An Analysis of Transport Phenomena in Multi-layered Walls Exposed to Hot Gas

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Abstract

This study was to develop a mathematical model in which a coupled heat and mass transfer was simulated in multi-layered walls exposed to hot gas. The different multi-layered walls with gravitational force were studied. The multi-layered wall was assumed to act as an unsaturated porous medium. The governing equations were solved by using Newton-Raphson method based on a finite volume technique. The present numerical model was validated against the results of the previous Results were in good agreement. published work. Effects of the prescribed boundary conditions and initial saturations on associated variables, *i.e.*, internal total pressure, temperature and moisture content, were also studied. It was found that the pressure, temperature, and saturation distribution within the given conditions varied according to time and distance. Particle size and thermal properties of walls profoundly affected the mechanisms of heat and of mass transfer. Regarding the flux vector, the results clearly indicated the magnitudes and the directions of mass movements. These findings were significant for further research development conducted in the similar patterns as well as for the applications of the porous media

Keywords: Porous Medium, Heat and Mass Transfer, Numerical Method, Multi - layered walls

1. Introduction

Drying process of porous media is a complicated process because it involves simultaneous, coupled heat and mass transfer phenomena. Heat and mass transfer that occurs during convective drying of porous materials is crucial. An application of such knowledge can result in a reduction of energy cost of drying, equipment and process design, and can preserve the quality of products. The analysis of heat and mass transfer in porous materials has been subjected of theoretical and experimental work for several decades. Most theories have been proposed to explain the physical phenomena of drying process in porous materials: the diffusion theory, the capillary flow theory and the evaporation-condensation theory. A convenient starting point of drying theory was found, in the work of Whitaker [1] who has derived appropriate locally volume averaged conservation equations for twophase capillary flow in porous media. The mathematical models for simultaneous heat and mass transfer during convective drying of porous media have been studied by many authors [2-12]

However, previous studies dealed mostly with the drying of uniform materials. Indeed, little effort has been reported on the study of drying process of nonuniform material. The knowledge of heat and mass transfer that occurs during convective drying of multilayered porous materials is necessary to provide a basis for fundamental understanding of convective drying of non-uniform materials. There is one published study conducted by Plumb et al. [13] of heat and mass transport in non-uniform material. Recently, Ratanadecho et al. [14] have carried out the first systematical study on a drying process of multi-layered packed bed by microwave energy. The effects of particle size and the layered structure on the overall drying kinetics have been studied This paper is an experimental study of heat and mass transfer in non-uniform material, and supporting numerical work...

In this study, a mathematical model, simulating the coupled heat and mass transfer in one dimensional multi-layered walls exposed to hot gas, has been developed. This study emphasizes the influence of particle size and layered structure effect in heat and mass transport phenomena. This study significantly simulates the timely combination of the magnitude and direction within fluid movements in each phase in the permeable heated multi-layered walls at various times. This model yields a number of considerations of changes in internal total pressure, temperature, and saturation during the hot gas exposure.

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2. Governing equation



Figure 1. Physical model of multi-layered wall exposed to fire.

By conservation of mass and energy in multi-layered wall, the main basic governing equation of mass and energy for all phases can be derived using finite control volume method. The microscopic mass conservation equations for liquid, water vapor, air and gas phases, are written, respectively, as:

Liquid phase

$$\rho_I \phi \frac{\partial s}{\partial t} + \rho_I \frac{\partial u_I}{\partial x} + \rho_I \frac{\partial w_I}{\partial z} = -n \tag{1}$$

Vapor phase

$$\frac{\partial}{\partial t} \{ \rho_V \phi (I - s) \} + \frac{\partial}{\partial x} [\rho_V u_V] + \frac{\partial}{\partial z} [\rho_V w_V] = n$$
(2)

Air phase

$$\frac{\partial}{\partial t} \{ \rho_a \phi(I - s) \} + \frac{\partial}{\partial x} [\rho_a u_a] + \frac{\partial}{\partial z} [\rho_a w_a] = 0$$
(3)

