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Analysis of moisture migration in two-dimensional unsaturated porous media with impermeable boundaries

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Abstract—The problem of the simultaneous heat and mass transfer in a two-dimensional unsaturated medium is studied using analytical and numerical methods. The porous medium has impermeable boundaries and is subjected to two commonly encountered thermal boundary conditions. The conservation equation for the temperature field is solved using the Laplace transform technique to obtain a series solution. The steady-state moisture solution is obtained from the steady-state temperature field using a mathematical theorem derived earlier by the authors (*Int. J. Heat Mass Transfer* **31**, 2587–2589 (1988)). In order to obtain the moisture field at intermediate times, a numerical solution is obtained of both the temperature and the moisture fields. The results for the case of the application of a constant heat flux at the left wall show a more rapid migration of the moisture compared to the results of a step change in temperature at the left wall. An increase in the Luikov number causes a more rapid migration of the moisture in the porous medium, whereas, an increase in the aspect ratio reduces the moisture migration activity. Finally, the development of a dryout region within the porous medium is observed.

INTRODUCTION

THE PHENOMENON of the moisture migration in an unsaturated porous medium which involves the combined heat and mass transfer with phase change occurs frequently in nature as well as in various engineering processes. Movement of moisture in soil and insulation material, drying and wetting processes in the chemical industry are just a few examples. An analysis of this phenomenon is complicated by various factors. The structure of the solid matrix in a porous medium varies widely in shape and size. It may, for instance, be composed of cells, fibers or grains. The randomly distributed voids in the unsaturated porous medium contain different distributions of moisture (in liquid and/or vapor phase) and air. Heat transfer in such a medium occurs by conduction in all the phases, as well as by advection in the fluid phases. Mass transport also occurs between the voids in the medium.

The porous medium, considered for this analysis, contains water as the liquid and air as the gas. Evaporation or condensation occurs at the interface between the water and the air so that the air is always mixed with a certain amount of water vapor. The mixture of air and water vapor may flow due to imposed pressure differences, whereas the liquid transport may be either due to pressure differences or gravity, or due to capillary, intermolecular or osmotic forces.

A detailed study of the transport processes occurring within the solid matrix and in the voids is, therefore, very complicated even for a regularly shaped matrix. The normal procedure in such a case is to consider the porous medium as a continuum. The heat and mass transfer processes then have to be described by conservation equations. It should be noted that the material strength of the medium does strongly vary with the structure of the porous medium, the moisture content, and the applied boundary conditions.

The general problem of the moisture movement in soils was investigated by Philip and De Vries [1]. More recently, the problem has been extensively studied by several investigators [2–6]. Eckert and co-workers [2–4] investigated the one-dimensional geometry both analytically and numerically. Prat [5] considered the cylindrical geometry and conducted both experiments and a numerical simulation of the problem. Shen and Ramsey [6] numerically studied moisture migration in a two-dimensional unsaturated porous medium. In their work the soil water matrix potential was used as the dependent variable and one of the surfaces of the medium was permeable to moisture flow. A general mathematical theorem to determine the steady-state moisture profile in an unsaturated porous medium with impermeable boundaries, knowing only the steady-state temperature profile, was obtained in ref. [7]. Furthermore, the possibility of the existence of a dryout region for given material properties, initial

NOMENCLATURE

$A_{m,n}$	$(m^2+n^2)/R^2$
$A_{m-1/2,n}$	$((m-1/2)^2+n^2)/R^2$
D_T	thermal mass diffusion coefficient [$m^2 s^{-1} {}^\circ C^{-1}$]
D_M	moisture mass diffusion coefficient [$m^2 s^{-1}$]
Fo	Fourier number, $\alpha\tau/L_x^2$
K_h	hydraulic conductivity [$m s^{-1}$]
K_T	thermal conductivity [$W m^{-1} {}^\circ C^{-1}$]
L_x, L_y	lengths in the x- and y-directions, respectively
Lu	Luikov number, D_m/α
q_0	left wall heat flux for Case B [$W m^{-2}$]
$\bar{q}_0$	dimensionless heat flux, $q_0 L_x/K_T \Delta T$
R	aspect ratio of the medium, L_y/L_x
T_i	initial temperature [°C]
T_0	left wall temperature for Case A [°C]
ΔT	reference temperature difference ($=(T-T_i)$ for Case A; $= T_i$ for Case B)
W	moisture concentration, ρ_l/ρ_{dry}
W_i	initial moisture concentration
x, y	space variables for the two-dimensional geometry
X, Y	dimensionless space variables.

