THERMAL NON-EQUILIBRIUM HEAT TRANSFER IN A POROUS CAVITY IN THE PRESENCE OF BIO-CHEMICAL HEAT SOURCE

by

Mohsen NAZARI*, Esmaeel Shakeri NEJAD, and Mohhamad Hasan KAYHANI

Department of Mechanical Engineering, University of Shahrood,
Shahrood, Iran

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This paper is concerned with thermal non-equilibrium natural convection in a square cavity filled with a porous medium in the presence of a biomass which is transported in the cavity. The biomass can consume a secondary moving substrate. The physics of the presented problem is related to the analysis of heat and mass transfer in a composting process that controlled by internal heat generation. The intensity of the bio-heat source generated in the cavity is equal to the rate of consumption of the substrate by the biomass. It is assumed that the porous medium is homogeneous and isotropic. A two-field model that represents the fluid and solid phase temperature fields separately is used for energy equation. A simplified Monod model is introduced along with the governing equations to describe the consumption of the substrate by the biomass. In other word, the transient biochemical heat source which is dependent on a solute concentration is considered in the energy equations. Investigation of the biomass activity and biochemical heat generation in the case of thermal non-equilibrium assumption has not been considered in the literature and they are open research topics. The effects of thermal non-equilibrium model on heat transfer, flow pattern, and biomass transfer are investigated. The effective parameters which have a direct impact on the generated bio-chemical heat source are also presented. The influences of the non-dimensional parameters such as fluid-to-solid conductivity ratio on the temperature distribution are presented.

Key words: *porous medium, thermal non-equilibrium, bio-chemical heat source, Monod model*

Introduction

Analysis of fluid flow and heat transfer in a porous medium has been a subject of continuous interest for the past decades because of the wide range of application. Growing environmental concerns have led to new approaches for the environmental management of organic waste. Several methods can be employed to transform the waste into products which are less damaging to the environment. In the area of sanitary landfill, bio-kinetic equations have been solved to take into account the microbial activity within the landfill. Also, the experimental results confirmed that the composting process is essentially controlled by internal heat generation from microbial oxidation, with a strong relationship between microbial activi-

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* Corresponding author; e-mail: nazari_me@yahoo.com

ty and chemical solute concentration ratios. Therefore, analysis of heat transfer and heat generation in the compost materials or sanitary landfill is a key point to understand their effective characteristics. As far as we know, this problem has not yet been studied in the available literature. In the other hand, for simulation of such materials, heat and mass transfer through porous materials should be considered.

Baytas and Pop [1] investigated thermal non-equilibrium free convection in a square porous cavity. 2-D steady free convection in a square was studied numerically by adopting a two-temperature model of heat transfer. Such a model, which allows the fluid and solid phases not to be in local thermal equilibrium, was found to modify the flow behavior and heat transfer rates. Knowledge of this behavior is important for the design of composting process and other practices.

Numerical investigations of steady natural convection flow through a fluid-saturated porous medium in a rectangular enclosure were also conducted by Varol *et al.* [2]. El-Fadel *et al.* [3] developed a complete numerical model to describe the generation and transport of gases and heat inside a landfill. The relationship between microbial activity levels and chemical species concentrations is strong, as presented by the experiments of Larsen and McCartney [4]. Anaerobic decomposition can be modeled using double-diffusive convection heat transfer in a porous medium with internal heat source. Regarding this topic, the double-diffusive problem for a gas mixture was analyzed by Chamkha [5]. In that research, heat and mass gradients applied on the vertical walls of an enclosure with a heat source depending linearly upon temperature.

The inverse natural convection problem in a porous medium with mass diffusion was proposed by Prud'homme and Jasmin [6] for the determination of volumetric heat source which is a function of the solute concentration. The conjugate gradient method with adjoint equations was also employed in the natural convection problem by Jasmin and Prud'homme [7], for the determination of an unknown heat source which is dependent on a solute concentration generation rate. A non-linear double diffusive convection in a multi-porous cavity is considered by Saghir [8]. The influence of the thermal Rayleigh number, the solutal Rayleigh number, and the Lewis number on the convection scheme was demonstrated for different Darcy numbers.

Analysis of free convection and non-uniform boundary conditions over a flat plate or in the porous enclosures were presented by Bilgen and Ben Yedder in 2007 [9], Storesletten and Pop [10], and Bradean, *et al.* [11]. Baytas and Pop [12] presented the numerical calculations for the steady-state free convection within an inclined cavity filled with a fluid-saturated porous medium. Flow and heat transfer characteristics were investigated for a wide range of values of the Rayleigh number, inclined angle and cavity aspect ratio. Thermal instability in an electrically conducting two component fluid-saturated-porous medium has been investigated by Bhadauria and Srivastava [13], considering temperature modulation of the boundaries.

This paper is concerned with natural convection in a square cavity filled with a porous medium in the presence of internal biochemical heat source. The physics of the presented problem is related to the analysis of heat and mass transfer in a composting process that controlled by internal heat generation. The intensity of the bio-heat source generated in the cavity is equal to the rate of consumption of the substrate by the biomass. The Monod model is also used to close the system of equations. The effects of thermal non-equilibrium assumption on heat transfer, bio-chemical heat source, flow pattern, and mass transfer are investigated. The influences of effective parameters such as dimensionless heat transfer coefficient and solid-fluid conductivity ratio are studied completely.

Governing equations and boundary conditions

The geometry of the problem and the boundary conditions are summarized in fig.1. The cavity is filled with a fluid-saturated porous medium and bounded by vertical impermeable plats. The physics of the presented problem is related to the analysis of heat and mass transfer in a composting process that controlled by internal heat generation. Also, there is a relationship between microbial activity and chemical solutes concentrations.