Gas phase

$$\frac{\partial}{\partial t} \left\{ \rho_g \phi (l - s) \right\} + \frac{\partial}{\partial x} \left[\rho_g u_g \right] + \frac{\partial}{\partial z} \left[\rho_g w_g \right] = n \tag{4}$$

Moisture Equation:

The phenomenon of moisture transport is described by the mass conservation equations for the liquid phase and the water vapor portion of the gas phase since it is the total water content that is of interest, these equations in one-dimensional forms can be added together to yield an equation for the total moisture content as follows :

$$\varphi \frac{\partial}{\partial t} \{s + Y_{v}(l - s)\} + \frac{\partial}{\partial z} \left[\frac{KK_{rl}}{\mu_{l}} \left(\frac{\partial p_{c}}{\partial z} - \frac{\partial p_{g}}{\partial z} + g_{z} \right) + Y_{v} \frac{KK_{rg}}{\mu_{g}} \left(-\frac{\partial p_{g}}{\partial z} + \rho_{g} g_{z} \right) - Y_{g} D_{m} \frac{\partial}{\partial z} (w_{v}) \right] = 0$$
(5)

Total Pressure Equation:

The partial pressure of the vapor is given by Kelvin's equation considered the capillary force defined by :

$$\phi \frac{\partial}{\partial t} \{Y_a(1-s)\} + \frac{\partial}{\partial z} \left[Y_a \frac{KK_{rg}}{\mu_g} \left(-\frac{\partial \rho_g}{\partial z} + \rho_g g_z \right) - Y_g D_m \frac{\partial}{\partial z} \left(\frac{\rho_a}{\rho_g} \right) \right] = 0 \quad (6)$$

Energy equation:

The temperature of the wall exposed the hot air stream with fixed characteristics is obtained by solving the conventional heat transport equation considering the enthalpy transport based on the water and gas flows, the conduction heat and latent heat transfer due to evaporation, the energy conservation equation is represented by :

$$\frac{\partial}{\partial t} \left\{ \left(\rho c_{p} \right)_{T} T \right\} + \frac{\partial}{\partial z} \left[\left\{ \rho_{l} c_{pl} w_{l} + \left(\rho_{a} c_{pa} + \rho_{v} c_{pv} \right) w_{g} \right\} T \right] \\
= \frac{\partial}{\partial z} \left[\lambda \frac{\partial T}{\partial z} \right] \\
- h_{lv} \left\{ \frac{\partial}{\partial t} \left\{ \rho_{v} \phi (1-s) \right\} + \frac{\partial}{\partial z} \left[\rho_{v} \frac{KK_{rg}}{\mu_{g}} \left(-\frac{\partial P_{g}}{\partial z} + \rho_{g} g_{z} \right) \right] \\
- \rho_{g} D_{m} \frac{\partial}{\partial z} \left(\frac{\rho_{v}}{\rho_{g}} \right) \right] \right\}$$
(7)

State Equations:

The gas phase is assumed to be an ideal mixture of perfect gases, so that the species density can be determined by the state equations, with the classical definitions for total density of the gas, ρ_g , and the mass average velocity of the gas .[15]

Phenomenological and Equilibrium Relations:

Darcy's law:

In order to complete the system of equations, the expressions for the superficial average velocity of the liquid and gas phases the generalized Darcy's law in the following form is used [1]:

$$\overline{u}_{I} = -\frac{KK_{rI}}{\mu_{I}} \left[\nabla p_{g} - \nabla p_{c} - \rho_{I} \vec{g} \right]$$
(8)

$$\overline{u}_g = -\frac{KK_{rg}}{\mu_g} \left[\nabla p_g - \rho_I \overline{g} \right] \tag{9}$$

Fick's law:

