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Melting effect on mixed convective heat transfer with aiding and opposing external flows from the vertical plate in a liquid-saturated porous medium

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Abstract

In this paper, melting effect on mixed convective heat transfer from a porous vertical plate with uniform wall temperature in the liquid-saturated porous medium with aiding and opposing external flows is numerically examined at steady state. The resulting boundary value problems (BVPs) are comprehensively solved by Runge–Kutta–Gill method and Newton's iteration for similarity solutions. As shown in the results, for aiding and opposing external flows, it is all found that the rate of convective heat transfer at the interface of solid and liquid phases is reduced with increasing melting strength. Additionally, the melting phenomenon decreases the thermal boundary layer regions of mixed convection in a porous medium. With melting effect, the heat transfer rate is also shown to be asymptotically approaching the forced or free convection as the value of Gr/Re approaches the limits of zero and infinity for aiding external flow; and the criteria for pure forced and mixed convection from an isothermal vertical flat plate in porous media with aiding and opposing external flows are established in melting process.
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Keywords: Melting effect; Mixed convective heat transfer, Aiding and opposing external flows; Vertical plate; Porous medium

1. Introduction

Convective heat transfer has been found a lot of application in thermal engineering, including geothermal energy recovery, oil extraction, thermal energy storage, ultra-filtration, and thermal insulation. In addition, heat transfer accompanied with melting (or solidification) effect received numerous interests in the area of magma solidification, the melting of permafrost, and silicon wafer process.

In the absence of porous medium, Roberts [1] firstly presented "shielding effect" to describe the melting phenomena of ice placed in a hot stream of air at a steady state. Later, from the point of view of boundary layer theory, film theory and penetration theory, Tien and Yen [2] studied the effect of melting on convective heat transfer between a melting body and surrounding fluid. Epstein and Cho [3] considered the laminar film condensation on a vertical melting surface for 1-D and 2-D system based on Nusselt's method to discuss the melting rate. They pointed out that as long as melting solid is large compared with the thickness of thermal boundary layer, transient effects in the solid would be neglected. Sparrow et al. [4] studied the velocity and temperature fields, the heat transfer rate, and the melting layer thickness by means of finite-difference scheme in the melting region for natural convection.

Additionally, Maples and Poirier [5] analyzed the solidification phenomena of alloys with natural convection to obtain the pressure and velocity fields as well as solute flux in the mushy region. Voller and Prakash [6] simulated the melting layer and velocity field in the mushy region for a fixed grid with insulated upper and lower walls. Voller and Brent [7] used a comprehensive method to reduce the two-phase into a one-phase of binary solidification system.

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Nomenclature

C_f	specific heat of convective fluid (J/(kg K))
C_s	specific heat of solid phase (J/(kg K))
f	dimensionless stream function
g	acceleration due to gravity (m/s^2)
Gr	Grashof number defined in Eq. (12)
h	local heat transfer coefficient (J/(s m^2 K))
k_{eff}	effective thermal conductivity (J/(s m K))
k_f	thermal conductivity of convective fluid (J/(s m K))
k_s	thermal conductivity of porous medium (J/(s m K))
K	permeability of the porous medium (m^2)
M	melting parameter defined in Eq. (16)
Nu	local Nusselt number defined in Eq. (18)
Pe	local Peclet number defined in Eq. (7)
q_w	wall heat flux (J/(s m^2))
R_e	local Reynolds number defined in Eq. (13)
T	temperature in thermal boundary layer (K)
u	Darcy's velocity in x-direction (m/s)
u_∞	velocity of external flow (m/s)
v	Darcy's velocity in y-direction (m/s)
x	coordinate along the melting plate (m)
y	coordinate normal to melting plate (m)

Greek symbols

α	equivalent thermal diffusivity (m^2/s)
β	coefficient of thermal expansion (1/K)
ε	porosity
η	dimensionless similarity variable defined in Eq. (7)
η_T	value of η at the edge of the thermal boundary layer
θ	dimensionless temperature in Eq. (9)
λ	latent heat of melting of solid (J/kg)
μ	dynamic viscosity of fluid (kg/(s m))
ν	kinematic viscosity of fluid (m^2/s)
ρ_f	density of convective fluid (kg/m^3)
ρ_∞	density of external fluid (kg/m^3)
ψ	stream function (m^2/s)

Subscripts

m	melting point
∞	condition at infinity
s	condition at solid

Bennon and Incropera [8,9] established a continuum model for species transport in binary solid–liquid phase systems through the Navier–Stokes equation and energy equation, and then simulated the solidification in a rectangular cavity. For the melting phenomena without mushy region in the forced, free and mixed convection has also been investigated. Pozvonkov et al. [10] studied the heat transfer at melting surface in the laminar boundary layer by using Kàrmàn–Pohlhausen method. Epstein and Cho [11] analyzed the steady laminar flows over a flat plate by using similarity solutions for the Nusselt number varying with Prandtal number.

In porous medium, Kazmierczak et al. [12] presented the similarity solutions to analyze the melting phenomenon induced by force convection of a dissimilar fluid. Furthermore, for natural convection, Kazmierczak et al. [13] examined the similarity solutions with aiding flows from a vertical plate to find the velocity and temperature profiles as well as the Nusselt number. Chen et al. [14] presented the similarity solutions for a solid immersed in a quiescent hot fluid to analyze the melting rate.

Considering the melting effect on mixed convection from a porous vertical plate in a fluid-saturated porous medium, through the fourth-order Runge–Kutta method and shooting approach, Bakier [15] studied the velocity profiles for an arbitrary wall temperature on the melting plate with aiding and opposing flows. He found that the heat transfer rate is reduced at the solid–liquid interface. But this physical model is actually not realized during phase changing process for pure material. Therefore, Gorla et al. [16] changed the arbitrary wall temperature by a uniform wall temperature at the solid–liquid interface to analyze the velocity and temperature fields in the presence of aiding flow. Recently, Tashtoush [17] studied the magnetic and buoyancy effects to investigate the velocity, energy profiles and heat transfer rate for melting phenomenon associated with uniform wall temperature based on non-Darcy flow by means of the collocation finite element method.