Greek symbols

α	thermal diffusivity [$m^2 s^{-1}$]
η	dimensionless hydraulic conductivity, $K_h L_x^2/D_M L_y$
ρ_{dry}	dry medium density [$kg m^{-3}$]
ρ_l	moisture (liquid) density [$kg m^{-3}$]
τ	time variable [s]
Ψ_M	dimensionless moisture concentration, $(D_M(W-W_i))/D_T \Delta T$
Ψ_T	dimensionless temperature, $(T-T_i)/\Delta T$.

Other symbols

∇^2	dimensionless Laplacian operator
$\langle\ \rangle$	volume average.

moisture concentration and thermal boundary conditions can be predicted.

At the time of construction, the building insulation materials that contain pores having moisture in them, are sandwiched between impermeable vapor barriers. The moisture trapped in the sandwiched porous material gets redistributed due to changes in ambient temperature. The redistribution of moisture within the porous medium will affect its mechanical strength. The present study involves a transient analysis of moisture migration in two-dimensional rectangular porous media with impermeable boundaries. The model equations are based on the mechanistic approach of Philip and De Vries [1]. The model equations used by Shen and Ramsey [6] are written in terms of solid water matrix potential. This work, therefore, differs from that of Shen and Ramsey [6] both in scope and in approach. This analysis will be carried out to determine the detailed moisture contours, both under transient conditions and at steady-state conditions. The applicability of such an analysis is in knowing the shapes of the contours as the initial moisture content of the porous medium undergoes a redistribution under certain imposed boundary conditions. Consideration is given to two commonly encountered thermal boundary conditions. In the first case the left wall is heated by subjecting it to a step change in temperature, and in the second, to a step change in heat flux. These heating conditions may occur on the outside of the insulation blanket either on the ceiling or on the side walls. To make the analysis tractable, the following simplifying assumptions are made. The medium is treated as being homogeneous and isotropic. The thermophysical properties of the porous medium are assumed to remain constant. The variation of pressure within the porous medium is neglected.

PROBLEM FORMULATION

Based on the discussion in the previous section, the governing equations for the transient heat and mass transfer in terms of dimensionless coordinates (Fig. 1) can be written as

$$\frac{\partial \Psi_T}{\partial Fo} = \nabla^2 \Psi_T \quad (1)$$

$$\frac{1}{Lu}\frac{\partial \Psi_M}{\partial Fo} = \nabla^2 \Psi_M + \frac{\partial \Psi_T}{\partial Fo} \quad (2)$$

in terms of the storage and diffusion terms, where

$$\nabla^2 = \frac{\partial^2}{\partial X^2} + \frac{1}{R^2}\frac{\partial^2}{\partial Y^2}.$$

As stated earlier, consideration is given to two different boundary conditions which are as follows.

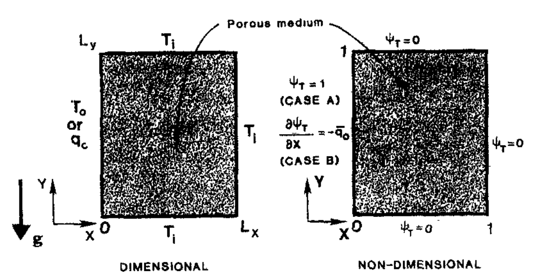

FIG. 1. Two-dimensional porous medium.