For the velocity of vapor water and air phase the generalized Fick's law for a two-component gas mixture can be expressed as [16]:

$$\rho_{\nu}\vec{u}_{\nu} = \rho_{\nu}\vec{u}_{g} - \rho_{g}D_{m}\nabla\left(\frac{\rho_{\nu}}{\rho_{g}}\right)$$
(10)

$$\rho_a \vec{u}_a = \rho_a \vec{u}_g - \rho_g D_m \nabla \left(\frac{\rho_a}{\rho_g}\right) \tag{11}$$

$$P_c = P_g - P_l \tag{12}$$

$$D_m = \frac{2\psi}{3 - \phi} (1 - s) D \tag{13}$$

$$k_{rI} = S_e^3 \tag{14}$$

$$k_{rg} = (I - s_e)^{S} \tag{15}$$

$$S_e = \frac{S - S_{ir}}{I - S_{ir}} \tag{16}$$

$$\lambda = \frac{0.8}{1 + 3.78e^{-5.95s}} \tag{17}$$

After manipulation, and give

$$\frac{\rho_a}{\rho_1} = Y_a$$

$$\frac{\rho_v}{\rho_1} = Y_v, \quad \frac{\rho_g}{\rho_1} = Y_g, \quad \frac{Y_v}{Y_g} = W_v \quad (18)$$

we obtained the moisture equation:

$$\phi \frac{\partial}{\partial t} \{ s + Y_{v}(l - s) \} + \frac{\partial}{\partial x} \left[\frac{KK_{rl}}{\mu_{g}} \left(\frac{\partial p_{c}}{\partial x} - \frac{\partial p_{g}}{\partial x} + g_{x} \right) + Y_{v} \frac{KK_{rg}}{\mu_{I}} \left(-\frac{\partial p_{g}}{\partial x} + \rho_{g} g_{x} \right) - Y_{g} D_{m} \frac{\partial}{\partial x} (W_{v}) \right] + Y_{v} \frac{KK_{rg}}{\mu_{g}} \left(-\frac{\partial p_{g}}{\partial z} + \rho_{g} g_{z} \right) - Y_{g} D_{m} \frac{\partial}{\partial z} (W_{v}) \right] = 0$$
(19)

After manipulation, we obtained the gas pressure equation:

$$\phi \frac{\partial}{\partial t} \{Y_a (l - s)\} + \frac{\partial}{\partial x} \left[Y_a \frac{KK_{rg}}{\mu_l} \left(-\frac{\partial p_g}{\partial x} \right) - Y_g D_m \frac{\partial}{\partial x} \left(\frac{\rho_a}{\rho_g} \right) \right] = 0 \quad (20)$$

Also, for the energy equation:

$$\frac{\partial}{\partial t} \left[\left(\rho_{I} c_{pI} \varphi s + \left\{ \left(\rho c_{p} \right)_{a} + \left(\rho c_{p} \right)_{v} \right\} \varphi (I - s) + \rho_{p} c_{pp} (I - \varphi) \right] T \right] \\ + \frac{\partial}{\partial x} \left[\left\{ \rho_{I} c_{p1} u_{I} + \left(\rho_{a} c_{pa} + \rho_{v} c_{pv} \right) u_{g} \right\} T \right] = \frac{\partial}{\partial x} \left[\lambda \frac{\partial T}{\partial x} \right] -$$

$$h_{I\nu} \Biggl\{ \frac{\partial}{\partial t} \{ \rho_{\nu} \phi (1-s) \} + \frac{\partial}{\partial x} \Biggl[\rho_{\nu} \frac{KK_{rg}}{\mu_{g}} \Biggl(-\frac{\partial P_{g}}{\partial x} + \rho_{g} g_{z} \Biggr) - \rho_{g} D_{m} \frac{\partial}{\partial x} \Biggl(\frac{\rho_{\nu}}{\rho_{g}} \Biggr) \Biggr] \Biggr\}$$
(21)

Boundary Conditions and Initial Conditions

The boundary conditions proposed for the permeable surface, for the exchange of energy at the open boundary can be described as in the following:

$$-\lambda \frac{\partial T}{\partial z} = h_{\mathcal{C}} \left(T - T_{\infty} \right) + \varepsilon \sigma \left(T_{fire}^{4} - T^{4} \right)$$
(22)

