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Original Research Paper

Melting effect on convective heat transfer from a vertical plate embedded in a non-Darcy porous medium with variable permeability

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ABSTRACT

We have presented an analysis to study the effect of melting with variable permeability on non-Darcy mixed convective flow over a vertical surface. The influence of thermal radiation was considered on the right hand side of energy equation. The variation of permeability in the vicinity of the solid boundary is approximated by an exponential function. The governing partial differential equations were transformed into ordinary ones using a similarity transformation and solved numerically by using Matlab `bvp4c` solver. The numerical results were validated by comparison with previously published results in the literature. The effects of physical parameters on the velocity, temperature and heat transfer coefficients are determined. We also tested how the variation in the variable permeability affects the physical parameters of the problem.

1. Introduction

Over the last few years the study of heat transfer with melting effect in porous media has been increased due to a wide variety of applications in industry such as magma solidification, melting of the permafrost, preparation of semiconductor materials and latent energy storage systems that use solid–liquid phase change materials (PCMs). In the absence of porous medium Roberts [1] was the first to study the shielding effect to describe the melting phenomena of ice placed in a hot stream of air in the steady state. Epstein and Cho [2] incorporated surface melting effects on the heat transport from submerged bodies. Afterwards, this work has been elongated by many authors to explore various aspects of the flow and heat transfer in vertical surface [3–7]. Melting effect on mixed convection boundary layer flow about a vertical surface embedded in a porous medium, opposing flow case was studied by Ahmad and Pop [8]. Their study reveals that the dual solution exists in some range of mixed convection parameter. Recently Merkin et al. [9] presented a note on the melting effect on mixed convection boundary-layer flow over a vertical flat surface embedded in a porous medium. The effect of non-Darcy mixed convection with thermal dispersion in a saturated porous medium was studied by Sobha et al. [7]. Their study reveals that the thermal dispersion and melting tend to increase the velocity within the boundary layer for both aiding and opposing flow.

Thermal radiation effects play an important role in controlling heat transfer in manufacturing processes where the quality of the final product may depend on heat control factors. In recent years there have been several applications in the cooled nuclear reactors, liquid metal fast reactors, power generation systems. Melting and radiation effects on mixed convection from a vertical surface embedded in a non-Newtonian fluid saturated non-Darcy porous medium for aiding and opposing flows was studied by Chamkha et al. [10]. They observed that the increase in melting parameter results, decrease in the velocity profile for opposing external flow and an increase in the aiding external flow. Prasad and Hemalatha [11] studied the effects of non-Darcy mixed convection with thermal dispersion–radiation in a saturated porous medium. They found that the combined effect of radiation and dispersion increases the velocity with melting in both aiding and opposing cases. Hossain and Takhar [12] studied the effects of Radiation and mixed convection along a vertical plate with uniform surface temperature. Mixed convection radiation interaction about an inclined plate through a porous medium was studied by Moradi et al. [13]. They solved the resulting system of equations by using HAM method. Their results demonstrate that increase in radiation parameter increases the thermal and hydromagnetic boundary layer thickness.

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Nomenclature

b	constant defined in Eq. (9)
C_f	Forchheimer empirical constant
C_s	specific heat of solid phase
C_p	specific heat at constant temperature
c_{pf}	specific heat of the convective fluid
d	constant defined in Eq. (9)
f	dimensionless stream function
F	non-Darcy parameter
g	acceleration due to gravity
h_{sf}	latent heat of melting of solid
K	permeability of porous medium
k_{eff}	effective thermal conductivity
k^*	mean absorption coefficient
k_f	thermal conductivity of the fluid
k_s	thermal conductivity of the solid
M	melting parameter
Nu_x	local Nusselt number
Pe_x	local Peclet number
q_r	radiative heat flux
q_w	heat flux at the wall
Ra_x	local Rayleigh number
R	radiation parameter
T	temperature
T_0	temperature at the solid region
T_∞	ambient temperature
u_∞	characteristic velocity
u, v	velocity components in x and y directions
x, y	coordinates along and normal to the plate
α	thermal diffusivity of the saturated porous medium
β	thermal expansion coefficient
ε	porosity of the porous medium
η	similarity variable
θ	dimensionless temperature
λ_f	thermal conductivity of fluid
λ_m	thermal conductivity of the saturated porous medium
λ_s	thermal conductivity of solid
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density of the fluid
ρ_∞	density at large values of y (ambient)
σ	ratio of thermal conductivity of the solid to the conductivity of the fluid
σ^*	Stefan–Boltzmann constant
ψ	stream function

Subscripts

m	melting point
∞	ambient condition
T	temperature

Superscript

$'$	differentiation with respect to η

Abbreviations

VP	variable permeability

On the other hand the effects of variable permeability have many applications such as in the fixed-bed catalytic reactors and packed bed heat exchangers. The variable porosity effect for forced convection flow was theoretically and experimentally investigated by Vafai [14] and Vafai et al. [15]. The flow past through a porous medium have been studied by Chandrasekhara et al. [16]. They investigated that the variation of the porosity and permeability has great influence on the velocity distribution and heat transfer. Hassanien [17] studied the effects of variable permeability on mixed convection along a vertical wedge in a porous medium with variable surface heat flux. He presented the velocity and temperature profiles for the mixed convection regime for both uniform and nonuniform permeabilities. Hassanien et al. [18] studied the onset of longitudinal vortices in mixed convection flow over an inclined surface in a porous medium with variable permeability. In their studies, they observed that variable permeability effect increases the velocity gradient. Recently Satyanarayana [19] studied the effects of variable permeability and radiation absorption on magnetohydrodynamic (MHD) mixed convective flow in a vertical wavy channel with traveling thermal waves. His study reveals that porosity parameter enhancing the velocity of the flow field at all the points.

In this article, we explore the significance of the combined effects of melting and variable permeability on non-Darcy mixed convective flow over a vertical plate. Most of the reported research in the literature have not contemplated the combined effects of melting and variable permeability. Sobha et al. [7] presented a related study on mixed convection and thermal dispersion on temperature profile. They have not considered the variable permeability effects in their study. Chamkha et al. [10] studied the effects of radiation and mixed convection on non-Newtonian fluid saturated in non-Darcy porous medium with aiding and opposing flows. They ignored the effects of variable permeability in their study. This study provides an understanding of melting with variable permeability for engineering and medical applications.

2. Mathematical formulation

In this problem we considered the melting and variable permeability effects on non-Darcy mixed convective two dimensional flow of an incompressible fluid over a vertical surface in a saturated porous medium. To analyze the mixed convection heat transfer we have to obtain the differential equation describing the motion of the fluid in the boundary layer. The flow configuration is shown in Fig. 1. The origin of the system is taken at the leading edge of the plate. Let us choose the x-coordinate along the plate and the y-coordinate perpendicular to the plate. It is assumed that the plate constitutes the interface between the liquid phase and

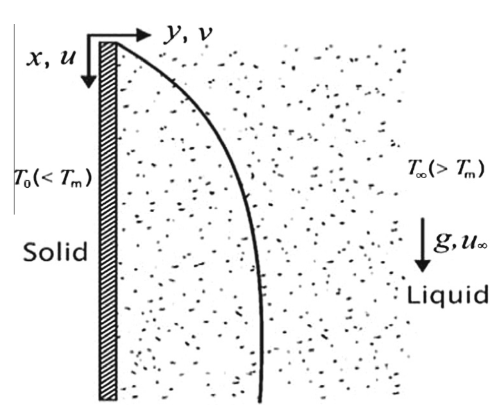

Fig. 1. Physical model and coordinate system.