In the present paper, the focus is on the melting effect on the mixed convective heat transfer from the vertical surface in a porous medium; but the resulting boundary value problem is comprehensively solved by using Runge–Kutta–Gill scheme along with Newton's iteration in the presence of aiding and opposing flows over a vertical flat with uniform wall temperature at steady state. This mixed mode of convection is extended from the study of Gorla et al. [16]. The aim of this work is to provide an alternate numerical route solving the problem of mixed convective heat transfer in porous medium with melting effect. Additionally, the criteria for forced, mixed and free convections from a vertical plate in a porous medium in the presence of melting effect are to be defined from the similarity solutions in this study.

2. Physical model and mathematical formulation

Consider the mixed convective flow and heat transfer in a liquid-saturated porous medium adjacent to the porous vertical plate, with uniform wall temperature, that constitutes the interface between an incompressible Newtonian fluid and solid phases during melting inside the porous matrix at steady state. Fig. 1 shows the coordinates and flow model. The x-coordinate is measured along the plate and the y-coordinate normal to it. This work will designate the flow condition sketched in Fig. 1a, as an aiding external flow, where the gravitational acceleration (g) is in a direction parallel to the x-direction and the free stream velocity, u_∞; on the other hand, this study will designate the flow condition sketched in Fig. 1b, as an opposing external flow, where the buoyancy force has a component parallel to the x-direction and the free stream velocity. The temperature on the porous vertical plate, T_m, is the melting temperature (or phase change temperature) of the material occupying the porous matrix. The liquid phase far from the plate is maintained at constant temperature T_∞ ($T_\infty > T_m$). In addition, the temperature of the solid porous medium far from the interface is constant and is denoted by T_s ($T_s < T_m$). Additionally, it is assumed that the convective

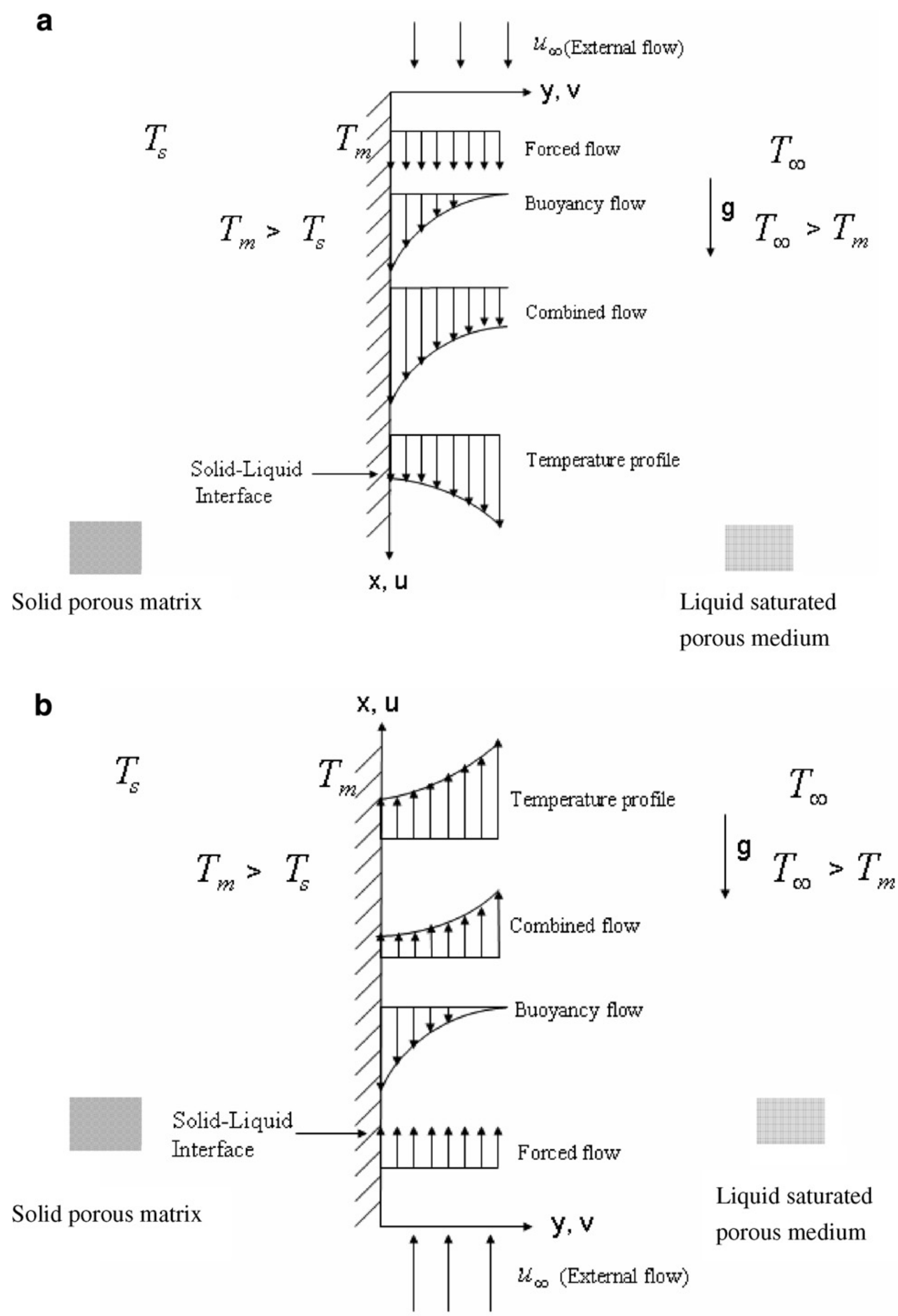

Fig. 1. The physical model investigated in this study: (a) aiding external flow and (b) opposing external flow.

fluid and the liquid-saturated porous medium are everywhere in local thermodynamic equilibrium. Properties of the fluid and the porous media such as viscosity (μ), thermal conductivity, specific heats, thermal expansion coefficient (β) and permeability (K) are constant; and the Darcy's flow [18] associated with the Boussinesq approximation [19] can be applied. Therefore, the continuity, momentum and energy transfer equations are, respectively, given as

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0, \tag{1}$$

$$\frac{\partial u}{\partial y}=\mp\frac{Kg\beta}{\nu}\frac{\partial T}{\partial y}, \tag{2}$$

and

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}, \tag{3}$$

where u and v are Darcy's velocity in the x and y directions; T is temperature in thermal boundary layer; $\nu=\mu/\rho_\infty$ is kinematic viscosity; and $\alpha=k_{\mathrm{eff}}/(\rho_\infty C_{\mathrm{f}})$ is the equivalent thermal diffusivity with denoting the product of density (ρ_∞) and specific heat (C_{f}) of convective fluid, and k_{eff} the effective thermal conductivity of the saturated porous medium given by $k_{\mathrm{eff}}=(1-\varepsilon)k_{\mathrm{s}}+\varepsilon k_{\mathrm{f}}$, where ε, k_{s}, and k_{f} are the porosity of the medium, thermal conductivity of the solid and convective fluid, respectively. Additionally, it is noticed that in Eq. (2), the "+" and "−" indicate cases of aiding and opposing external flows, respectively, which is different from the system modeled by Bakier [15].