Mass transfer at the permeable surface is modeled by means of a locally constant mass transfer coefficient, which is related to the local water vapor flux density:

$$\rho_I w_I + \rho_V w_V = h_{MS} (\rho_{VS} - \rho_{V\infty})$$
⁽²³⁾

The mass transfer coefficient at the permeable surface or upper surface depends on the surface saturation coefficient which varies with varying average water saturation. The total pressure at permeable surface can be defined as:

$$P_g = P_0 \tag{24}$$

The capillary pressure, mass transfer and temperature are assumed to be continuous at the interface of layered wall:

$$p_{c,F} = p_{c,C} \tag{25}$$

$$\rho_l w_{l,F} = \rho_l w_{l,C} \tag{26}$$

$$\rho_g w_{g,F} = \rho_g w_{g,C} \tag{27}$$

$$T_F = T_C \tag{28}$$

3. Numerical Method

The coupled non-linear set of heat and mass equations with regard to water saturation or pressure of gas phase, P_g and temperature, T, were solved numerically by using the finite control volume. The advantage of this method is that it ensures flux conservation, and thus avoiding generation of parasitic sources. This leads to the solution which is sufficiently converged. The basic strategy of finite control volume discretization method is to divide the calculated domain into a number of control volumes and then integrate the conservation equations over this control volume over an interval of time. At the boundaries of the calculated domain, the conservation equations were discretized by integrating over half the control volume and by taking into account the boundary conditions. At the corners of the calculated domain we used a quarter of control volume. At each increment time, the nodal value of moisture content, pressure of gas phase and temperature were solved iteratively and convergence was checked on both variables. The Newton-Raphson method was employed at each iteration to quicker the convergence.

From moisture transport equation, applied volume average technique, we obtained:

$$\begin{split} \frac{\phi}{\Delta t} & \left\{ (1-s_{ir})(s_{ek}^{n+1}-s_{ek}^{n}) + (1-s_{ir})(Y_{vk}^{n+1}(1-s_{ek}^{n+1})) \right\} \\ & -Y_{vk}^{n}(1-s_{ek}^{n}) \\ & -Y_{vk}^{n}(1-s_{ek}^{n}) \\ & -\frac{KK_{rl}}{\mu_{l}} \bigg|_{k+\frac{1}{2}} \left(\frac{P_{ck+1}^{n+1}-P_{ck}^{n+1}}{\Delta z} - \frac{P_{gk+1}^{n+1}-P_{gk}^{n+1}}{\Delta z} + g_{z} \right) \\ & -\frac{KK_{rl}}{\mu_{l}} \bigg|_{k-\frac{1}{2}} \left(\frac{P_{ck}^{n+1}-P_{ck-1}^{n+1}}{\Delta z} - \frac{P_{gk}^{n+1}-P_{gk-1}^{n+1}}{\Delta z} + g_{z} \right) \\ & +\frac{1}{\Delta z} \left\{ +Y_{vk}^{n+1} \left[\frac{KK_{rg}}{\mu_{g}} \bigg|_{k+\frac{1}{2}} \left(\frac{-P_{gk+1}^{n+1}+P_{gk-1}^{n+1}}{\Delta z} + \rho_{g}g_{z} \right) \\ & -\frac{n+1}{\rho_{vk-1}} \frac{KK_{rg}}{\mu_{g}} \bigg|_{k-\frac{1}{2}} \left(\frac{-P_{gk}^{n+1}+P_{gk-1}^{n+1}}{\Delta z} + \rho_{g}g_{z} \right) \\ & -\frac{n+1}{mk+\frac{1}{2}} \left(\frac{w_{vk+1}^{n+1}-w_{vk-1}^{n+1}}{\Delta z} \right) \\ & = 0 \end{split} \right\}$$