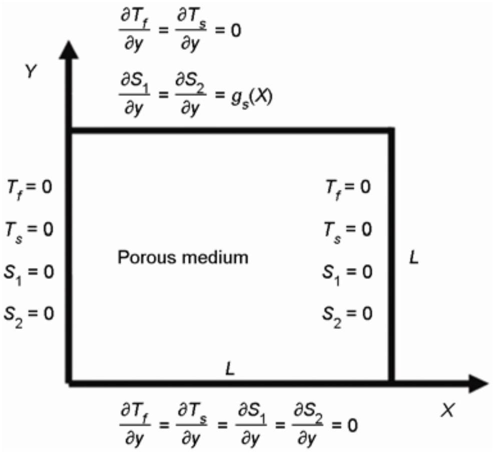


Figure 1. Geometry of problem and co-ordinate axis

It is assumed that a substantial temperature difference exists between solid and fluid phases; therefore, thermal non-equilibrium assumption is employed in the governing equations. The Darcy model is valid for low-speed flow in the porous media. In this problem which is related to the free convection in the composting process, the low Reynolds number assumption is a valid hypothesis. The problem of free convection of heat and mass in the porous cavity subject to cross diffusion (namely the Soret and Dufour effects) is a task which can be considered in a separate work in the porous media. In the presented model of the composting process, the energy equation and the concentration equations (*i. e.* substrate and biomass) are coupled by the biochemical heat source which is proportional to the rate of dominant reaction. Our heat transfer model is compatible with the previous modelings of the *composting process* or the *sanitary landfill.* The governing equations of stream function, temperature for fluid and solid phases and concentrations (substrate and biomass) can be written:

$$\frac{\partial u}{\partial y} - \frac{\partial v}{\partial x} = -\frac{g\beta K}{\nu}\frac{\partial T}{\partial x} \tag{1}$$

$$\begin{aligned}\varphi(\rho c_P)_f \frac{\partial T_f}{\partial t} + (\rho c_P)_f \left(u\frac{\partial T_f}{\partial x} + v\frac{\partial T_f}{\partial y} \right) = \\ = \varphi k_f \left(\frac{\partial^2 T_f}{\partial x^2} + \frac{\partial^2 T_f}{\partial y^2} \right) + h(T_s - T_f) + q(\dot{s}_1, \dot{s}_2)\end{aligned} \tag{2}$$

$$(1-\varphi)(\rho c_P)_s \frac{\partial T_s}{\partial t} = (1-\varphi)k_s \left(\frac{\partial^2 T_s}{\partial x^2} + \frac{\partial^2 T_s}{\partial y^2} \right) + h(T_f - T_s) \tag{3}$$

$$\varphi\frac{\partial s_1}{\partial t} + u\frac{\partial s_1}{\partial x} + v\frac{\partial s_1}{\partial y} = D_{m1}\left(\frac{\partial^2 s_1}{\partial x^2} + \frac{\partial^2 s_1}{\partial y^2} \right) + \varphi\left(\frac{\mu_1^* s_1}{K_{s1}^* + s_1} \right) s_2 \tag{4}$$

$$\varphi\frac{\partial s_2}{\partial t} + u\frac{\partial s_2}{\partial x} + v\frac{\partial s_2}{\partial y} = D_{m2}\left(\frac{\partial^2 s_2}{\partial x^2} + \frac{\partial^2 s_2}{\partial y^2} \right) + \varphi\left(\frac{\mu_2^* s_1}{K_{s2}^* + s_1} - K_D^* \right) s_2 \tag{5}$$

where D_m and φ are mass diffusivity and porosity of the porous cavity, μ^* is the maximum specific growth rate constant, K_s^* – the half saturation constant, and K_D^* – the death rate constant. These constants will be clearly defined in the Monod model. The appropriate scaling of length, velocity, temperature, concentration, and time is considered as:

$$X,Y=\frac{(x,y)}{L},\ U,V=\frac{(u,v)L}{\varphi\alpha_f},\ \theta_f=\frac{(T_f-T_0)}{\Delta T},\ \theta_s=\frac{(T_s-T_0)}{\Delta T},\ S=\frac{s}{\Delta S},\ \tau=\frac{k_f}{(\rho c_p)_f L^2}t \tag{6}$$

where T_0 is a reference temperature and L is a characteristic length. The initial value S_i can be used in order to define the scale ΔS. Using eq. (6), the non-dimensional governing equations, can be written as:

$$\frac{\partial^2\Psi}{\partial X^2}+\frac{\partial^2\Psi}{\partial Y^2}=-\mathrm{Ra}\frac{\partial\theta}{\partial X} \tag{7}$$

$$\frac{\partial\theta_f}{\partial\tau}+\frac{\partial\Psi}{\partial Y}\frac{\partial\theta_f}{\partial X}-\frac{\partial\Psi}{\partial X}\frac{\partial\theta_f}{\partial Y}=\frac{\partial^2\theta_f}{\partial X^2}+\frac{\partial^2\theta_f}{\partial Y^2}+H(\theta_s-\theta_f)+Q(\dot{S}_1,\dot{S}_2) \tag{8}$$

$$\Gamma\frac{\partial\theta_s}{\partial\tau}=\frac{\partial^2\theta_s}{\partial X^2}+\frac{\partial^2\theta_s}{\partial Y^2}+H\gamma(\theta_f-\theta_s) \tag{9}$$

$$\frac{\partial S_1}{\partial\tau}+U\frac{\partial S_1}{\partial X}+V\frac{\partial S_1}{\partial Y}=\frac{1}{\mathrm{Le}_1}\left(\frac{\partial^2 S_1}{\partial X^2}+\frac{\partial^2 S_1}{\partial Y^2}\right)+\dot{S}_1 \tag{10}$$

$$\frac{\partial S_2}{\partial\tau}+U\frac{\partial S_2}{\partial X}+V\frac{\partial S_2}{\partial Y}=\frac{1}{\mathrm{Le}_2}\left(\frac{\partial^2 S_2}{\partial X^2}+\frac{\partial^2 S_2}{\partial Y^2}\right)+\dot{S}_2 \tag{11}$$

