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Jet impingement cooling of a horizontal surface in an unconfined porous medium: Mixed convection regime

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ABSTRACT

Two-dimensional slot jet impingement cooling of an isothermal horizontal surface immersed in an unconfined porous medium is simulated numerically to gain insight into thermal characteristics under mixed convection conditions with the limitation of the Darcy model. The jet direction is considered to be perpendicular from the top to the horizontal heated element; therefore, the jet flow and the buoyancy driven flow are in opposite directions. The results are presented in the mixed convection regime with wide ranges of the governing parameters: Péclet number ($1 \leqslant Pe \leqslant 1000$), Rayleigh number ($10 \leqslant Ra \leqslant 100$), half jet width ($0.1 \leqslant D \leqslant 0.5$), and the distance between the jet and the heated portion ($0.1 \leqslant H \leqslant 1.0$). It is found that the average Nusselt number increases with increase in either Rayleigh number or jet width for high values of Péclet number. The average Nusselt number also increases with decrease in the distance between the jet and the heated portion. It is shown that mixed convection mode can cause minimum average Nusselt number at two values of Péclet number and a maximum average Nusselt number occurs in between theses two Péclet numbers at higher Rayleigh number due to counteraction of jet flow against buoyancy driven flow. Hence careful consideration must be given while designing a system of jet impingement cooling through porous medium.

1. Introduction

The jet impingement cooling through horizontal porous layer are important from theoretical as well as application points of view. The buoyancy driven phenomena in porous media has attracted many researchers interests due to a large number of technical applications, such as, fluid flow in geothermal reservoirs, insulation of buildings, separation processes in chemical industries, dispersion of chemical contaminants through water saturated soil, solidification of casting, migration of moisture in grain storage system, crude oil production, solar collectors, electronic components cooling, etc. Comprehensive literature survey concerned with this subject is given by Gebhart et al. [1], Kaviany [2], Nield and Bejan [3], Pop and Ingham [4], Bejan and Kraus [5], Ingham et al. [6], Bejan et al. [7] and Vafai [8]. The literature shows that the jet impingement through pure (non-porous) fluid has been studied extensively (see, for example [9–18]).

Recently many researchers considered the impinging jet through porous media. Fu and Huang [19] investigated numerically the effects of a laminar jet on the heat transfer performance of three different shape (rectangle, convex and concave) porous blocks mounted on a heated plate. They neglected the buoyancy effects and considered the forced convection mode only. Their results show that the heat transfer is mainly affected by a fluid flowing near the heated region. For a lower porous block, the three types of porous block enhance the heat transfer. However, for a higher porous block, the concave porous block only enhances heat transfer.

A detailed flow visualization experiment was carried out by Prakash et al. [20] to investigate the effect of a porous layer on flow patterns in an overlying turbulent flow without heat transfer. They studied the effect of the parameters such as the jet Reynolds number, the permeability of the porous foam, the thickness of the porous foam and the height of the overlying fluid layer. Jeng and Tzeng [21] studied numerically the air jet impingement cooling of a porous metallic foam heat sink in the forced convection mode. They found the porous aluminum foam heat sink could enhance the heat transfer from the heated horizontal source by impinging cooling. Their results show that the heat transfer performance of the aluminum foam heat sink is 2–3 times larger than that without it. Saeid and Mohamad [22] studied numerically the jet impingement cooling of heated portion of an isothermal horizontal surface immersed in a fluid saturated porous media in the mixed convection regime. It was found for high values of Péclet number that increasing either

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Nomenclature

d	half of the width of the jet (m)
D	non-dimensional half of the width of the jet (d/L)
g	acceleration due to gravity (m s^{-2})
h	distance between the jet and the heated portion (m)
H	dimensionless distance between the jet and the heated portion (h/L)
k	thermal conductivity (W m^{-1} K^{-1})
K	permeability of the porous medium (m^2)
L	half of the heat source length (m)
Nu	local Nusselt number
p	pressure (Pa)
Pe	Péclet number ($Pe = V_0L/\alpha$)
Ra	Rayleigh number for porous medium ($Ra = g\beta K\Delta TL/\nu\alpha$)
r	distance from the jet inlet to the top of the solution domain (m)
R	dimensionless distance from the jet inlet to the top of the solution domain (r/L)
s	distance from the heated portion to the end of the solution domain (m)
S	dimensionless distance from the end of heated portion to the solution domain (s/L)
t	non-dimensional time
t^*	time (s)
T	temperature (K)
u, v	velocity components along x- and y-axes, respectively (m s^{-1})
V_0	jet velocity (m s^{-1})
U, V	non-dimensional velocity components along X and Y-axes, respectively
x, y	Cartesian coordinates (m)
X, Y	non-dimensional Cartesian coordinates