Case A: left wall subjected to step change in temperature

$Fo = 0$: $\Psi_T = 0, \Psi_M = 0$ for all X and Y

$Fo \geqslant 0^+$: $\Psi_T = 1$ for $X = 0$ and all Y

$\Psi_T = 0$ for $X = 1$ and $Y = 0, 1$

$$\left.\begin{aligned} &\frac{\partial \Psi_M}{\partial X} + \frac{\partial \Psi_T}{\partial X} = 0 \text{ at } X = 0, \text{ 1 and all } Y \\ &\frac{\partial \Psi_M}{\partial Y} + \frac{\partial \Psi_T}{\partial Y} = 0 \text{ at } Y = 0, \text{ 1 and all } X \end{aligned}\right\} \text{the impermeable boundary condition at the walls.} \quad (3)$$

Case B: left wall subjected to step change in heat flux

$Fo = 0$: $\Psi_T = 0, \Psi_M = 0$ for all X and Y

$Fo \geqslant 0^+$: $\frac{\partial \Psi_T}{\partial X} = -\bar{q}_0$ for $X = 0$ and all Y

$\Psi_T = 0$ for $X = 1$ and $Y = 0, 1$

$$\left.\begin{aligned} &\frac{\partial \Psi_M}{\partial X} + \frac{\partial \Psi_T}{\partial X} = 0 \text{ at } X = 0, \text{ 1 and all } Y \\ &\frac{\partial \Psi_M}{\partial Y} + \frac{\partial \Psi_T}{\partial Y} = 0 \text{ at } Y = 0, \text{ 1 and all } X \end{aligned}\right\} \text{the impermeable boundary condition at the walls.} \quad (4)$$

The gravity effect will be reflected by the presence of an additional term in the moisture equation (equation (2)) as

$$\frac{1}{Lu}\frac{\partial \Psi_M}{\partial Fo} = \nabla^2 \Psi_M + \frac{\partial \Psi_T}{\partial Fo} - \eta \frac{\partial \Psi_M}{\partial Y} \quad (5)$$

where η is the dimensionless hydraulic conductivity (K_h).

SOLUTION SCHEME

The governing equations (equations (1) and (2)) are parabolic in time and elliptic in space. The solution of the moisture equation (2) is dependent on that of the temperature equation (1). For practising engineers, both the transient and steady-state moisture fields are of interest. Preliminary computations showed that the temperature field reaches steady state in a relatively short time, whereas it takes a rather long time for the moisture field to reach steady state. The temperature equation (1) is amenable to analytical solution techniques like the Laplace transform method. The solutions for the temperature equation with the two sets of boundary conditions are obtained using the Laplace transform technique as follows.

Case A

$$\Psi_T(X, Y, Fo) = \frac{4}{\pi} \sum_{n=1,3,5} \frac{\sinh[(1-X)n\pi/R]}{n \sinh(n\pi/R)} \times \sin(n\pi Y) - \frac{8}{\pi^2} \sum_{n=1,3,5}^{\infty} \sum_{m=1}^{\infty} \frac{m \sin(m\pi X) \sin(n\pi Y)}{n A_{m,n}} \times \exp(-A_{m,n}\pi^2 Fo). \quad (6)$$

Case B

$$\Psi_T(X, Y, Fo) = \frac{4R\bar{q}_0}{\pi^2} \sum_{n=1,3,5}^{\infty} \frac{\sinh[(1-X)n\pi/R]}{n^2 \cosh(n\pi/R)} \sin(n\pi Y) - \frac{8\bar{q}_0}{\pi^3} \sum_{n=1,3,5}^{\infty} \sum_{m=1}^{\infty} \frac{\cos[(m-1/2)\pi X] \sin(n\pi Y)}{n A_{m-1/2,n}} \times \exp(-A_{m-1/2,n}\pi^2 Fo). \quad (7)$$

It should be recalled that the theorem derived in ref. [7] enables one to predict the steady-state moisture profile by knowing only the steady-state temperature profile for impermeable boundaries. The theorem states that the non-dimensional steady-state moisture (Ψ_M) and temperature (Ψ_T) profiles are related by $\Psi_M = -\Psi_T + \langle \Psi_T \rangle$, irrespective of the thermal boundary conditions, domain geometry, and dimensionality of an unsaturated porous medium with impermeable boundaries, provided that the steady-state temperature profile (Ψ_T) exists. Accordingly, the steady-state moisture profiles for both boundary conditions are given below.