The stream function is defined in such a way that:

$$U=\frac{\partial\Psi}{\partial Y},\quad V=-\frac{\partial\Psi}{\partial X} \tag{12}$$

where U and V are the velocity components in the X and Y directions. The subscripts 1 and 2 refer to the solute concentration species, $\mathrm{Ra}=g\,K\,\beta\,\Delta T\,L/\varphi\,\alpha_f\,\upsilon$, is the Rayleigh number and $\mathrm{Le}=\alpha/Dm$ is the Lewis number which is the ratio of the thermal diffusivity to the solutal diffusivity of the system. In the definition of the Ra number, β is the thermal expansion coefficient. α_f and υ are the fluid thermal diffusivity and kinematic viscosity, respectively. K is the permeability of the porous medium.

The initial and boundary conditions are:

$$\text{for } \tau<0:\quad \theta_f=\theta_s=S_1=S_2=\psi=U=V=0,$$

$$\text{for } \tau>0:$$

$$\theta_f(0,Y)=\theta_s(0,Y)=S_1(0,Y)=S_2(0,Y)=0,\quad \theta_f(1,Y)=\theta_s(1,Y)=S_1(1,Y)=S_2(1,Y)=0, \tag{13}$$

$$\frac{\partial\theta_f}{\partial Y}(X,1)=\frac{\partial\theta_s}{\partial Y}(X,1)=0,\quad \frac{\partial S_1}{\partial Y}(X,1)=\frac{\partial S_2}{\partial Y}(X,1)=g_s(X),$$

$$\frac{\partial\theta_f}{\partial Y}(X,0)=\frac{\partial\theta_s}{\partial Y}(X,0)=\frac{\partial S_1}{\partial Y}(X,0)=\frac{\partial S_2}{\partial Y}(X,0)=0$$

The concentration profile on the active boundary is considered $g_s(X) = \sin(\pi X)$ at $Y = 1$.

The presented governing equations can now be closed by introduction of Monod model. The source terms in the mass transfer equations can be expressed in dimensionless form:

$$\dot{S}_1 = \frac{\mu_1 S_1}{K_{S1} + S_1} S_2, \qquad \dot{S}_2 = \left(\frac{\mu_2 S_1}{K_{S2} + S_1} - K_D \right) S_2 \tag{14}$$

The non-dimensional parameters related to eqs. (7-11) and eq. (14) are defined as:

$$\mu = \mu^* \frac{L^2}{\alpha_f}, \quad K_s = \frac{K_s^{\,*}}{\Delta S}, \quad K_D = K_D^{\,*} \frac{L^2}{\alpha_f}, \quad H = \frac{hL^2}{\varphi k_f}, \quad \gamma = \frac{\varphi k_f}{(1-\varphi) k_s}, \quad \Gamma = \frac{\alpha_f}{\alpha_s} \tag{15}$$

It is assumed that the heat source, Q, is a function of the concentrations S_1 and substrate S_2, which is transported across the domain by natural convection. The transport of substrate across a domain is applicable to packed bed filters. It is important to notice that, the proposed method is also applicable to the case where the substrate S_1 is stationary. In this paper, we consider that the heat source is proportional to the rate of the dominant reaction [3]. Therefore, it is assumed that the source term in the cavity is equal to the average solute concentration generation of species 1 in the vertical direction:

$$Q(\dot{S}_1, \dot{S}_2) = w \dot{S}_{1,\text{avg.}} = \int_0^1 w\, \dot{S}_1 \,\mathrm{d}Y \tag{16}$$

where w is the heat proportionality constant, that is set to "–1" to simulate an exothermic reaction. An exothermic reaction is a chemical reaction that is accompanied by release of heat.

Numerical procedure

The finite volume method is used to solve the governing equations [14]. 71×71 uniform grids were considered in the computational domain and the results were independent of the grid size. The biochemical heat source at the channel center was calculated in the numerical method to obtain the suitable grid size. The governing equations were discretized in time and space domains. Fully implicit method was used in the time discretization and TDMA algorithm was employed to solve the problem. The time step is considered $\Delta\tau = 10^{-3}$. The iteration process is terminated when the following condition is satisfied:

$$\frac{\sum \left| \xi_{i,j}^{\;m} - \xi_{i,j}^{\;m-1} \right|}{\sum \left| \xi_{i,j}^{\;m} \right|} \le 10^{-5} \tag{17}$$

where ξ stands for either θ, S_1, S_2 or Ψ, and m denotes the iteration step. The computations have been carried out for $K_{S1} = K_{S2} = 1$, $\mu_1 = -10$, $K_D = 10$, $\mu_2 = 10$, $\mathrm{Le}_1 = \mathrm{Le}_2 = 1$, $\Gamma = 0.25$.

Results and discussions

As shown in fig. 2, the biochemical heat source, Q, is calculated at the center of the cavity for different values of H and γ at steady-state condition.