The boundary conditions necessary to complete the problem formulations are

$$y=0,\quad T=T_{\mathrm{m}},\quad k_{\mathrm{eff}}\frac{\partial T}{\partial y}=\rho_{\mathrm{f}}[\lambda+C_{\mathrm{s}}(T_{\mathrm{m}}-T_{\mathrm{s}})]v, \tag{4}$$

and

$$y\to\infty,\quad T=T_\infty,\quad u=u_\infty, \tag{5}$$

where λ and C_{s} are latent heat of solid and specific heat of the solid phase, respectively. Particularly, the boundary condition (4) means that the temperature on the plate is uniform; and the thermal flux of heat conduction to the melting surface is equal to the heat of melting plus the sensible heat required raising the temperature of solid T_{s} to its melting temperature T_{m} [1,20].

The stream function ψ is defined by

$$u=\frac{\partial\psi}{\partial y},\quad\text{and}\quad v=-\frac{\partial\psi}{\partial x}, \tag{6}$$

then continuity equation (1) will be automatically satisfied. For similarity solution, the following transformed variables [18] are introduced:

$$\eta=\frac{y}{x}Pe^{\frac{1}{2}}, \tag{7}$$

where $Pe=\frac{u_\infty x}{\alpha}$, local Peclet number

$$\psi=\alpha Pe^{1/2}f(\eta), \tag{8}$$

where $f(\eta)$ is dimensionless stream function; and

$$\theta(\eta)=\frac{T-T_{\mathrm{m}}}{T_\infty-T_{\mathrm{m}}}. \tag{9}$$

In terms of new variables (7)–(9), momentum equation (2) and energy equation (3) can be rewritten as

$$f''\pm\frac{Gr}{Re}\theta'=0; \tag{10}$$

and

$$\theta''+\frac{1}{2}f\theta'=0, \tag{11}$$

where the primes denote differentiation with respect to the similarity variable η; and the ratio of

$$Gr=\frac{Kg\beta(T_\infty-T_{\mathrm{m}})x}{\nu^2} \tag{12}$$

to

$$Re=\frac{u_\infty x}{\nu} \tag{13}$$

is a measurement of mixed convective flow, which limiting case of $Gr/Re=0$ expresses the pure forced convection. The corresponding boundary conditions are

$$\eta=0,\quad\theta=0,\quad f(0)+2M\theta'(0)=0; \tag{14}$$

and

$$\eta\to\infty,\quad\theta=1,\quad f'=1, \tag{15}$$

where

$$M=\frac{C_{\mathrm{f}}(T_\infty-T_{\mathrm{m}})}{\lambda+C_{\mathrm{s}}(T_{\mathrm{m}}-T_{\mathrm{s}})} \tag{16}$$

is the melting parameter combining Stefan numbers [11]

$$\frac{C_{\mathrm{f}}(T_\infty-T_{\mathrm{m}})}{\lambda}\quad\text{and}\quad\frac{C_{\mathrm{S}}(T_{\mathrm{m}}-T_{\mathrm{S}})}{\lambda} \tag{17}$$

for the liquid and solid phases, respectively.

In practical applications, the rate of heat transfer is usually expressed as the local Nusselt number,

$$Nu=\frac{hx}{k_{\mathrm{eff}}}=\frac{q_{\mathrm{w}}x}{(T_\infty-T_{\mathrm{m}})k_{\mathrm{eff}}}=\theta'(0)Pe^{1/2}, \tag{18}$$

where h denotes the local heat transfer coefficient; and $q_{\mathrm{w}}=-k_{\mathrm{eff}}[\partial T/\partial y]_{\mathrm{y=0}}$ is wall heat flux.

3. Numerical method

The above dimensionless equations (10) and (11) associated to conditions (14) and (15) are coupled in nature for the boundary value problem and depend on the mixed convection parameter Gr/Re and the melting parameter M. In this work, a Runge–Kutta–Gill integrated method combined with Newton's iteration is employed to obtain the solutions as function of the strength of melting phenomena.

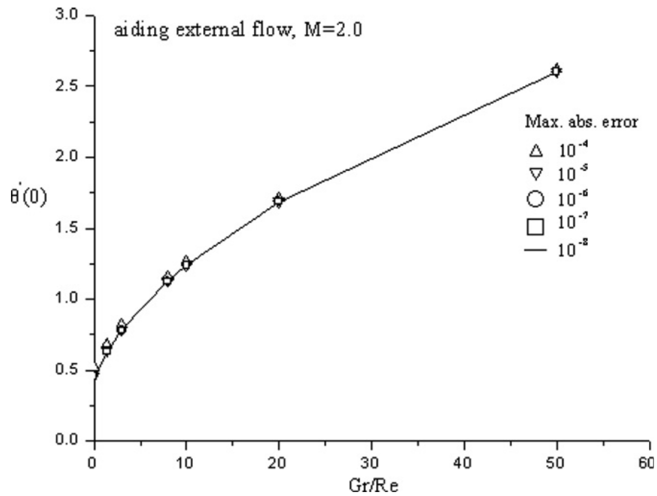

Fig. 2. Validation of maximum absolute error between two successive iterations for values of $\theta'(0)$ varying with parameter Gr/Re in the case of aiding flow and melting strength $M = 2.0$.

This numerical scheme is robust and reliable for the stiff system.

In convergence, the maximum absolute error between two successive iterations is set as 10^{-7}, which validation is demonstrated in Fig. 2 for values of $\theta'(0)$ obtained from the case of aiding external flow and melting strength $M = 2$ varying with the mixed convective strength. The total number of computation grid in the η direction is variable according to the mixed convective parameter to ensure the convergence of the solution at the free stream.

