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Analytical investigation of heat transfer enhancement in a channel partially filled with a porous material under local thermal non-equilibrium condition

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A B S T R A C T

Forced convection through a channel partially filled with a porous medium is investigated analytically in the present work. Thermally developed condition is considered and the local thermal non-equilibrium model is utilized to obtain the exact solutions of both fluid and solid temperature fields for flow inside the porous material as well as for flow in the clear region. Nusselt number is obtained in terms of the porous insert thickness (S), porosity (ε) as well as pertinent parameters such as thermal conductivity ratio (k), Biot number (Bi), and Darcy number (Da). The values of S by which the temperature difference between the two phases approach to zero, for different values of Bi, k, and Da number are obtained. It is found that three mechanisms affect the Nu number i: clear fluid conduction ii: internal heat exchange in the porous medium iii: channeling effect in the clear flow. The value of S, which yields the highest Nu number is found to vary linearly from 0.8 to 0.97 as the value of Da decreases from 10^{-3} to 10^{-7}. At the expense of reasonable pressure drop the optimum thickness of porous material in order to enhance the heat transfer rate is found $S = 0.8$.

1. Introduction

The employment of different types of porous materials in forced convection heat transfer has been extensively studied due to the wide range of potential engineering applications, such as electronic cooling, drying processes, solid matrix heat exchangers, heat pipes, etc [1]. The assumption of local thermal equilibrium (LTE) widely used in many of these applications. However the LTE assumption is not valid when a substantial temperature difference exists between the solid and fluid phases [2]. Vafai and Thiyagaraja [3] presented analytical solutions for the velocity and temperature fields for the interface region using the Brinkman–Forchheimer extended Darcy equation. They considered three fundamental types of the interface namely, the interface between two porous regions, between a porous medium and a fluid layer and the interface between a porous medium and an impermeable medium. Amiri and Vafai [4] employed a general fluid flow model and a two-phase energy equation to investigate the forced convection heat transfer within a channel filled with porous medium under constant wall temperature. They included the effects of variable porosity and thermal dispersion in their analysis and error maps for validation of LTE model were established in their work. Lee and Vafai [5] employed the local thermal non-equilibrium model to investigate the forced convection flow through a channel filled with a porous medium subject to a constant heat flux. They obtained analytical solutions for the fluid and solid phase temperature distributions. In their work, the validity of one-equation model was presented. Marafie and Vafai [6] obtained analytical expressions for the fluid and solid phase temperature distributions, for convective flow through the channel with a constant heat flux applied at walls and accounting for both boundary and inertia effects. Darcy–-Brinkman–Forchheimer model has been used to represent the fluid transport through the porous medium.

High thermal conductivity porous substrate is also used to enhance forced convection heat transfer in many engineering applications, such as, nuclear cooling, heat exchangers and solar collectors [7–9].

Furthermore, partial filling of a channel with a porous material forces the flow to escape from the core region, reduces the boundary layer thickness and consequently increases the rate of heat transfer [7]. Al-Nimr and Alkam [10–12] numerically investigated the problem of transient forced convection flow in an annuli partially filled with a porous medium either on the inner or the outer cylinder, under local thermal equilibrium condition. An increase, up to 12 times in the Nusselt number was reported. Chikh et al. [13,14] presented an analytical solution for the fully developed flow in annulus configuration partially filled with the porous

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