Calculation of the transient bio-chemical heat source which is depending on the concentration field is one of the main contributions of this paper. Increasing the interstitial heat transfer coefficient, *i. e. h*, is among the important reasons of increasing the value of parameter H. It means that there is an interstitial convective heat transfer between fluid and solid phases in the porous medium. High value of H corresponds to high convective heat transfer at the pore

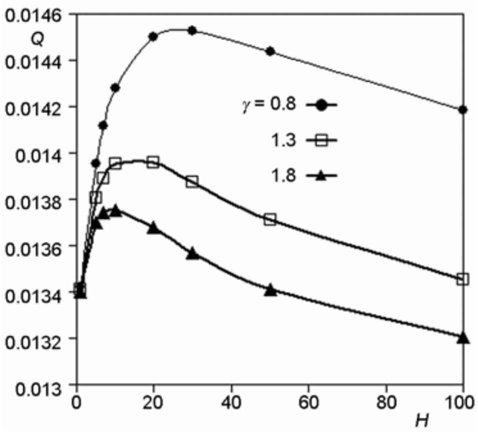


Figure 2. The bio-chemical heat source at the center of cavity at $t = t_f$

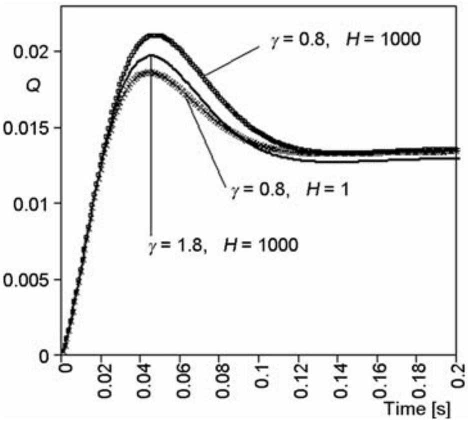


Figure 3. The effects of non-dimensional parameters on the transient biochemical heat source at the channel center

level. It is interesting to notice that as the parameter H increases, the bio-chemical heat source approaches a maximum value in a specific value of H. A similar trend is seen in the case of transient calculation of the generated heat source.

Also, the amount of generated heat source at the center of the cavity depends on the parameter γ. As the value of parameter γ increases, the bio-chemical heat source which is produced in the porous cavity decreases. As mentioned before, the bio-chemical heat source is proportional to the rate of the dominant reaction and it is assumed that the amount of heat generation in the cavity is equal to the average solute concentration of species "1" in the vertical direction. At the steady-state condition, the value of generated heat source is almost constant.

Shown in fig. 3, is the transient heat source at the center of the cavity for Ra = 10^5. As expected, taking γ as a constant parameter, increasing the coefficient H will result in an increase in the maximum value of the bio-chemical heat source. This increase may be due to a large interstitial heat transfer between solid and fluid phases. Moreover, in the case of constant value for parameter H, increasing the coefficient γ will decrease in the maximum value of the bio-chemical heat source. Analysis of the generated heat source in a composting process is very important because this process is controlled by internal heat generation.

The variations of S_1 and S_2 at the steady condition are shown in fig. 4. The effects of the non-dimensional parameters, *i. e.* H and γ, on the concentrations (substrate and biomass) are also presented in this figure. By increasing the parameter H, the amount of concentration species 1 and 2 at the center of the cavity will be increased. Also, increasing the parameter γ will tend to decrease in the amount of concentration species 1 and 2 at the cavity center.

Considering the Monod model, the source term in the porous cavity is strongly depended on the variation of the concentration species. It is important to notice that, by increasing the values of γ and H, the temperature difference between fluid and solid phases will be decreased. The temperature of the fluid phase at the center of the cavity is larger than the solid temperature for all values of γ and H.

Shown in fig. 5, is the transient temperatures for both fluid and solid phases at the center of the cavity for Ra = 10^5. The results show that, increasing the parameter H will increase the solid temperature while it will decrease the fluid temperature. Increasing the parameter γ will cause an increase in the temperature of both fluid and solid phases. As presented in fig. 3, the bio-chemical heat source approaches a maximum value at the early times. A similar trend is observed for the temperature of each phase in fig. 5.

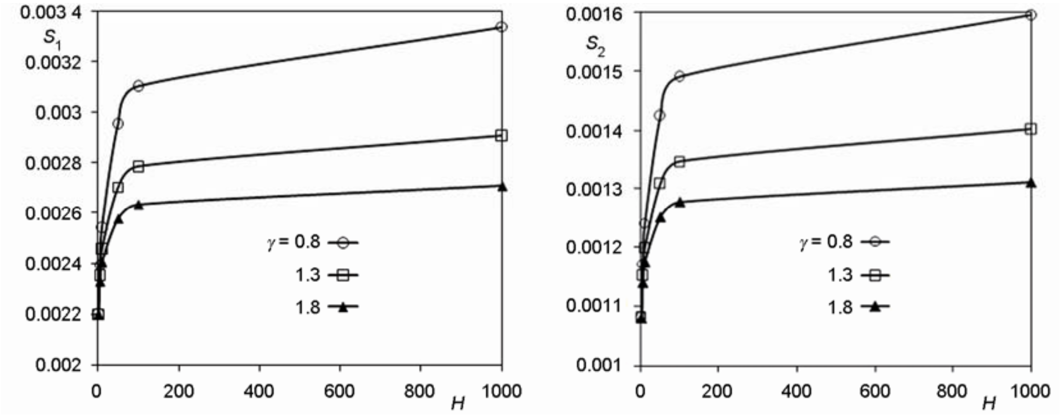


Figure 4. The solute concentration, S_1 and S_2, at the center of cavity at $t = t_f$