$$\begin{split} \frac{(\rho c_{p})_{Tk}^{n+1} - (\rho c_{p})_{Tk}^{n}}{\Delta t} &+ \frac{\rho_{l} c_{pl}}{\Delta z} \left(w_{lk}^{n+1} T_{k}^{n+1} - w_{lk-1}^{n+1} T_{k-1}^{n+1} \right) \\ &+ \frac{(\rho c_{p})_{av}}{\Delta z} \left(w_{gk}^{n+1} T_{k}^{n+1} - w_{gk-1}^{n+1} T_{k-1}^{n+1} \right) \\ &- \frac{1}{\Delta z} \left[\lambda_{n+1}^{n+1} \left(\frac{T_{k+1}^{n+1} - T_{k}^{n+1}}{\Delta z} \right) - \lambda_{n-1}^{n+1} \left(\frac{T_{k}^{n+1} - T_{k-1}^{n+1}}{\Delta z} \right) \right] \\ &+ \frac{h_{lv} \rho_{v} \phi}{\Delta t} \left\{ (1 - s_{ir}) (s_{ek}^{n+1} - s_{ek}^{n}) \right\} \\ &+ \frac{h_{lv} \rho_{v} \phi}{\Delta t} \left\{ (1 - s_{ir}) (s_{ek}^{n+1} - s_{ek}^{n}) \right\} \\ &- \frac{1}{\Delta z} \left\{ \begin{pmatrix} \rho_{vk}^{n+1} \frac{KK_{rg}}{\mu_{g}} \\ - \rho_{vk-1}^{n+1} \frac{KK_{rg}}{\mu_{g}} \\ R - \frac{1}{2} \begin{pmatrix} -P_{gk+1}^{n+1} + P_{gk-1}^{n+1} \\ \Delta z \end{pmatrix} - \rho_{vk-1}^{n+1} \frac{KK_{rg}}{\mu_{g}} \\ - \rho_{vk-1}^{n+1} \frac{\rho_{gk}^{n+1} \rho_{gk}^{n+1} - \left(\frac{\rho_{v}}{\rho_{g}} \right)_{k+1}^{n+1} - \left(\frac{\rho_{v}}{\rho_{g}} \right)_{k}^{n+1} \\ - \rho_{gk-1}^{n+1} \rho_{gk-1}^{n+1} \\ - \rho_{gk-1}^{n+1} \rho_{gk-1}^{n+1} \frac{\left(\frac{\left(\frac{\rho_{v}}{\rho_{g}} \right)_{k+1}^{n+1} - \left(\frac{\rho_{v}}{\rho_{g}} \right)_{k-1}^{n+1} - \left(\frac{\rho_{v}}{\rho_{g}} \right)_{k-1}^{n+1} \\ - \rho_{gk-1}^{n+1} \rho_{gk-1}^{n+1} \frac{\left(\frac{\left(\frac{\rho_{v}}{\rho_{g}} \right)_{k}^{n+1} - \left(\frac{\rho_{v}}{\rho_{g}} \right)_{k-1}^{n+1} - \left(\frac{\rho_{v}}{\rho_{g}} \right)_{k-1}^{n+1} \\ - \rho_{gk-1}^{n+1} \rho_{gk-1}^{n+1} \frac{\left(\frac{\left(\frac{\rho_{v}}{\rho_{g}} \right)_{k}^{n+1} - \left(\frac{\rho_{v}}{\rho_{g}} \right)_{k-1}^{n+1} - \left(\frac{\rho_{v}}{\rho_{g}} \right)_{k-1}^{n+1} \\ - \rho_{gk-1}^{n+1} \rho_{gk-1}^{n+1} \frac{\left(\frac{\rho_{v}}{\rho_{g}} \right)_{k}^{n+1} - \left(\frac{\rho_{v}}{\rho_{g}} \right)_{k-1}^{n+1} \\ - \rho_{gk-1}^{n+1} \rho_{gk-1}^{n+1} \frac{\left(\frac{\rho_{v}}{\rho_{g}} \right)_{k}^{n+1} - \left(\frac{\rho_{v}}{\rho_{g}} \right)_{k-1}^{n+1} \\ - \rho_{gk-1}^{n+1} \rho_{gk-1}^{n+1} \frac{\left(\frac{\rho_{v}}{\rho_{g}} \right)_{k}^{n+1} - \left(\frac{\rho_{v}}{\rho_{g}} \right)_{k-1}^{n+1} \\ - \rho_{gk-1}^{n+1} \rho_{gk-1}^{n+1} \frac{\rho_{v}}{\rho_{g}} \right\} \right\}$$