Table 1
Comparison of present results with values obtained by Gorla et al. [16] for the melting strength $M = 2.0$ in the different mixed convective strength with an aiding external flow

Parameter M	Parameter $\frac{Gr}{Re}$	$f'(0)$ (Gorla et al. [16])	$f'(0)$ (present)	$\theta'(0)$ (Gorla et al. [16])	θ (present)
2.0	0.0	1.000	1.000	0.2799	0.2706
	1.4	2.400	2.400	0.3823	0.3801
	3.0	4.000	4.000	0.4754	0.4745
	8.0	9.000	9.000	0.6902	0.6902
	10.0	11.00	11.00	0.7594	0.7594
	20.0	21.00	21.00	1.038	1.0383
	50.0	51.00	51.00	1.607	1.6066

Table 2
Comparison of present results with values obtained by Cheng [21] for the opposing external flow in the case of $M = 0$

Parameter M	Parameter $\frac{Gr}{Re}$	$\theta'(0)$ (Cheng [21])	$\theta'(0)$ (present)	η_T (Cheng [21])	η_T (present)
0.0	0.2	0.5269	0.5270	3.8	3.8
	0.4	0.4865	0.4866	3.9	3.9
	0.6	0.4420	0.4421	4.2	4.2
	0.8	0.3916	0.3917	4.5	4.5
	1.0	0.3320	0.3321	4.9	4.9

The present work is proved by comparing with the results obtained from Gorla et al. [16] for melting strength $M = 2$ in aiding external flow and Cheng [21] for melting

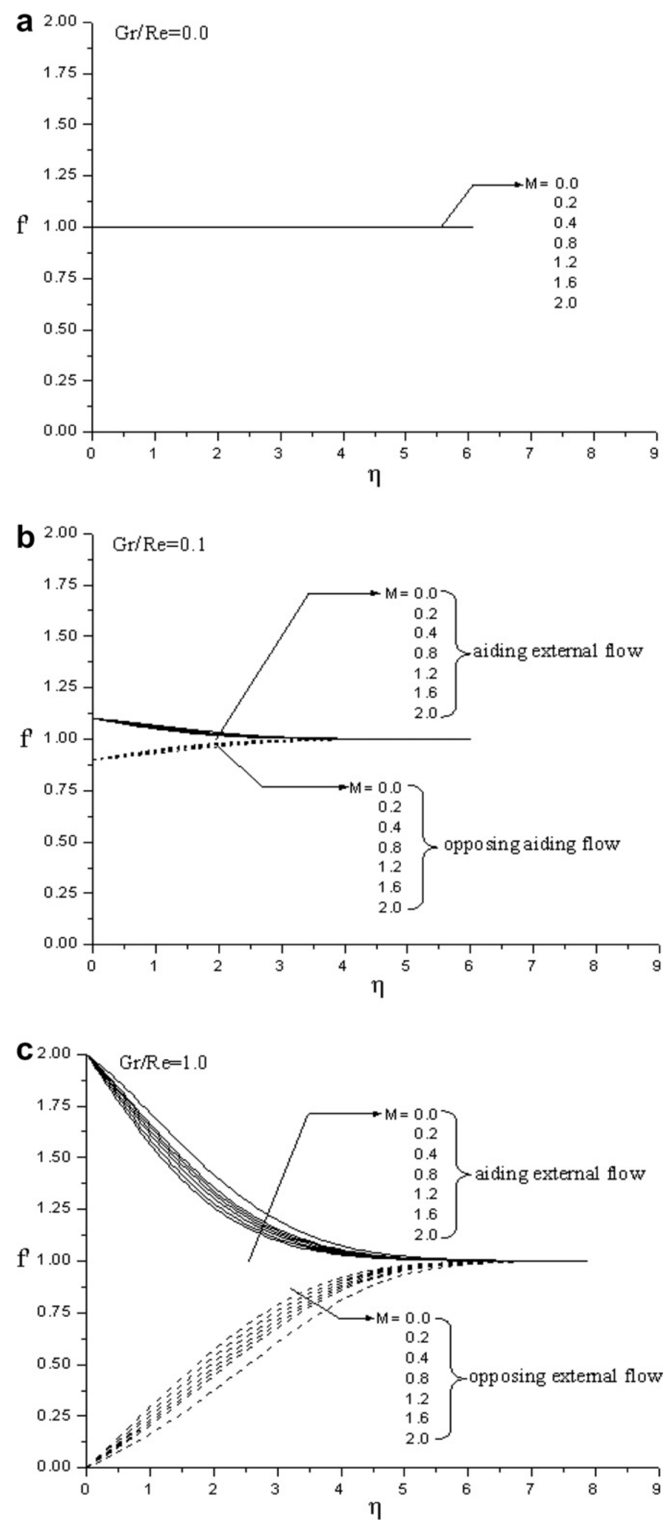

Fig. 3. Dependence of dimensionless velocity varying with the similarity coordinate η on the melting parameter M for cases of (a) $Gr/Re = 0$; (b) $Gr/Re = 0.1$; and (c) $Gr/Re = 1$ in the presence of aiding and opposing external flows, respectively.