Case A

$$\Psi_M(X, Y) = -\frac{4}{\pi} \sum_{n=1,3,5}^{\infty} \frac{\sinh[(1-X)n\pi/R] \sin(n\pi Y)}{n \sinh(n\pi/R)} + \frac{8R}{\pi^3} \sum_{n=1,3,5}^{\infty} \frac{\cosh(n\pi/R) - 1}{n^3 \sinh(n\pi/R)}. \quad (8)$$

Case B

$$\Psi_M(X, Y) = -\frac{4R\bar{q}_0}{\pi^2} \sum_{n=1,3,5}^{\infty} \frac{\sinh[(1-X)n\pi/R] \sin(n\pi Y)}{n^2 \cosh(n\pi/R)} + \frac{8R^2\bar{q}_0}{\pi^4} \sum_{n=1,3,5}^{\infty} \frac{\cosh(n\pi/R) - 1}{n^4 \cosh(n\pi/R)}. \quad (9)$$

Although the above expressions represent closed-form solutions for the steady-state moisture profiles, the moisture contours at intermediate times are not determinable using these expressions. Hence, a numerical method was adopted to solve the complete transient equations (equations (1) and (2)) for both the temperature and the moisture fields in the porous medium.

The governing equations and the boundary con-

Table 1. Properties for loose sand [2]

$\alpha = 1.4 \times 10^{-7}\ \mathrm{m^2\,s^{-1}}$
$K_T = 0.52\ \mathrm{W\,m^{-1}\,{}^\circ C^{-1}}$
$D_T = 0.954 \times 10^{-11}\ \mathrm{m^2\,s^{-1}\,{}^\circ C^{-1}}$
$D_M = 1.185 \times 10^{-9}\ \mathrm{m^2\,s^{-1}}$
$Lu = D_M/\alpha = 0.00846$
$K_h = 1 \times 10^{-8}\ \mathrm{m\,s^{-1}}$

ditions were discretized in a finite-difference scheme using the ADI (alternating direction implicit) method. Using a grid-independence study, a (41 × 41) grid for the X–Y directions was adopted. Therefore, the spatial step size ($\Delta X = \Delta Y$) would be 0.025 and a time step size (ΔFo) of 0.00135 ($\Delta\tau = 2.68$ h) was found to yield a non-oscillating, stable solution.

RESULTS AND DISCUSSION

An examination of the governing equations (equations (1) and (2)) reveals that, the aspect ratio (R) and Luikov number (Lu) are the independent parameters. Calculations were made for loose sand with material properties given in Table 1.

The geometrical parameters of the two-dimensional medium and two specific cases of imposed boundary conditions are

$$L_x = L_y = 1\ \mathrm{m}, \quad R = \frac{L_y}{L_x} = 1.$$

Case A

$$T_i = 25^\circ\mathrm{C},\ T_0 = 60^\circ\mathrm{C},\ W_i = 0.1\ (10\%).$$

Case B

$$T_i = 25^\circ\mathrm{C},\ q_0 = 250\ \mathrm{W\,m^{-2}},\ W_i = 0.1\ (10\%).$$