= 0

$$\begin{aligned} & \text{total pressure equations} \\ & \frac{\phi}{\Delta t} \left\{ (1 - s_{ir}) \left[(Y_{vk}^{n+1} (1 - s_{ek}^{n+1}) - Y_{vk}^{n} (1 - s_{ek}^{n}) \right] \right\} \\ & + \left[\left\{ \begin{array}{c} \left\{ Y_{ak}^{n+1} \left[\frac{KK_{rg}}{\mu_g} \right]_{k+\frac{1}{2}} \left(\frac{-P_{gk+1}^{n+1} + P_{gk}^{n+1}}{\Delta z} + \rho_g g_z \right) \right] \\ & - \frac{KK_{rg}}{\mu_g} \right]_{k-\frac{1}{2}} \left[\frac{-P_{gk}^{n+1} + P_{gk-1}^{n+1}}{\Delta z} + \rho_g g_z \right] \right] \\ & + \frac{1}{\Delta z} \left\{ - \frac{N_{gk}^{n+1}}{Rk + \frac{1}{2}} \left[\frac{\left(\frac{\rho_a}{\rho_g} \right)_{k+1}^{n+1} - \left(\frac{\rho_a}{\rho_g} \right)_{k}^{n+1} \right] \\ & - \frac{N_{gk}^{n+1}}{Rk + \frac{1}{2}} \left[\frac{\left(\frac{\rho_a}{\rho_g} \right)_{k+1}^{n+1} - \left(\frac{\rho_a}{\rho_g} \right)_{k-1}^{n+1} \right] \\ & - \frac{N_{gk}^{n+1}}{Rk - \frac{1}{2}} \left[\frac{\left(\frac{\rho_a}{\rho_g} \right)_{k}^{n+1} - \left(\frac{\rho_a}{\rho_g} \right)_{k-1}^{n+1} \right] \\ & - \frac{N_{gk}^{n+1}}{Rk - \frac{1}{2}} \left[\frac{\left(\frac{\rho_a}{\rho_g} \right)_{k}^{n+1} - \left(\frac{\rho_a}{\rho_g} \right)_{k-1}^{n+1} \right] \\ & - \frac{N_{gk}^{n+1}}{Rk - \frac{1}{2}} \left[\frac{\left(\frac{\rho_a}{\rho_g} \right)_{k}^{n+1} - \left(\frac{\rho_a}{\rho_g} \right)_{k-1}^{n+1} \right] \\ & - \frac{N_{gk}^{n+1}}{Rk - \frac{1}{2}} \left[\frac{\left(\frac{\rho_a}{\rho_g} \right)_{k}^{n+1} - \left(\frac{\rho_a}{\rho_g} \right)_{k-1}^{n+1} \right] \\ & - \frac{N_{gk}^{n+1}}{Rk - \frac{1}{2}} \left[\frac{\left(\frac{\rho_a}{\rho_g} \right)_{k}^{n+1} - \left(\frac{\rho_a}{\rho_g} \right)_{k-1}^{n+1} \right] \\ & - \frac{N_{gk}^{n+1}}{Rk - \frac{1}{2}} \left[\frac{\left(\frac{\rho_a}{\rho_g} \right)_{k}^{n+1} - \left(\frac{\rho_a}{\rho_g} \right)_{k-1}^{n+1} \right] \\ & - \frac{N_{gk}^{n+1}}{Rk - \frac{1}{2}} \left[\frac{\left(\frac{\rho_a}{\rho_g} \right)_{k}^{n+1} - \left(\frac{\rho_a}{\rho_g} \right)_{k-1}^{n+1} \right] \\ & - \frac{N_{gk}^{n+1}}{Rk - \frac{1}{2}} \left[\frac{\left(\frac{\rho_a}{\rho_g} \right)_{k}^{n+1} - \left(\frac{\rho_a}{\rho_g} \right)_{k-1}^{n+1} \right] \\ & - \frac{N_{gk}^{n+1}}{Rk - \frac{1}{2}} \left[\frac{\left(\frac{\rho_a}{\rho_g} \right)_{k}^{n+1} - \left(\frac{\rho_a}{\rho_g} \right)_{k-1}^{n+1} \right] \\ & - \frac{N_{gk}^{n+1}}{Rk - \frac{1}{2}} \left[\frac{\left(\frac{\rho_a}{\rho_g} \right)_{k}^{n+1} - \left(\frac{\rho_a}{\rho_g} \right)_{k-1}^{n+1} \right] \\ & - \frac{N_{gk}^{n+1}}{Rk - \frac{1}{2}} \left[\frac{\left(\frac{\rho_a}{\rho_g} \right)_{k}^{n+1} - \left(\frac{\rho_a}{\rho_g} \right)_{k-1}^{n+1} \right] \\ & - \frac{N_{gk}^{n+1}}{Rk - \frac{1}{2}} \left[\frac{\rho_a}{Rk - \frac{1}{2}} \left[\frac{\rho_a}{Rk - \frac{1}{2}} \right] \\ & - \frac{N_{gk}^{n+1}}{Rk - \frac{1}{2}} \left[\frac{\rho_a}{Rk - \frac{1}{2}} \left[\frac{\rho_a}{Rk - \frac{1}{2}} \right] \\ & - \frac{N_{gk}^{n+1}}{Rk - \frac{1}{2}} \left[\frac{\rho_a}{Rk - \frac{1}{2}} \left[\frac{\rho_a}{Rk - \frac{1}{2}} \right] \\ & - \frac{N_{gk}^{n+1}}{Rk - \frac{1}{2}} \left[\frac{\rho_a}{Rk - \frac{1}{2}}$$