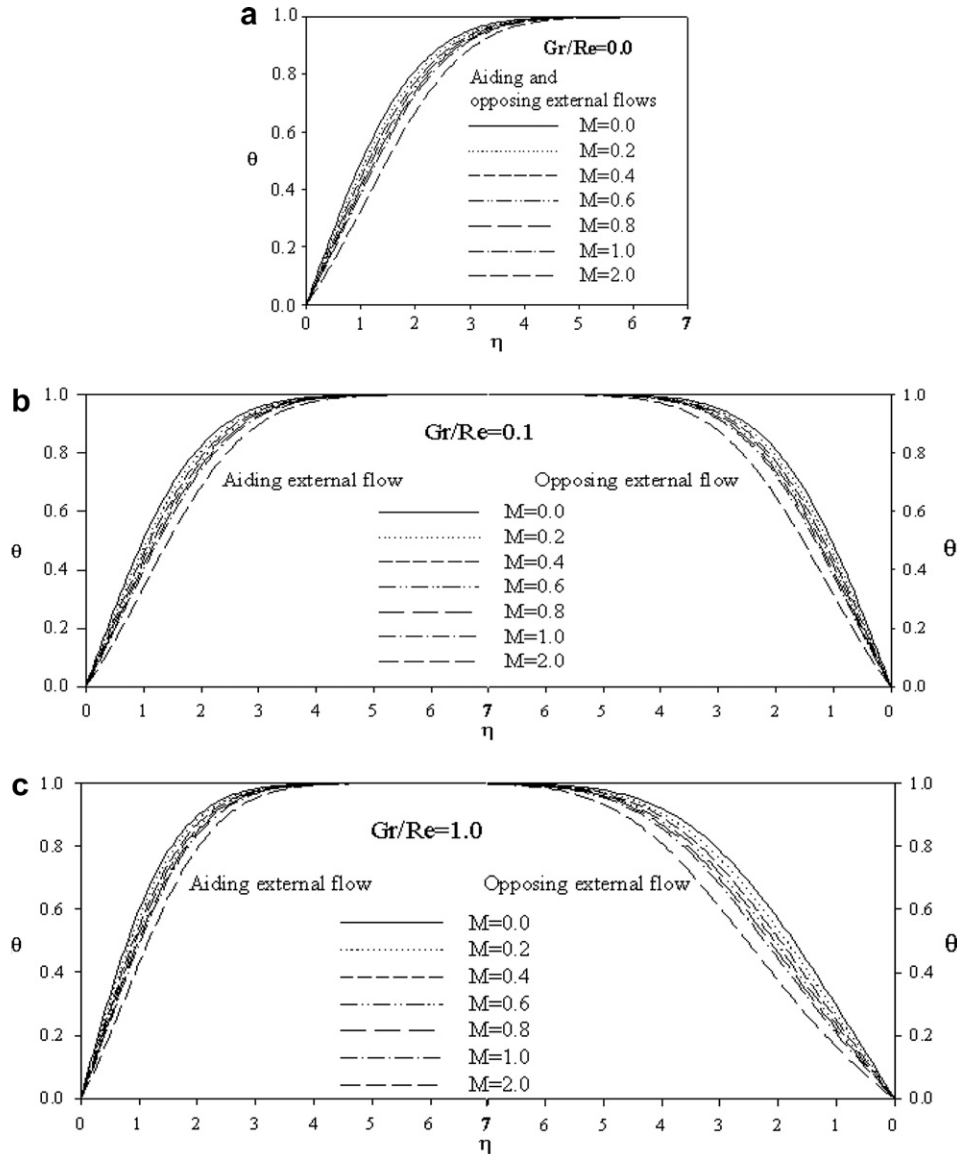

Fig. 4. Dependence of dimensionless temperature varying with the similarity coordinate η on the melting parameter M for cases of (a) $Gr/Re = 0$; (b) $Gr/Re = 0.1$; and (c) $Gr/Re = 1$ in the presence of aiding and opposing external flows, respectively.

strength $M = 0$ in opposing external flow varying with the mixed convective strength, as listed in Tables 1 and 2, respectively. As shown in tables, all data from the references are in agreement with the numerical results obtained in this study.

4. Results and discussion

As shown in Eq. (10) and boundary condition (14), governing parameters for the problem under study are the melting strength, M, and the mixed convective strength, Gr/Re. The melting strength is found to compete with the mixed convective strength for the phase change and convective heat transfer in porous medium. Furthermore, the mixed convective strength is limited by the thermal boundary-layer theory for the heat transfer in liquid-saturated porous medium with an opposing external flow. Therefore, in this work the range of governing parameters, $0 \leqslant M \leqslant 2$ and $0 \leqslant Gr/Re \leqslant 50$, is selected according to the specified system.

Fig. 3 shows the dependence of dimensionless velocity profiles on the melting strength M for mixed convective strength $Gr/Re = 0$, 0.1, and 1, respectively, for aiding and opposing external flows. In the figure, velocity gradient is reduced with increasing the melting strength. Additionally, it is noticed for pure forced convection, namely, $Gr/Re = 0$, the velocity field is independent of melting effect for both aiding and opposing external flows, that is the melting process can not be disturbed by the flow field when heat transfer is dominated by pure forced convection in liquid-saturated porous medium. This can be further validated by the analytical solution, $f' = 1$, obtained by solving Eq. (10) subject to boundary condition (15) for the case of $Gr/Re = 0$.

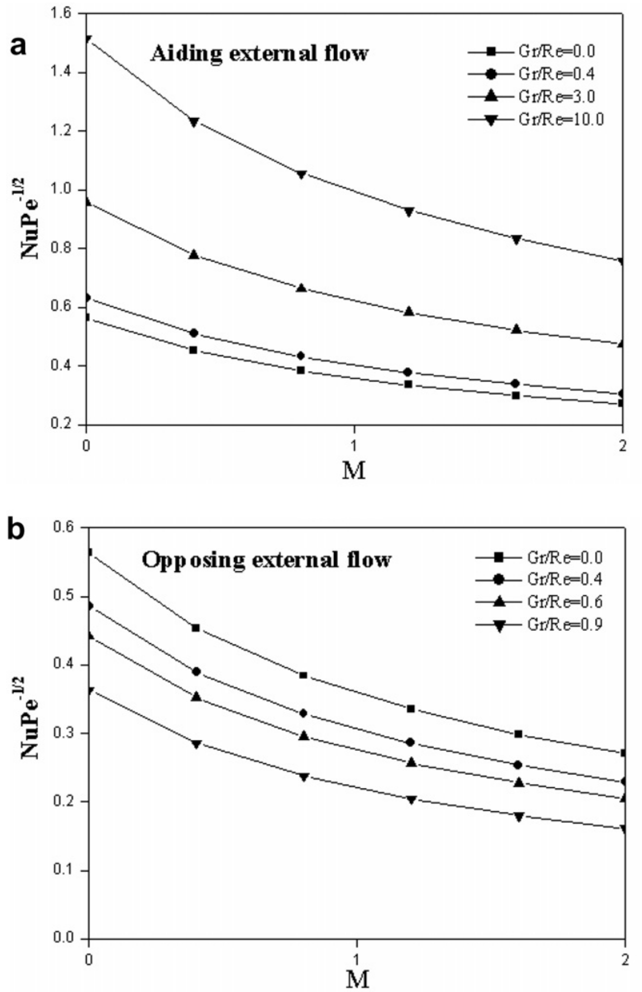

Fig. 5. (a) The local Nusselt number varying with the melting parameter M for (a) aiding external flow and (b) opposing external flow in the different mixed convection strength.

