insulation thickness and energy savings, and shorter payback periods.

In general, most studies that take the solar heat effects into account do not couple the heat and moisture phenomena. However, moisture transfer is highly dependent on the heat diffusion, which includes the solar radiation phenomena. It is also well known that the condensation of moisture promotes the growth of mould and other pathologies.

Tamene et al. [14] uses a finite difference model to study heat and mass transfer through a single layer wall exposed to solar heat flux. In his model, the thermal conductivity, diffusivity, and mass transport coefficient associated with the moisture content gradient were assumed to be constant (linear model). This model also used volumetric moisture content, which would be a discontinuous function in the presence of a multi-layered wall. By comparing the results between the coupling and no coupling heat and mass transfer approaches, Tamene et al. was able to evaluate the influence of the humidity on the temperature and vice versa.

In the present paper, the governing transport partial-differential equations of the transport phenomena are coupled and solved simultaneously for primitive continuous field functions, i.e. temperature and relative humidity. The HAM model accommodates non-linear transport and storage material properties, moisture transport by vapour diffusion, capillary and gravity driven liquid water transport, and convective heat and moisture transport through a multi-layered porous solid [15,16]. In this paper, the partial-differential equations of the transport phenomena are manipulated so as to simulate exposure to solar heat fluxes.

The HAM numerical simulation model used in this study is based on the boundary element method (BEM) using a parabolic diffusion fundamental solution. The numerical model uses a macro-elements approach with quadratic approximation over space and a linear approximation over time for all field functions.

2. Governing transport equations for a two-phase system

The set of partial differential equations governing the transport phenomena of a two-phase thermodynamic system of liquid/-vapour water components in a porous solid of a domain Ω bounded by a surface Γ, can be formulated as follows [4,15], i.e. the moisture diffusion transport equation can be given as,

$$\theta \frac{\partial \varphi}{\partial t} = \vec{\nabla} \cdot \left(D_\varphi \vec{\nabla} \varphi + D_T \vec{\nabla} T - D_l \rho_l \vec{g} \right), \tag{1}$$

where $\theta = dW/d\varphi$ is the slope of the sorption isotherm $W = W(\varphi)$, and the quantities W, T, ρ_l and $\vec{g}$ represent the mass moisture content, temperature, liquid water mass density and the gravity acceleration. The primitive variable in Eq. (1) is the relative humidity field function $\varphi(r_j, t)$. The transport coefficients D_φ and D_T are given as [4,15]:

$$D_\varphi = \delta_p p_s + D_l R_w \rho_l \frac{T}{\varphi} \quad \text{and} \quad D_T = \delta_p \frac{dp_s}{dT} \varphi + D_l R_w \rho_l \ln(\varphi), \tag{2}$$

where the transport properties δ_p and D_l stand for the vapour and liquid permeability of a solid material, defined with the following constitutive models for the vapour diffusion $\vec{j}_v$ and liquid conduction $\vec{j}_l$ mass fluxes:

$$\vec{j}_v = -\delta_p \vec{\nabla} p_v \quad \text{and} \quad \vec{j}_l = -D_l \vec{\nabla} p_l + +D_l \rho_l \vec{g}, \tag{3}$$

where the driving potentials p_v and p_l are the vapour pressure and the pore liquid pressure, respectively, and the quantities R_w and p_s are the water vapour gas constant and the vapour saturation pressure. Eq. (1) is explicitly coupled to the heat energy transport equation due to the temperature gradient term, and implicitly coupled because of the nonlinear transport properties.

The heat energy balance equation considers accumulation within the solid matrix, sensible and latent heat energy fluxes in and out of the control volume, as follows:

$$\rho_m c_{p,eff} \frac{\partial T}{\partial t} = -\vec{\nabla} \cdot \left(\vec{q}_{sens} + \vec{q}_{lat} \right), \tag{4}$$

where the specific capacities per mass $c_{p,eff} = c_{pm} + c_{pl} W/\rho_m, c_{pm}$ and c_{pl} refer to the effective, dry porous material and to liquid water, ρ_m denotes solid matrix mass density, whilst the sensible $\vec{q}_{sens}$ and the latent $\vec{q}_{lat}$ heat energy fluxes are,

$$\vec{q}_{sens} = -\lambda_{eff} \vec{\nabla} T \quad \text{and} \quad \vec{q}_{lat} = h_{lat} \vec{j}_v = \left[h_e + (c_{pv} - c_{pl}) T \right] \vec{j}_v, \tag{5}$$

where h_{lat} denotes specific latent enthalpy, h_e is the specific latent enthalpy of evaporation or condensation, c_{pv} stands for the specific heat per mass of water vapour, and the thermal conductivities $\lambda_{eff} = \lambda_m + \lambda_{mst} W/\rho_l$ and λ_m refer to the effective and dry porous material, respectively. Substituting heat flux Eq. (5) into conservation Eq. (4) gives

$$c_{eff} \frac{\partial T}{\partial t} = \vec{\nabla} \cdot \left[\lambda_{eff} \vec{\nabla} T - h_{lat} \vec{j}_v \right], \tag{6}$$

where the coefficient $c_{eff} = \rho_m c_{p,eff}$ is the effective specific heat per unit volume.