Also, for heat transport equation, for internal node, applied volume average technique:



Figure 2. Computational scheme.

To verify the accuracy of the presented numerical study, its result is validated against the results obtained by J.A. Rogers et.al. [5]. Figure 3a shows the predicted result [5] and Figure 3b shows the results from the presented mode. Both are in good agreement.



Figure 3 Saturation profiles with respect to elapsed time: a. Predicted result from J.A. Rogers et.al. [5] b. Predicted result from presented mode

4. Result and Discussion

In one dimensional porous multi-layered walls exposed to hot gas, one surface of the wall (z = 0 cm) is exposed to hot gas at 170 °C and another surface (z = 20 cm) remains under atmospheric conditions, allowing heat and mass to freely transfer from the medium to the surrounding as shown in Figure 1. This study is a simulation of 3 types of porous materials: light concrete, brick, and sandstone. The transport phenomena in the

two-layered porous walls is analyzed. First, the composite wall of brick-light concrete-and of sandstone-light concrete are arranged; and the wall of light concrete-light concrete and brick-brick. For the two-layered wall with different types of material but the same particle size -0.25 mm. in diameter - is investigated in order to see the result from layered structure. For the two-layered wall with the same types of material but different particle sizes -0.15 mm. and 0.40 mm. - are investigated in order to see the result from the sizes of particle. Table 1 shows thermal properties used in the calculation.

Table 1. Thermal properties used in the calculation.

Item	Notation	Light	Brick	sandstone
		concrete	[18]	[19]
		[17]		
Density	ρ	960	1800	2718
$[\text{kg}/\text{m}^3]$	-			
Specific heat		1825	1200	816
capacity	Ср			
[J / kg-K]	υŗ			
Thermal	k	1.88	1.80	1.852
conductivity				
[W / m-K]				
Permeability	K	$1.1 \text{X} 10^{-12}$	2.5X10 ⁻¹²	1.68X10 ⁻¹¹
$[m^2]$				
Porosity	ϕ	0.16	0.26	0.379

The results of this study can be summarized as follows:

Results of heat and mass transfer in a multi-layered wall with same types of porous material

Since the multi-layered walls with similar types of porous maternal but different particle sizes, the saturation within the finer layer is higher during the initial drying process and the saturation is not continuous as measured at the interface of layered wall as shown in Figure 4. Because its capillary pressure within the fine layer is higher than that within the coarse layer, the liquid flows from the coarse layer to the fine one.