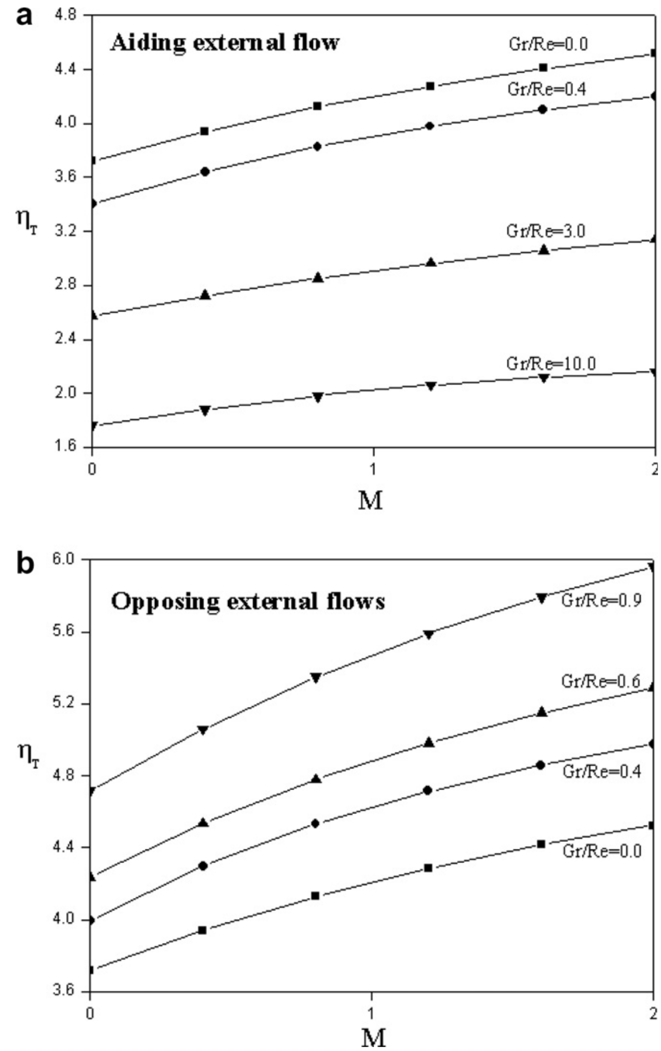

Fig. 6. The thickness of thermal boundary-layer varying with the melting parameter M for (a) aiding external flow and (b) opposing external flow in the different mixed convection strength.

Similarly, taking $Gr/Re = 0$, 0.1, and 1 as examples, Fig. 4 displays the melting effect on the temperature distributions for aiding and opposing external flows, respectively. As observed from the figure, thermal gradient is reduced with increasing melting strength because convective heat transfer is inhibited from the liquid-saturated porous medium to the solid porous vertical plate for cases of aiding and opposing external flows; but the thickness of thermal boundary layer can be reduced and thicken by increasing the mixed convective strength for heat transfer in a liquid-saturated porous medium with aiding and opposing external flows, respectively, in the presence of melting effect.

The impact of the melting strength M on the local heat transfer rate to the plate is sketched in Fig. 5, with the help of the Nusselt number defined in Eq. (18). As found in Fig. 5a and b, increasing value of M significantly decreases the local heat transfer rate for both aiding and opposing external flows. The presents are in agreement with the results reported by Refs. [12–16] for melting phenomenon from a vertical plate induced by forced convection of a warm fluid. As decreasing value of M, a plateau is reached, which features the maximum value of Nusselt number without melting effect [12]. Fig. 6a and b correspond to the thickness of thermal boundary layer, η_T, as $\theta(\eta) = 99.99\%$, varying with the melting strength for aiding and opposing external flows. Clearly, increasing the melting parameter M increases the thickness of thermal boundary layer. Therefore, the melting process acts, in a sense, like a blowing boundary condition at the plate and tends thicken the thermal boundary and reduce the heat transfer through the solid–liquid interface.

To establish the critical values of Gr/Re for forced, mixed and free convections over a vertical plate embedded in saturated porous medium, according the 5% deviation rule suggested by Sparrow et al. [22], the local heat transfer rate, with melting parameters $M = 0$, 1, and 2, as a function of parameters Gr/Re for aiding and opposing external flows are shown in Figs. 7 and 8, respectively. It will be of interest to plot the corresponding expressions for pure forced and free convections in the same figure. For aiding