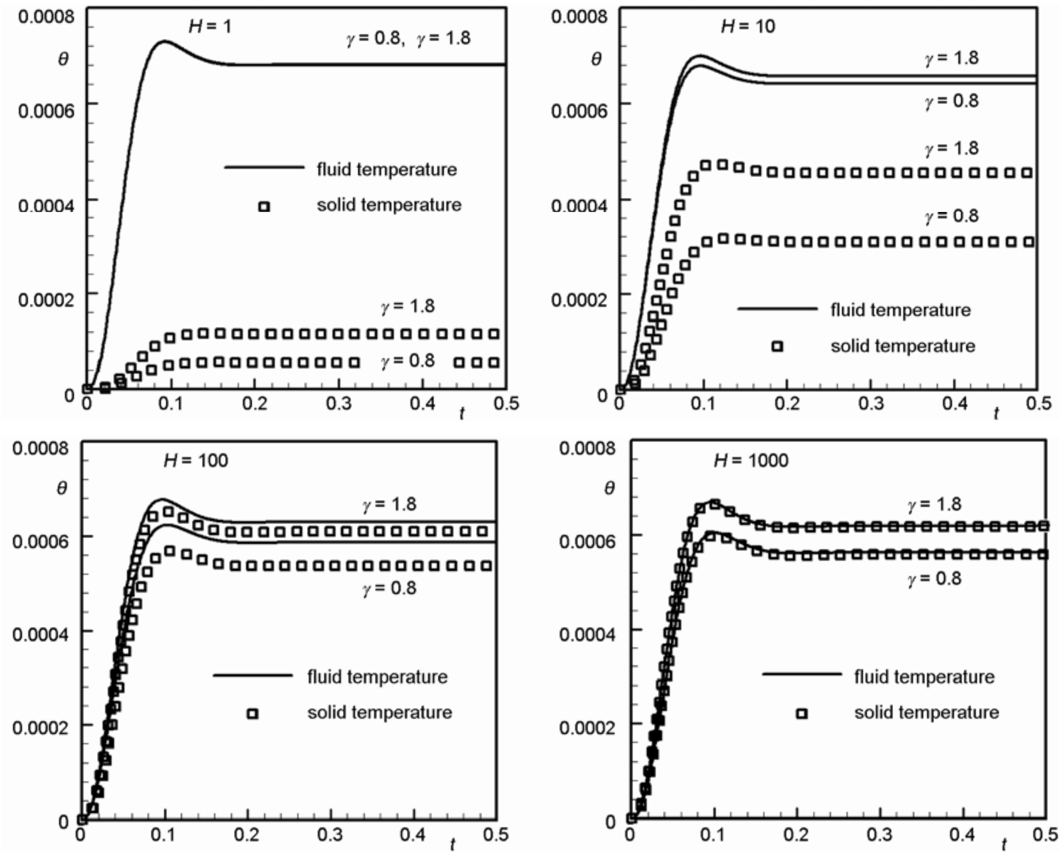
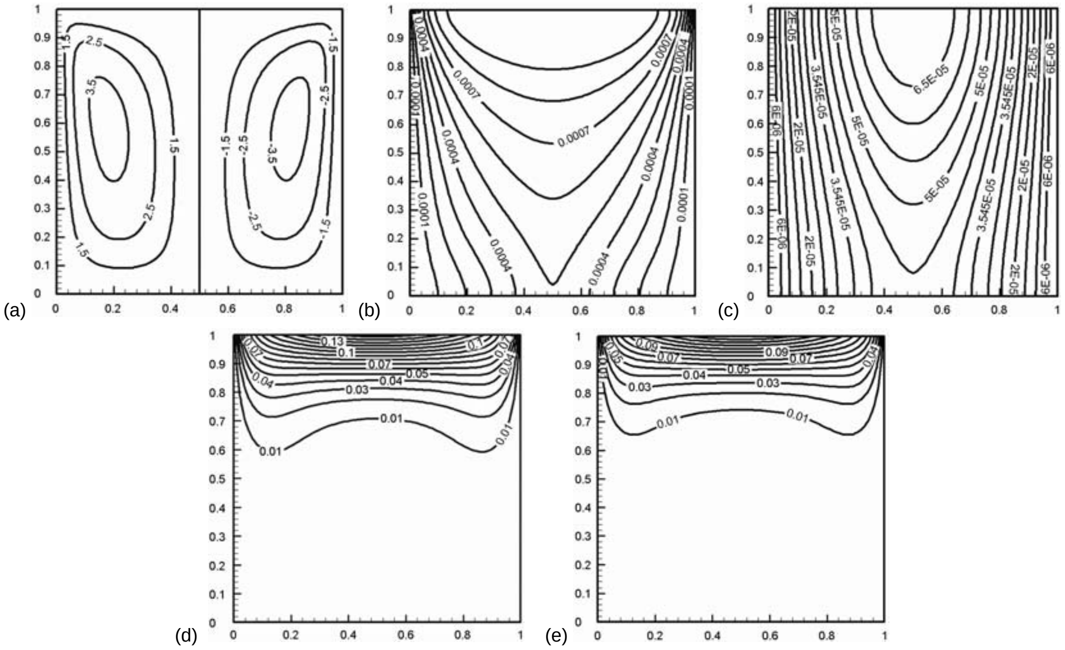


Figure 5. Fluid and solid temperature distribution at the channel center

The isotherm contours for both solid and fluid phases, streamlines, and the concentration species (S_1, S_2) are shown in figs. 6 and 7 in the range of $1 \leq H \leq 1000$, and Ra = 10^5. The effects of variation of the values of H and γ on the streamlines and concentration are clearly shown in these figures. A comparison between these figure and the previous results can be instructive, since the similarities help to highlight nuances.