Figure 6 shows a rapid increase of gas pressure distribution within the fine layer. The gas pressure at the fine layer is higher due to its higher porosity. Also, the density of the material of the wall has high effects on the gas pressure; the higher density of the material causes lower gas pressure; therefore, the increase of gas pressure depends on the density of the material. Changes of temperature within the multi-layerd wall with the same type of material – the wall of light concrete, *i.e.*, light concrete and the wall of brick, *i.e.*, brick – are similar in terms of temperature distribution and degree as illustrate in Figures 8-9. This is due to the similarlity in thermal properties of the brick and light concrete used in the calculation. As the temperature is higher, the saturation averagely decreases. Therefore, the multi-layered wall with different size of particles has more effects on mass transfer than on thermal properties.

Results of heat and mass transfer in a multi-layered wall with different types of porous material.

For multi-layered with different types of porous material with the same size of particle, Figure 5 shows that the distribution of saturation within porous layer varies continuously. The decrease of liquid causes change of saturation. Liquid movement is driven mainly by capillary force. Later, the drying rate decreases rapidly since the saturation of porous wall decreases. It was found that there was no different between the gas pressure distributions in each layer in the wall of brickconcrete from Figure 7. In each layer, the difference was trivial because of the same paticle size. Result of calculation of temperature in different material reveal similarity of distribution in the same material.

In order to see the fluid movement, by using flux vector, in the initial time, at 2 hours, the liquid flux moved from cold surface to hot surface. Vapor flux moved into cold surface due to the evaporation at the evaporation front. It is interesting seen from Figure 10 that in concreteconcrete wall, liquid flux started moving from the interface, while in brick-concrete wall from Figure 11, the liquid flux was from the cold surface. So, mass transfer in multi-layered wall with different material but the same size of particles is similar as in the one-layer wall. This is because the same size of particle causes similar capillary force. Six hours later, the vapor flux was higher because of the evaporation, see Figures 12 and 13.



Figure 4. Saturation distribution between concreteconcrete wall with different particle sizes.



Figure 5. Saturation distribution between brick-concrete wall with the same particle sizes.



Figure 6. Gas pressure distribution between concreteconcrete wall with different particle sizes.



Figure 7. Gas pressure distribution between brickconcrete wall with the same particle sizes.



Figure 8. Temperature distribution between concreteconcrete wall with different particle sizes.



Figure 9. Temperature distribution between brickconcrete wall with the same particle sizes.



Figure 10. Fluid movement pattern in concrete –concrete wall at 2 hours.



Figure 11. Fluid movement pattern in brick –concrete wall at 2 hours.



Figure 12. Fluid movement pattern in concrete –concrete wall at 6hours.



Figure 13. Fluid movement pattern in brick –concrete wall at 6 hours.

5. Conclusion

The distribution of gas pressure, temperation, saturation and mass transfer in multi-layered walls can be covered by mass conservation law, energy conservation law, Darcy's law, Fick's law under the given condition. Mass transfer is caused by capillary force, mass diffusion, phase change, gradient of gas pressure and the gravitational force. When multi-layered wall is exposed to hot gas, liquid existing in the pore moves to hot surface. While vapor that evaporates on evaporation front moves to the cold surface, the gas condenses into liquid along the colder path. When dry zone occurs, some vapor moves to hot surface because of the pressure gradient. In addition, air moves to hot surface to fill the void.

The important factors controlling the heat and mass transfer within the multi-layered walls exposed to hot gas include amount of the heat, porosity of the wall, initial saturation, thermal properties with regard to thermal conductivity and density of wall structure.

Notation

 D_m = effective molecular mass diffusion (m²/s)

S = water saturation

 $T = \text{temperature } (^{\circ}\text{C})$

- H_v = specific heat of vaporization (J/kg)
- t = time (s)
- p = pressure (Pa)
- n = phase change term (kg/m³s)
- w =velocity (m/s)
- λ = effective thermal conductivity (W/mK)
- $k = \text{permeability} (\text{m}^2)$
- ϕ = porosity
- g = gravitational constant (m/s²)
- ρ = density (kg/m³)
- μ_l = dynamic viscosity of liquid (Pa s)
- μ_g = dynamic viscosity of gas (Pa s)
- h_c = heat transfer constant (W/m²K)
- h_m = mass transfer constant (W/m²K)

Subscripts

r= relativep= particlea= airv= water vaporc= capillary,coarsel= liquid waterg= gasF= fine

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