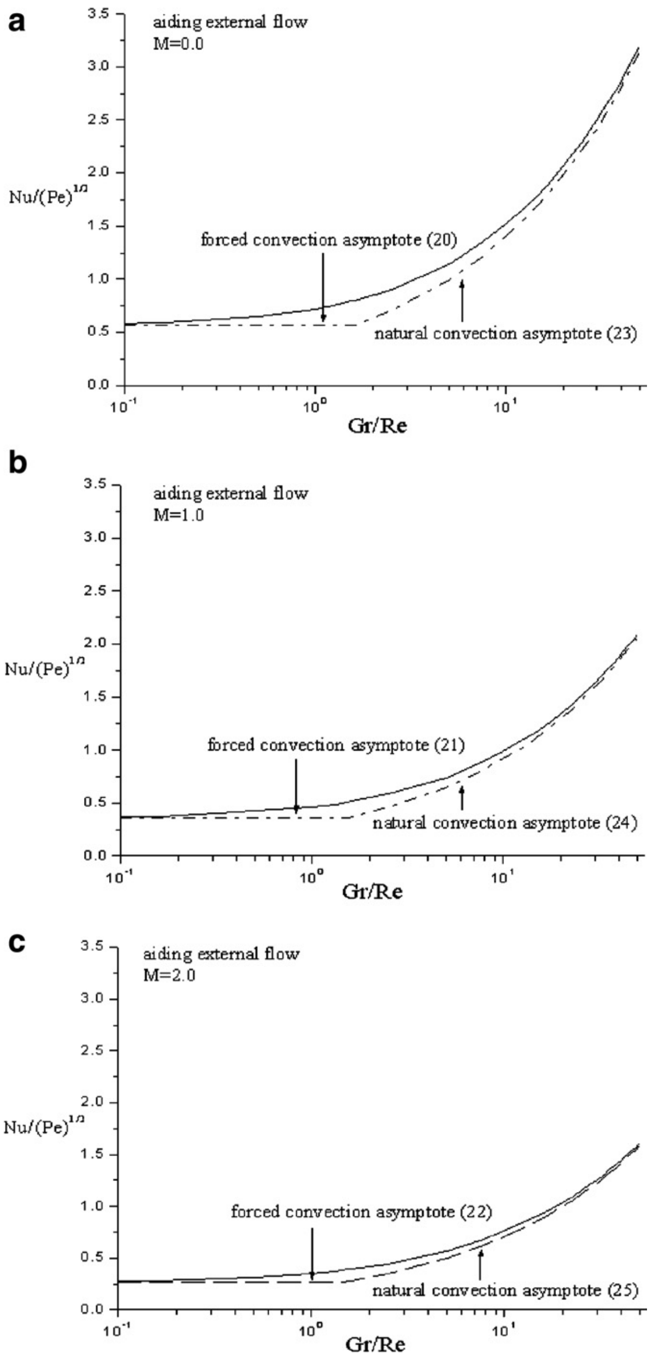

Fig. 7. Melting effects on heat transfer results for aiding external flows with (a) $M = 0$; (b) $M = 1$; and (c) $M = 2$.

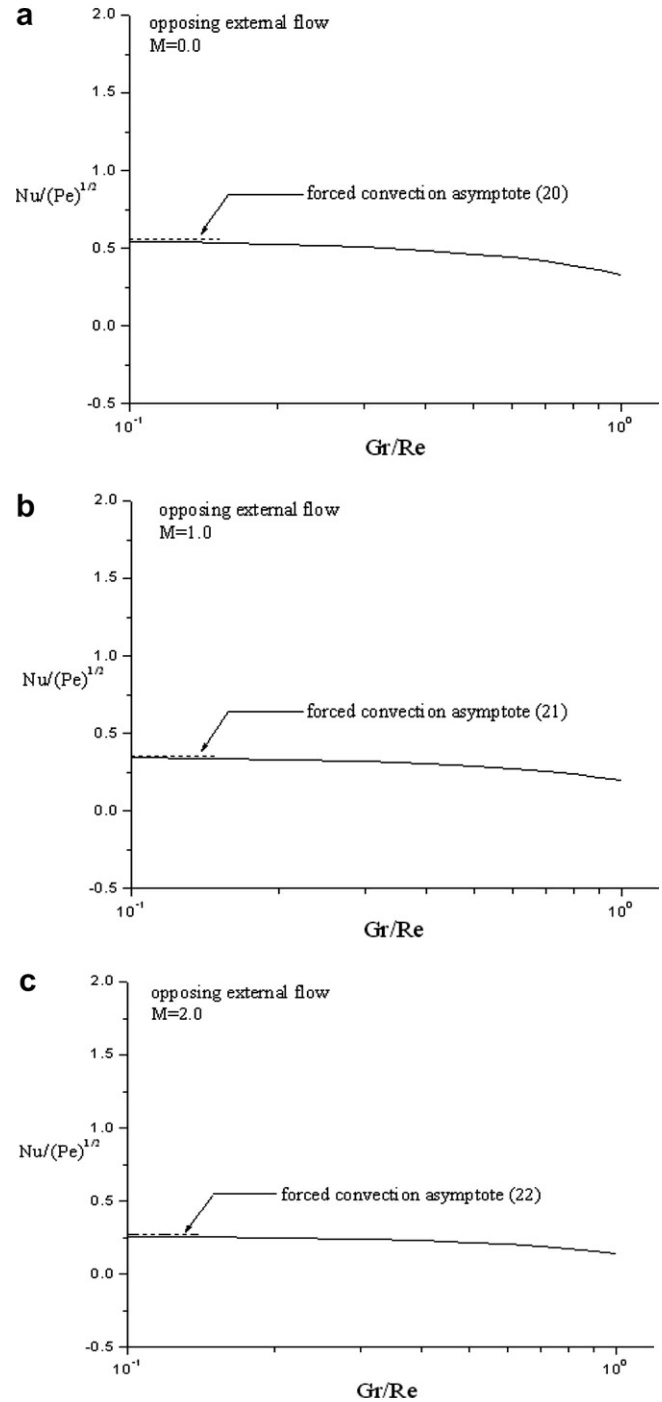

Fig. 8. Melting effect on heat transfer results for opposing external flow with (a) $M = 0$; (b) $M = 1$; and (c) $M = 2$.

external flow and $Gr/Re = 0$, the forced convection asymptote with different melting strength can be obtained as

$$\frac{Nu}{Pe^{\frac{1}{2}}} = 0.5641 \text{ [21]}, \quad \text{for } M = 0, \tag{19}$$

$$\frac{Nu}{Pe^{\frac{1}{2}}} = 0.3579, \quad \text{for } M = 1, \tag{20}$$

and

$$\frac{Nu}{Pe^{\frac{1}{2}}} = 0.2706, \quad \text{for } M = 2. \tag{21}$$

On the other hand, the free convection asymptote with different melting strength can be expressed by

$$\frac{Nu}{Pe^{\frac{1}{2}}} = 0.444\left(\frac{Gr}{Re}\right)^{\frac{1}{2}} \text{ [21]}, \quad \text{for } M = 0; \tag{22}$$

$$\frac{Nu}{Pe^{\frac{1}{2}}} = 0.291\left(\frac{Gr}{Re}\right)^{\frac{1}{2}} \text{ [13]}, \quad \text{for } M = 1; \tag{23}$$

Table 3
The criteria of forced convection, mixed convection, and natural convection for (a) aiding external flow and (b) opposing external flow in the different melting strength

M	Forced convection	Mixed convection	Natural convection
(a)			
0.0	$0 < \frac{Gr}{Re} < 0.15$	$0.15 < \frac{Gr}{Re} < 16$	$16 < \frac{Gr}{Re}$
1.0	$0 < \frac{Gr}{Re} < 0.146$	$0.146 < \frac{Gr}{Re} < 14.9$	$14.9 < \frac{Gr}{Re}$
2.0	$0 < \frac{Gr}{Re} < 0.139$	$0.139 < \frac{Gr}{Re} < 14.5$	$14.5 < \frac{Gr}{Re}$
(b)			
0.0	$0 < \frac{Gr}{Re} < 0.15$	$0.15 < \frac{Gr}{Re}$	N/A
1.0	$0 < \frac{Gr}{Re} < 0.146$	$0.146 < \frac{Gr}{Re}$	N/A
2.0	$0 < \frac{Gr}{Re} < 0.139$	$0.139 < \frac{Gr}{Re}$	N/A

and

$$\frac{Nu}{\Pr^{\frac{1}{2}}} = 0.224\left(\frac{Gr}{Re}\right)^{\frac{1}{2}} \text{[13]}, \quad \text{for } M = 2. \tag{24}$$

The subdivisions for forced, mixed, and free convections with melting strengths $M = 0$, 1, and 2 are listed in Table 3(a).

