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Effects of thermal spot configurations on the flow through porous media driven by natural and forced convection

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Abstract

A study concerning the flow of a Newtonian fluid through a porous medium for the particular case natural convection is produced by hot and cold spots placed in the solid phase is presented. Results involving the interaction of forced convection with thermal spots are reported to visualize the mechanisms associated with the generation of complex flow patterns in the porous medium. For this purpose the computation of a two-field model is carried out. Two systems are studied: one is a rectangular porous cavity (RPC) of square cross section and the other is an annular porous cavity (APC) comprised by two concentric vertical cylindrical walls. It is shown, in general, that the flow patterns associated with each configuration and intensities of the thermal spots may be qualitatively inferred by following rules that are established through a basic study of mixed convection in the RPC.

Keywords: Natural convection; Mixed convection; Thermal spots; Porous media; Two-field model

1. Introduction

At present, the evaluation of the velocity field and the heat flux, both generated by natural and forced convection in a porous medium containing cold and hot spots of variable intensity, is a relevant subject of practical interest. Multiple technological applications in different industrial equipments and electronic devices require the detailed knowledge of velocity and temperature fields under this particular situation. For instance, it has been reported that the quality of grain and cereal storage and drying in silos is affected by the generation of hot spots in the granular bed, which are caused by fungal growth and grain germination, among other naturally occurring phenomena [1,2]. Also, flow maldistributions may induce hot spots in packed-bed reactors as a consequence of destabilization of the basic uniform flow typically assumed in designs; thus, the effective conversion of reactants may be quite different from the nominal value expected, usually with an inhomogeneous product due to undesired side reactions [3,4]. In similar systems, strongly localized stationary and traveling hot spots arise when changes in gas velocity occur in the catalytic combustion of hydrogen in monolith reactors [5]. Another challenging problem involves thermal control by appropriate air cooling of integrated circuits, which are at present configured under significant miniaturization and reduction of spaces between them [6,7]. Thus,

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Nomenclature

a	thermal dispersion coefficient
a_v	specific surface of porous medium, m^{-1}
b	Forchheimer inertial constant, m
C_f^0	fluid heat capacity at constant pressure, J/kg K
d_p	particle diameter, m
D	width of porous cavity, m
Da	Darcy number ($=K_\infty/D^2$)
Fs	Forchheimer number ($=b_\infty/D$)
$\boldsymbol{g}$	gravity acceleration, $\mathrm{m/s^2}$
G_0	dimensionless source or sink intensity ($=S_0D^2/\Delta T k_{\mathrm{m}\infty}$)
Gr	Grashoff number ($=(\rho_\mathrm{f}^0)^2 g\beta K_\infty D\Delta T/(\mu_\mathrm{f}^0)^2$)
h_f	fluid heat-transfer coefficient, $\mathrm{W/m^2\,K}$
h_s	solid heat-transfer coefficient, $\mathrm{W/m^2\,K}$
h_sf	solid–fluid heat-transfer coefficient, $\mathrm{W/m^2\,K}$
H	Sparrow number ($=h_\mathrm{sf}D^2a_v/k_{\mathrm{m}\infty}$)
$\boldsymbol{I}$	unity tensor
k_α	thermal conductivity, W/m K ($\alpha = \mathrm{s,f}$)
k_m	stagnant thermal conductivity of the saturated porous medium, W/m K
$\boldsymbol{k}_\mathrm{d}^*$	dimensionless thermal dispersion tensor
K	permeability of the porous medium, $\mathrm{m^2}$
l_c	characteristic length for heat transfer in the solid phase, m
L	height of the porous cavity, m
Pe	Peclet number ($=U_\infty D/\alpha_\mathrm{f}^0$)
Pr_f	fluid Prandtl number ($=C_\mathrm{f}^0\mu_\mathrm{f}^0/k_\mathrm{f}^0$)
Q_h	dimensionless heat flux at the hot wall, defined by Eq. (7)
Q_c	dimensionless heat flux at the cold wall, defined by Eq. (8)
r_i	inner radius of porous cavity, m
r_o	outer radius of porous cavity, m
r_v	($=V/\widehat{V}$)
Ra	Rayleigh number ($=\rho_\mathrm{f}^0 g\beta K_\infty D\Delta T/\mu_\mathrm{f}^0\alpha_{\mathrm{m}\infty}$)
Ra_f	fluid Rayleigh number ($=Ra/Da\lambda$)
Re_p	particle Reynolds number ($=\rho_\mathrm{f}^0\varepsilon\lvert\boldsymbol{v}_\mathrm{f}\rvert d_\mathrm{p}/\mu_\mathrm{f}^0$)
S_0	source or sink intensity of thermal spot, $\mathrm{W/m^3}$
T_α	temperature, K ($\alpha = \mathrm{s,f}$)
T_i	wall temperature, K ($i = \mathrm{h,c}$)
U_∞	maximum superficial velocity at the cavity entry, m/s
$\boldsymbol{v}_\mathrm{f}$	fluid velocity, m/s
$\boldsymbol{V}$	dimensionless superficial velocity for natural convection
$\widehat{\boldsymbol{V}}$	dimensionless superficial velocity for forced convection
x	horizontal coordinate, m
X	($=x/D$)
z	vertical coordinate, m
Z	($=z/D$)

Greek symbols

$\alpha_{\mathrm{m}\infty}$	thermal diffusivity of saturated porous medium ($=k_{\mathrm{m}\infty}/\rho_\mathrm{f}^0C_\mathrm{f}^0$), $\mathrm{m^2/s}$
β	isobaric thermal expansion coefficient, K^{-1}
γ	($=d_\mathrm{p}/D$)
ε	porous medium porosity
Θ_α	dimensionless temperature ($\alpha = \mathrm{s,f}$)
κ	($=r_\mathrm{o}/r_\mathrm{i}$)
λ	($=k_\mathrm{f}^0/k_{\mathrm{m}\infty}$)
μ_f^0	fluid viscosity, Pa s
ν	($=k_\mathrm{s}^0/k_{\mathrm{m}\infty}$)
ρ_f^0	fluid density, $\mathrm{kg/m^3}$ ($\alpha = \mathrm{s,f}$)
σ	heat dispersion around the peak
Ψ	streamline

Subscripts

c	cold wall
f	fluid phase
h	hot wall
m	properties of composite (solid and fluid)
s	solid phase
w	wall
∞	any property far from cavity walls

Superscript

0	property of pure species

since the circuit densities are significantly increased with inevitable higher power dissipation, the internal offset fin structures may be modeled as a saturated non-isothermal porous medium [8]. Therefore, for design purposes, heat transfer limitations must be appropriately evaluated in relation to the relative position of hot and cold spots. In this sense, although natural convection can be used as a mean of thermal control providing a vibration-free environment in contraposition to forced convection [9], one observes that flow paths are rather complex around thermal spots, affecting thus the intensity of heat transfer and placing the need to seek for the optimal cooling configuration.

In a wider context of practical situations, rather different from that described above, it is also clear that natural and mixed convections of a fluid saturating a porous medium has received much attention in the literature at present [10,11] mainly without the inclusion of heat sources; those including thermal spots are significantly a few less [2,12–14]. In particular, the presence