H = 1



H = 1000

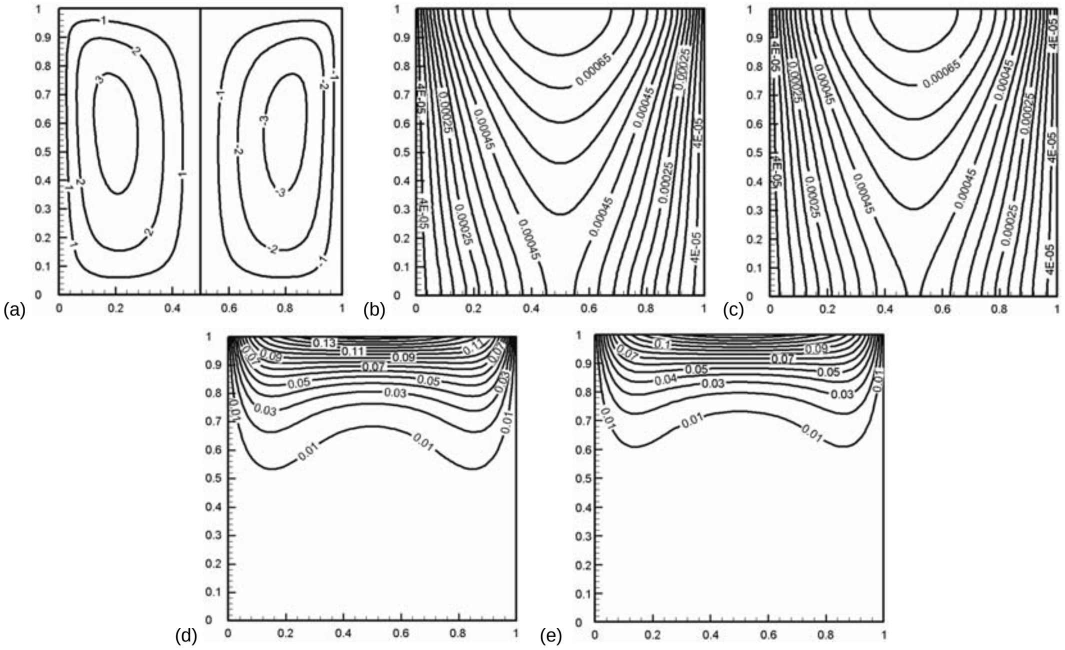


Figure 6. Streamlines (a), isotherm contours (b, c), and concentration (d, e) for species S_1 and S_2, respectively, for $\gamma = 0.8$

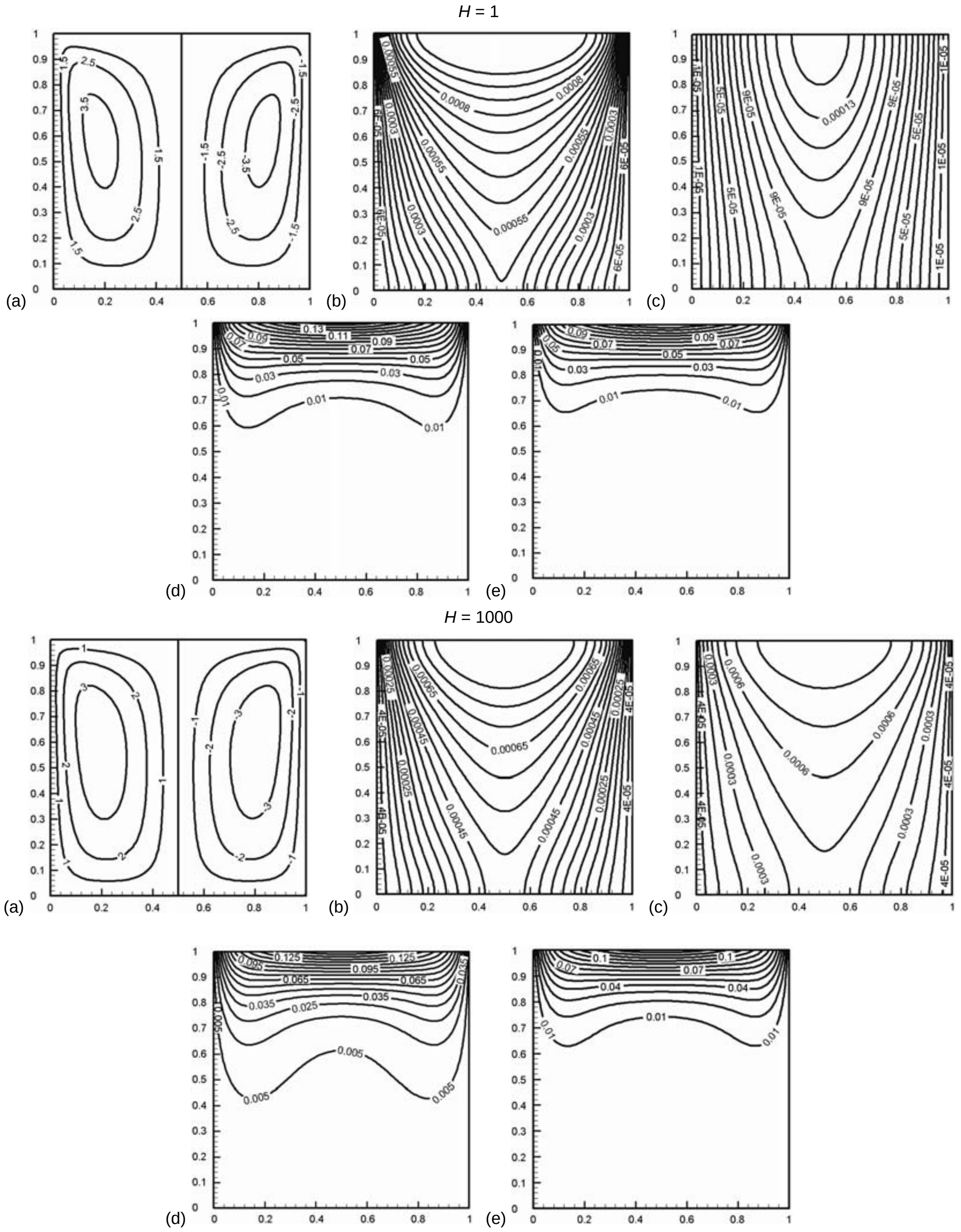


Figure 7. Streamlines (a), isotherm contours (b, c), and concentration (d, e) for species S_1 and S_2, respectively, for $\gamma = 1.8$