The steady-state condition for the temperature profiles was defined as the time step beyond which the values of the temperatures at a location did not differ by more than 1%. These time steps for Cases A and B were found to be 263 and 538, respectively. The corresponding values of Fo are 0.3551 and 0.7263, respectively. The transient moisture profiles (contour lines of constant moisture) for Case A are shown in Figs. 2–5. The moisture profiles are shown after a passage of 11.16 and 111.6 days, respectively, in Figs. 2 and 4, without the gravity effect. The moisture contours exhibit a symmetric nature with respect to the centerline ($Y = 0.5$) and reach higher concentrations away from the left wall where the heating boundary condition has been applied. This migration of the moisture is more towards the cooler surface, which is the inside of the building in the summer, or the outside of the building in the winter. The gravity effect, which is controlled by the value of the dimensionless hydraulic conductivity, η, of the porous medium and which, in turn, depends on the pore distribution, induces a downward migration of the moisture. This causes a higher accumulation of the moisture to occur at the bottom wall compared to the top, as can be seen in Figs. 3 and 5. This effect will be even more pronounced for larger initial moisture concentrations. The moisture contours for Case B with gravity effect are shown in Figs. 6 and 7. It is evident from Figs. 6 and 7 that moisture near the heated left wall at earlier times (11.16 days) penetrates into the medium with time (60.04 days). As the heating continues, the moisture concentration goes to zero near the left wall, while it accumulates near the left top and bottom corners. The moisture concentration in the left corners are highest in the medium. This pattern of moisture migration is explained by the fact that the moisture concentration flux is proportional to the temperature gradient and this gradient is a minimum in the central ($Y = 0.5$) region due to symmetry. Comparing Cases

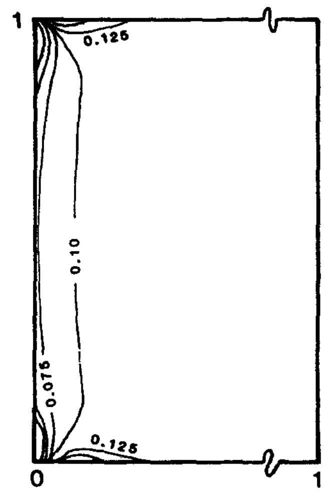

FIG. 2. Moisture contour after 11.16 days ($Fo = 0.1351$) without gravity effect. Case A: left wall subjected to step change in temperature.

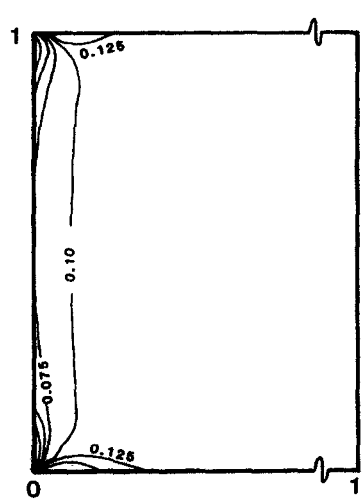

FIG. 3. Moisture contour after 11.16 days ($Fo = 0.1351$) with gravity effect. Case A: left wall subjected to step change in temperature.

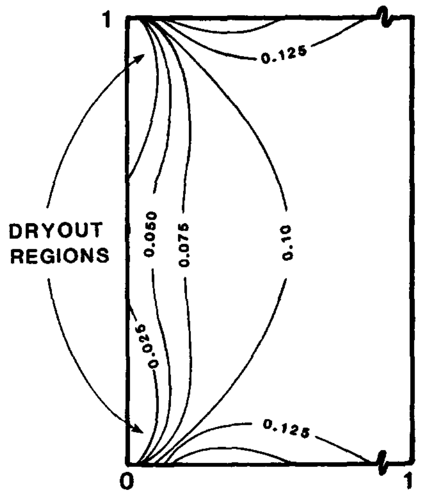

FIG. 4. Moisture contour after 111.6 days ($Fo = 1.3507$) without gravity effect. Case A: left wall subjected to step change in temperature.

