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Limiting Nusselt numbers for laminar forced convection in asymmetrically heated annuli with viscous dissipation☆

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ABSTRACT

Analytical expressions for the Nusselt number at the inner and outer pipes, kept at unequal temperatures, for laminar forced convection through annuli including viscous dissipation have been obtained in the conduction limit. This article examines the dependence of the limiting Nusselt numbers on the Brinkman number and the degree of asymmetry in inner and outer pipe temperatures. Further, the limiting temperature profile obtained when viscous dissipation is included serves the purpose of providing the downstream boundary condition needed in solving the elliptic form of conservation of thermal energy equation that arises when axial conduction is included.

1. Introduction

Interest to study laminar internal flow heat transfer through concentric annuli subjected to asymmetric heating has been increasing owing to the present day applications like fuel cells, catalytic reactors and solar receivers or absorbers. Viscous dissipation effects are also expected to be significant in contemporary applications. This article, as a first step, aims to obtain the limiting temperature profiles and the Nusselt numbers.

Studies pertaining to forced convection in channels, the walls of which have been kept at unequal temperatures can be found in Hatton and Turton [1], Mitrovic et al. [2] and recently in Ramjee and Satyamurty [3]. Mitrovic and Maletic [4] investigated heat transfer in asymmetrically heated annuli. All these studies assumed fully developed flow field and neglected axial conduction. Studies on asymmetrically heated channels and annuli, filled with porous material can be found in [5,6]. In the case of channels kept at unequal temperatures, when viscous dissipation is not included, the limiting Nusselt number is 4 and is independent of the degree of asymmetry. Similarly, Barletta [7] obtained the limiting Nusselt number to be 17.5, when viscous dissipation is included and the parallel plates are kept at equal temperature. This value of 17.5 is independent of the Brinkman number, which characterizes viscous dissipation. Recently Ramjee and Satyamurty [8] have shown that the limiting Nusselt number depends on both the degree of asymmetry and the Brinkman number when viscous dissipation is included and the channel is heated unequally. Such studies have not been performed for flows though annuli. The limiting Nusselt numbers in the case of annuli can be expected to be dependent on an additional geometric parameter, viz. the radius ratio.

2. Mathematical formulation

The physical model considered that of a concentric annular pipe of inner radius, r_i and outer radius, r_o is shown in Fig. 1(a) and (b) along with the coordinate system. r is the radial coordinate. The fluid enters the annulus with an average velocity of u_{avg} and a uniform temperature of T_e. The flow is assumed to be hydrodynamically fully developed. The inner and outer pipes of the annular duct are maintained at constant but unequal temperatures, T_{wi} and T_{wo} respectively.

The asymmetry in the wall temperatures is characterized by the parameter A, defined by,

$$A = (T_{wo} - T_e) / (T_{wi} - T_e). \tag{1}$$

$A = 1$ refers to the case of symmetric heating or cooling, when $T_w = T_{wi} = T_{wo}$.

The non-dimensional radial coordinate, R, the fully developed velocity, U and the temperature, θ, the radius ratio, $r^*$are defined as following.

$$R = (r - r_i) / [2(r_o - r_i)];\ U = u / u_{avg} \text{ and } \theta = (T - \overline{T}_w) / (T_e - \overline{T}_w); r^* = r_i / r_o. \tag{2}$$

In Eq. (2), $[2(r_o - r_i)]$, is also the hydraulic diameter for the annulus. $u\ (r)$ and $T\ (r)$ are the dimensional fully developed velocity and the temperature of the fluid. $\overline{T}_w$, the average wall temperature is defined by,

$$\overline{T}_w = (T_{wi} + T_{wo}) / 2. \tag{3}$$

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