The temperature distribution for both solid and fluid phases is shown at the mid-plane of the cavity, *i. e.* $Y = 0.5$, in fig. 8. As parameter H increases, the fluid temperature

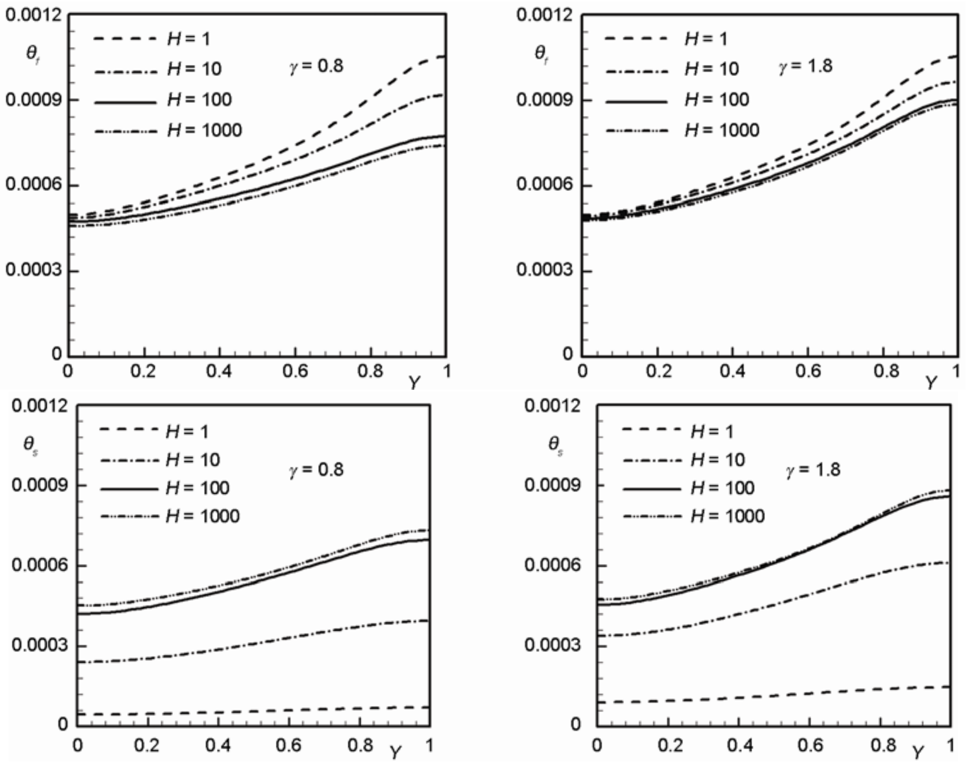


Figure 8. Temperature profiles at the vertical mid-plane of the cavity for both fluid and solid phases at $t = t_f$

decreases while the solid temperature increases in the cavity. On the other hand, by increasing the parameter γ, the temperature of both fluid and solid phases will be increased. Moreover, increasing the non-dimensional parameters, *i. e.* H and γ, will result in a decrease in the temperature differences between fluid and solid phases. The temperature of the fluid and solid phases at the top region of the cavity is larger than the temperature values at the bottom region. When the parameter H is small, the heat transfer between solid and fluid phases is evidently poor; therefore, the temperature of the fluid phase is greater than the temperature of the solid phase. This is due to the bio-chemical heat generation in the fluid phase of the porous cavity.

Jasmin and Prud'homme [7] investigated natural convection in a square cavity filled with a porous medium in the presence of internal biochemical heat source in the case of thermal equilibrium condition. In the study, we have extended the previous study of [7]. In other word, we investigated the effects of thermal non-equilibrium condition. Here, the LTNE is modeled by two separate equations of heat transport, one for the fluid phase and one for the solid phase. The interstitial transfer of heat between the phases is modeled macroscopically by a simple source/sink term which is proportional to the local temperature difference between the phases.

For very large values of H, the thermal equilibrium model is a valid assumption and it is important to notice that the TNE effects are decreased for large values of γ [15]. Thus the results of the present study are compared with those of thermal equilibrium model. The heat source profile *vs.* x obtained at $t = t_f$ is displayed in fig. 9 for Ra = 10^5, $H = 10000$, and $\gamma = 50$ (large values of γ and H). A comparison with [7] is also shown in this figure. It can be seen from this figure that a suitable agreement exists between the results.

Conclusions

Thermal non-equilibrium natural convection is studied in a square cavity filled with a porous medium in the presence of mass diffusion. The transient bio-chemical heat source which is dependent on a solute concentration generation rate is considered in the energy equations. The Monod model is also employed to introduce the biochemical heat source in the composting process. The results showed that the interstitial heat transfer coefficient between fluid and solid phases has significant effect on the value of produced bio-chemical heat source term. Moreover, the effective conductivity ratio plays an important role in this process. The results show that increasing the interstitial heat transfer coefficient between fluid and solid phases will increase the maximum value of the bio-chemical heat source term in the porous cavity. The fluid and solid temperature profiles approach maximum value at the early time because of growing behavior of the bio-chemical heat source in the physical domain. This problem can be extended by adding Soret and Dufour effects. The generalized momentum equation in the porous media, *i. e.* Forchheimer–Brinkman-extended Darcy model, can be also used to represent the fluid motion inside the porous cavity.