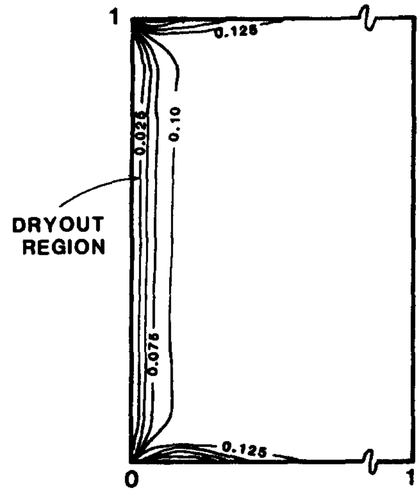

FIG. 6. Moisture contour after 11.16 days ($Fo = 0.1351$) with gravity effect. Case B: left wall subjected to step change in heat flux.

A and B, there is a more rapid moisture activity in the latter case, and this, of course, would depend on the heating intensity, q_0.

It can also be observed that a dryout region (where the moisture concentration goes to zero) begins to develop from the left two corners of the porous medium for Case A (Figs. 4 and 5), while it seems to begin at the central core region for Case B (Figs. 6 and 7). The extent to which this region will develop is dependent on the magnitude of the step change in the wall temperature or the heat flux at the left wall, the initial moisture concentration and the Luikov number. There is a detailed discussion on the determination of the dryout region and its extent in ref. [7].

The effect of a change in the value of Luikov number is illustrated in Figs. 8 and 9. Figure 8 shows the moisture contours with a five-fold increase in Luikov number for Case A (compare with Fig. 2). The penetration of the moisture further into the porous medium is evident. The Luikov number effect is more graphically illustrated by the shorter number of days the moisture takes to reach zero concentration at a given location in Fig. 9. This also shows that for a given geometry a quicker dryout will be achieved in the porous medium at higher Luikov numbers. On the other hand, for a given material an increase in the aspect ratio, R, of the porous medium delays the dryout process, as can be seen from the increased number of days the moisture takes to reach zero concentration at a given location (Fig. 10).

CONCLUSIONS

Moisture migration in an unsaturated two-dimensional porous medium is primarily governed by the

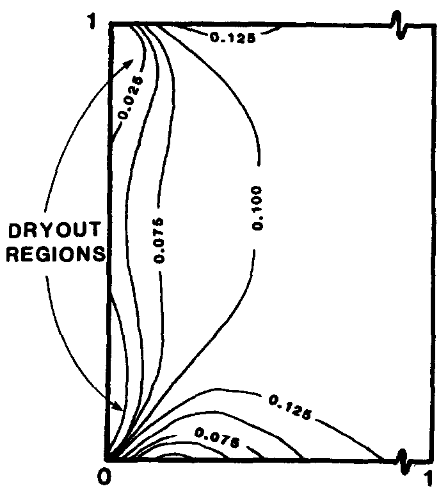

FIG. 5. Moisture contour after 111.6 days ($Fo = 1.3507$) with gravity effect. Case A: left wall subjected to step change in temperature.

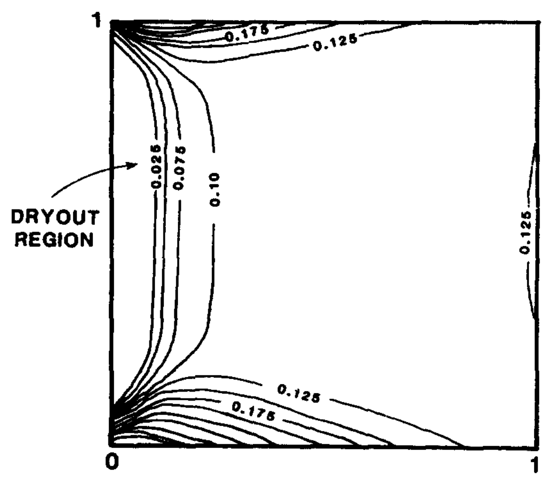

FIG. 7. Moisture contour after 60.04 days ($Fo = 0.7267$) with gravity effect. Case B: left wall subjected to step change in heat flux.