Greek symbols

α	effective thermal diffusivity (m^2 s^{-1})
β	coefficient of thermal expansion (K^{-1})
θ	non-dimensional temperature
μ	dynamic viscosity (Ns m^{-2})
ν	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
ψ	stream function (m^2 s^{-1})
Ψ	non-dimensional stream function

Subscripts

avg	average
c	cold
h	hot

Rayleigh number or jet width lead to increase the average Nusselt number. Narrowing the distance between the jet and the heated portion could increase the average Nusselt number. Jeng et al. [23] carried out experimental investigation on heat transfer associated with air jet impingement on rotating porous Aluminum foam heats sink. They investigated the effects of jet Reynolds number (Re) in the forced convection mode, the relative nozzle-to-foam tip distance (C/d), the rotational Reynolds number (Re_r) and the relative side length of the square heat sink (L/d). They found that, when Re and L/d were small and C/d was large, the increase in Re_r increases the average Nusselt number. Sivasamy et al. [24] presented numerical investigation of jet impingement cooling of a constant heat flux horizontal surface immersed in a confined porous channel under mixed convection conditions.

Jet impingement cooling of a horizonalt surface in a porous medium with out confinement wall is not investigated so far. The objective of the present study is to investigate the thermal characteristics of the jet impingement cooling of a horizontal surface with buoyancy effect in porous media in the mixed convection regime. A parametric study is carried out to investigate various parameters influences to the heat transfer performance.

2. Problem description

In the present study, the effect of the buoyancy on the jet impingement cooling of an isothermal horizontal surface immersed in a fluid saturated porous media is considered as shown in Fig. 1. The objective of the present study is to characterize the thermal performance of the jet impingement cooling in porous media in the mixed convection regime with the limitation of the Darcy model. The governing parameters in the present problem are the half jet width d, the jet velocity V_0, the distance between the jet and the heated portion h, and the heat source length $2L$ in additional to the physical properties of the porous media and the fluid. These parameters can be reduced to a number of dimensionless groups as given below. The physical properties are assumed to be constant except the density in the buoyancy force term which is satisfied by the Boussinesq's approximation. Further it is assumed that the temperature of the fluid phase is equal to the temperature of the solid phase everywhere in the porous region, and local thermal equilibrium (LTE) model is applicable in the present investigation. The viscous drag and inertia terms of the momentum equations are negligible, which are valid assumptions for low Darcy and particle Reynolds numbers.

Under these assumptions, the conservation equations for mass, momentum and energy for the two-dimensional unsteady flow are:

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

$$u = -\frac{K}{\mu}\frac{\partial p}{\partial x} \tag{2}$$

$$v = -\frac{K}{\mu}\left\{\frac{\partial p}{\partial x} + \rho_0 g[1 - \beta(T - T_0)]\right\} \tag{3}$$

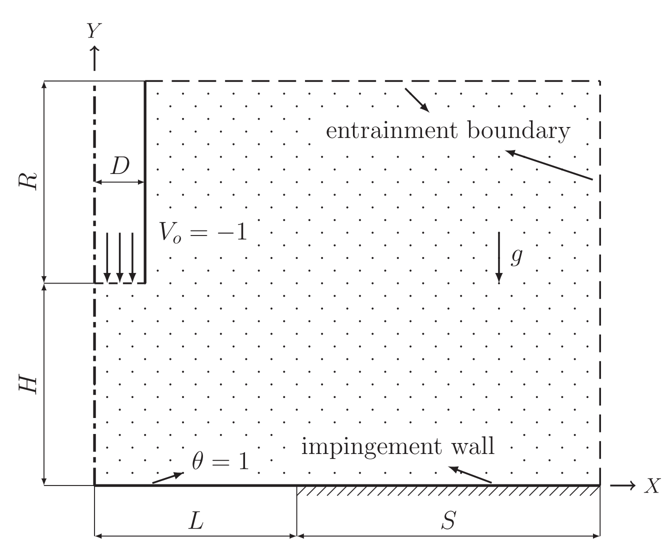

Fig. 1. Schematic diagram of the physical model and coordinate system.