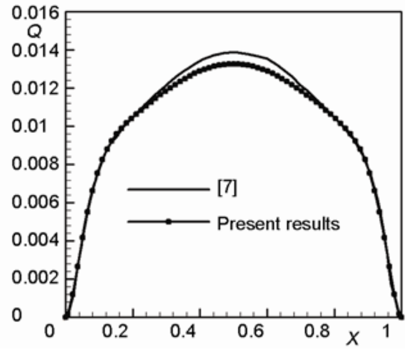


Figure 9. The heat source profile *vs.* x obtained at $t = t_f$

Nomenclature

c_p – specific heat at constant pressure, [Jkg^{-1}K^{-1}]
D – mass diffusivity, [m^{2}s^{-1}]
d – diameter of solid spheres, [m]
g – acceleration due to gravity, [ms^{-2}]
h – interstitial heat transfer coefficient at pore level, [–]
h_S – enthalpy of reaction, [kcal]
K – permeability of the porous medium, [m^2]
K_D – death rate constant, [h^{-1}]
K_S – half saturation constant, [mgL^{-1}]
M_S – molecular weight of the substrate, [gr]
Q – heat source
S – dimensionless value of s, [–]
s – substrate concentration, [mgL^{-1}]
T – temperature, [K]
t – time, [s]
u, v – velocity components, [ms^{-1}]
x, y – Cartesian co-ordinates, [m]
w – heat proportionality constant, [–]

Greek symbols

α – thermal diffusivity, [m^{2}s^{-1}]
β – coefficient of thermal expansion, [K^{-1}]
Γ – fluid to solid diffusivity ratio
γ – effective conductivity ratio, [–]
θ – dimensionless temperature, [–]
μ – max. specific growth rate constant, [1h^{-1}]
ν – fluid kinematic viscosity, [m^{2}s^{-1}]
ρ – density, [kgm^{-3}]
σ – specific heat ratio
τ – dimensionless time
φ – porosity
Ψ – stream function

References

[1] Baytas, A. C., Pop I., Free Convection in a Square Porous Cavity Using a Thermal non-Equilibrium Model, *Int. J. Therm. Sci., 41* (2002), 9, pp. 861-870

[2] Varol, Y., *et al.*, Numerical Analysis of Natural Convection for a Porous Rectangular Enclosure with Sinusoidally Varying Temperature Profile on the Bottom Wall, *Int. Commun. Heat Mass Transfer, 35* (2008), 1, pp. 56-64

[3] El-Fadel, M., *et al.*, Numerical Modeling of Generation and Transport of Gas and Heat in Landfill I Model Formulation, *Waste Manag. Res., 14* (1996), 5, pp. 483-504

[4] Bradean, R., Ingham, D. B., Free Convection Fluid Flow due to a Periodically Heated and Cooled Vertical Flat Plate Embedded in a Porous Media, *Int. J. Heat Mass Transfer, 39* (1996), 12, pp. 2545-2557

[5] Kayhani, M. H., *et al.*, The Effects of Fluid-to-Solid Conductivity Ratio, Rayleigh Number and Interstitial Heat Transfer Coefficient on the Free Convection in a Porous Enclosure, *Transp. Porous Med., 87* (2011), 2, pp. 625-633

[6] Prud'homme, M., Jasmin, S., Determination of a Heat Source in Porous Medium with Convective Mass Diffusion by an Inverse Method Mass Transfer, *Int. J. Heat Mass Transfer, 46* (2003), 11, pp. 2065-2075

[7] Jasmin, S., Prud'homme, M., Inverse Determination of a Heat Source from a Solute Concentration Generation Model in Porous Medium, *Int. Commun. Heat Mass Transfer, 32* (2005), 1-2, pp. 43-53

[8] Saghir, M. Z., Heat and Mass Transfer in a Multi-Porous Cavity, *Int. Comm. Heat Mass Transfer, 25* (1998), 7, pp.1019-1030

[9] Bilgen, E., Ben Yedder, R., Natural Convection in Enclosure with Heating and Cooling by Sinusoidal Temperature Profiles on One Side, *Int. J. Heat Mass Transfer, 50* (2007), 1-2, pp. 139-150

[10] Storesletten, L., Pop, I., Free Convection in a Vertical Porous Layer with Walls at non-Uniform Temperature, *Fluid Dyn. Res., 17* (1996), 3, pp.107-119

[11] Bradean, R., *et al.*, Free Convection Fluid Flow due to a Periodically Heated and Cooled Vertical Flat Plate Embedded in a Porous Media, *Int. J. Heat Mass Transfer, 39* (1996), 12, pp. 2545-2557

[12] Baytas, A. C., Pop, I., Free Convection in Oblique Enclosures filled with a Porous Medium, *Int. J. Heat Mass Transfer, 42* (1999), 6, pp. 1047-1057

[13] Bhadauria, B. S., Srivastava, A. K., Magneto-Double Diffusive Convection in an Electrically Conducting-Fluid-Saturated Porous Medium with Temperature Modulation of the Boundaries, *Int. J. Heat Mass Transfer, 53* (2010), 11-12, pp. 2530-2538

[14] Patankar, S., *Numerical Heat Transfer and Fluid Flow,* Hemisphere Publ. Corp., New York, USA, 1980

[15] Kayhani, M. H., *et al.*, The Effects of Fluid-to-Solid Conductivity Ratio, Rayleigh Number and Interstitial Heat Transfer Coefficient on the the Free Convection in a Porous Enclosure, *Transp. Porous Med., 87* (2011), 2, pp. 625-633

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