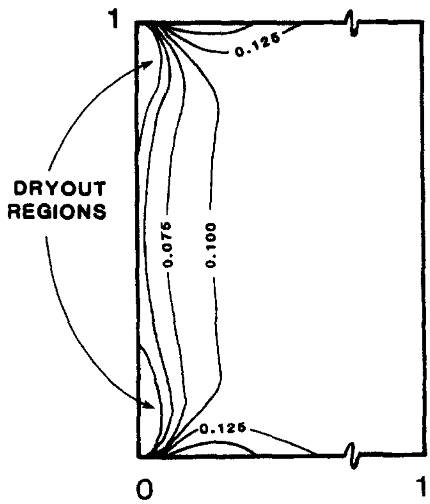

FIG. 8. Moisture contour after 11.16 days ($Fo = 0.1351$) without gravity effect, $Lu = 5(0.00846)$. Case A: left wall subjected to step change in temperature.

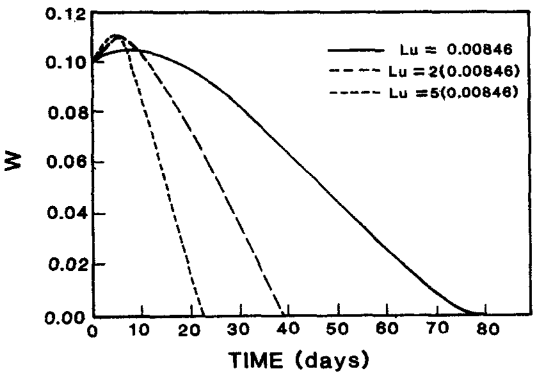

FIG. 9. Drying transient for different Luikov numbers at $(X, Y) = (0.1, 0.5)$. Case A: left wall subjected to step change in temperature.

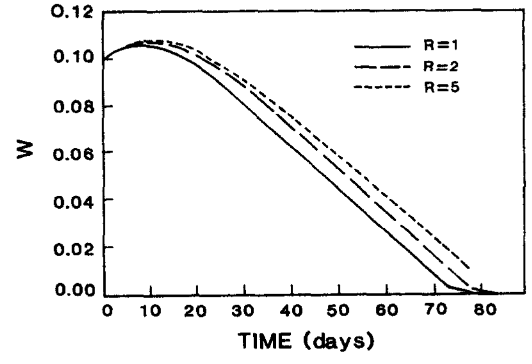

FIG. 10. Drying transient for different aspect ratios at $(X, Y) = (0.1, 0.5)$. Case A: left wall subjected to step change in temperature.

imposed heating intensity, the initial moisture concentration, and the thermo-physical properties of the medium such as the mass diffusion coefficient and the thermal diffusion coefficient. It has been shown that the imposed boundary condition of a step change in wall temperature or wall heat flux with impermeable boundaries lends itself to a closed-form analytical solution for the transient temperature field (equations (6) and (7)) and the steady-state moisture field (equations (8) and (9)). Numerical solutions have also been obtained for the detailed contour plots of the temperature and moisture fields at intermediate times before the steady-state condition is reached. The dimensionless results for Case B (application of a constant heat flux at the left wall) showed a more rapid migration of the moisture compared to those for Case A (step change in temperature at the left wall). The physical values of moisture transport, of course, would depend on the level of the heating intensity.

The effect of including the gravity term in the mass diffusion equations was to cause a greater accumulation of the moisture near the bottom wall compared to the top wall. An increase in the Luikov number causes a more rapid migration of the moisture in the porous medium.

Finally, the development of a dryout region within the porous medium has been observed for both cases. The extent of the development depends, primarily, on the physical properties of the medium, the externally imposed boundary conditions, and the initial moisture concentration.