For an opposing external flow, Fig. 8 displays values of $Nu/(Pe)^{1/2}$ varying with Gr/Re in the presence of effects as $M = 0$, 1, and 2, respectively. As shown in the figure, for small values of Gr/Re the curve approaches the forced convection asymptote; and if the 5% deviation rule is again applied, the criteria can be obtained as listed in Table 3(b). This shows the range of Gr/Re values for pure and mixed convection are both narrowed with increasing the melting strength. The criteria for pure free convection from a vertical plate in liquid-saturated porous medium with opposing external flow cannot be defined because the thermal boundary layer approximation is not realized as over limiting value of Gr/Re in this study.

5. Conclusion

In this paper, the melting effect on mixed convective heat transfer from a solid porous vertical plate with uniform wall temperature embedded in the liquid-saturated porous medium has been comprehensively studied in the presence of aiding and opposing external flows. The governing equation was derived by the boundary layer and Boussinesq approximation. A boundary condition to account for melting was used at the interface between the solid and liquid phases. These equations were then transferred using similarity transformation and solved by the Runge–Kutta–Gill algorithm associated with Newton's iteration. Graphical results regarding the velocity and temperature distributions as well as the Nusselt number were presented and discussed for different melting parameters. Additionally, in aiding external flow, the criteria of Gr/Re values for forced, mixed and free convections over a solid porous vertical plate embedded in liquid-saturated porous medium with melting effect were established in this work.

References

[1] Leonard Roberts, On the melting of a semi-infinite body of ice placed in a hot stream of air, J. Fluid Mech. 4 (1958) 505–528.
[2] C. Tien, Y.C. Yen, The effect of melting on forced convection heat transfer, J. Appl. Meteorol. (1965) 523–527.
[3] M. Epstein, D.H. Cho, Laminar film condensation on a vertical melting surface, ASME J. Heat Transfer 98 (1976) 108–113.
[4] E.M. Sparrow, S.V. Patankar, S. Ramadhyani, Analysis of melting in the presence of natural convection in the melt region, ASME J. Heat Transfer 99 (1977) 520–526.
[5] A.L. Maples, D.R. Poirier, Convection in the two-phase zone of solidifying alloys, Metall. Trans. B 15 (1984) 163–172.
[6] V.R. Voller, C. Prakash, A fixed grid numerical modeling methodology for convection–diffusion mushy region phase-change problems, Int J. Heat Mass Transfer 30 (8) (1987) 1709–1719.
[7] V.R. Voller, A.D. Brent, The modeling of heat, mass and solute transport in solidification systems, Int. J. Heat Mass Transfer 32 (9) (1989) 1719–1731.
[8] W.D. Bennon, F.P. Incropera, A continuum model for momentum heat and species transport in binary solid–liquid phase change systems – I. Model formulation, Int. J. Heat Mass Transfer 30 (10) (1987) 2161–2170.
[9] W.D. Bennon, F.P. Incropera, A continuum model for momentum, heat and species transport in binary solid–liquid phase change systems – II: Application to solidification in a rectangular cavity, Int. J. Heat Mass Transfer 30 (10) (1987) 2171–2187.
[10] F.M. Pozvonkov, E.F. Shurgalskii, L.S. Akselrod, Heat transfer at a melting flat surface under conditions of forced convection and laminar boundary layer, Int. J. Heat Mass Transfer 13 (1968) 957–962.
[11] M. Epstein, D.H. Cho, Melting heat transfer in steady laminar flows over a flat plate, J. Heat Transfer 98 (1976) 531–533.
[12] M. Kazmierczak, D. Poulikakos, D. Sadowski, Melting of a vertical plate in porous medium controlled by forced convection of a dissimilar fluid, Int. Comm. Heat Mass Transfer 14 (1987) 507–517.
[13] M. Kazmierczak, D. Poulikakos, I. Pop, Melting from a flat plate embedded in a porous medium in the presence of steady natural convection, Numer. Heat Transfer 10 (1986) 571–581.
[14] M.M. Chen, R. Farhadieh, L. Baker Jr., On free convection melting of a solid immersed in a hot dissimilar fluid, Int. J. Heat Mass Transfer 29 (8) (1986) 1087–1093.
[15] A.Y. Bakier, Aiding and opposing mixed convection flow in melting from a vertical flat plate embedded in a porous medium, Transp. Porous Media 29 (1997) 127–139.
[16] R.S.R. Gorla, M.A. Mansour, I.A. Hassanien, A.Y. Bakier, Mixed convection effect on melting from a vertical plate, Transp. Porous Media 36 (1999) 245–254.
[17] B. Tashtoush, Magnetic and buoyancy effects on melting from a vertical plate embedded in saturated porous media, Energy Convers. Manage. 46 (2005) 2566–2577.
[18] J. Bear, Dynamics of Fluids in Porous Media, American Elsevier, New York, 1972, pp. 355–357.
[19] Hermann Schlichting, Boundary Layer Theory, fourth ed., McGraw-Hill, New York, 1960, p. 333.
[20] H.S. Carslaw, J.C. Jaeger, Conduction of Heat in Solids, second ed., Oxford University Press, 1959.
[21] P. Cheng, Combined free and forced convection flows about inclined surfaces in porous media, Int. J. Heat Mass Transfer 20 (1977) 807–814.
[22] E.M. Sparrow, R. Eichoorn, J.L. Gregg, Combined forced and free convection in a boundary layer flow, Phys. Fluids 2 (1958) 319–328.