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ANALYSE DE LA MIGRATION D'HUMIDITE DANS DES MILIEUX POREUX BIDIMENSIONNELS NON SATURES, AVEC DES FRONTIERES IMPERMEABLES

Résumé—Le problème des transferts simultanés de chaleur et de masse dans un milieu bidimensionnel et non saturé est étudié en utilisant des méthodes analytique et numérique. Le milieu poreux a des frontières imperméables et il est soumis aux deux conditions aux limites thermiques usuelles. L'équation de bilan pour le champ de température est résolu, par la transformation de Laplace, en une solution en série. La solution stationnaire d'humidité est obtenue à partir du champ de température stationnaire en exploitant un théorème mathématique établi ultérieurement par les auteurs (*Int. J. Heat Mass Transfer* **31**, 2587–2589 (1988)). De façon à atteindre le champ d'humidité à différents instants, une solution numérique est obtenue à la fois pour les champs de température et d'humidité. Les résultats, dans le cas d'un flux thermique constant appliqué sur la paroi à gauche, montrent une migration plus rapide de l'humidité par comparaison aux résultats d'un changement de température en échelon sur cette paroi. Un accroissement du nombre de Luikov provoque une migration plus rapide de l'humidité dans le milieu poreux, tandis qu'une augmentation du rapport de forme réduit la migration. Finalement est observé le développement de la région séche dans le milieu poreux.

ANALYSE DES FEUCHTIGKEITSTRANSPORTS IN ZWEIDIMENSIONALEN UNGESÄTTIGTEN PORÖSEN MEDIEN MIT UNDURCHLÄSSIGEN BEGRENZUNGEN

Zusammenfassung—Das Problem des gleichzeitigen Wärme- und Stofftransports in einem zweidimensionalen ungesättigten porösen Medium wird mit analytischen und numerischen Methoden untersucht. Das poröse Medium hat undurchlässige Begrenzungen und ist zwei häufig auftretenden thermischen Randbedingungen unterworfen. Bei der Erhaltungsgleichung für das Temperaturfeld wird die Laplace-Transformation angewandt, um eine Reihenlösung zu erhalten. Im stationären Zustand erhält man die Lösung für die Feuchtigkeit aus dem stationären Temperaturfeld, indem ein mathematisches Verfahren angewandt wird, das schon früher von den Autoren vorgestellt wurde (*Int. J. Heat Mass Transfer* **31**, 2587–2589 (1988)). Um das Feuchtigkeitsfeld für mittlere Zeiten zu erhalten, wird das Temperatur- und das Feuchtigkeitsfeld numerisch berechnet. Bei konstanter Wärmestromdichte an der linken Wand ergibt sich ein schnellerer Feuchtigkeitstransport als bei einer sprunghaften Änderung der Temperatur an der linken Wand. Eine Zunahme der Luikov-Zahl bewirkt einen schnelleren Feuchtigkeitstransport in dem porösen Medium, wogegen eine Vergrößerung des Seitenverhältnisses den Feuchtigkeitstransport herabsetzt. Schließlich wird die Entwicklung eines austrocknenden Gebietes innerhalb des porösen Mediums beobachtet.

АНАЛИЗ ПЕРЕНОСА ВЛАГИ В ДВУМЕРНЫХ НЕНАСЫЩЕННЫХ ПОРИСТЫХ СРЕДАХ С НЕПРОНИЦАЕМЫМИ ГРАНИЦАМИ

Аннотация—Аналитически и численно исследуется задача взаимосвязанного тепло- и массопереноса в двумерной ненасыщенной пористой среде. Пористая среда имеет непроницаемые границы, на которых ставятся обычно используемые граничные условия двух родов. Для получения решения в виде ряда уравнение сохранения энергии решается методом преобразований Лапласа. Решение для стационарного влагопереноса найдено на основе стационарного температурного поля с использованием ранее выведенной авторами математической теоремы. (*Int. J. Heat Mass Transfer* **31**, 2587–2589 (1988)). Для расчета поля влагосодержания при промежуточных значениях времени получено численное решение полей температуры и влажности. Результаты решения в случае постоянного теплового потока на левой стенке указывают на более интенсивный перенос влаги, чем результаты при ступенчатом изменении температцры на этой же стенке. При увеличении числа Лыкова скорость влагопереноса в пористой среде возрастает, в то время как при увеличении отношения сторон эта скорость снижается. Наблюдается также развитие критической зоны в пориэтой среде.