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Slip flow forced convection in a microchannel with semi-circular cross-section ☆

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ABSTRACT

This paper offers theoretical results for fully developed slip-flow forced convection through a microchannel of semicircular cross-section. Numerical results are also presented to study the developing region. Velocity slip and temperature jump boundary conditions are applied at the uniformly heated walls. The results from the two different sources are cross validated and those pertaining to the limiting case of no-slip flow are found to be in good agreement with those available in the literature.

1. Introduction

Studying heat and fluid flow through microchannels are getting more and more attention in the electronic industry, chemical reactors, ground water movements, insulation design, and biological systems [1–26]. The rapid development of the electronic systems resulted in large heat at high fluxes and the heat removal of such systems becomes an important concern for the safety and reliability of such devices [27]. Microchannel heat sinks have found superior performance in refrigeration systems and lead to notable charge reduction in such systems [28,29]. In moving towards efficient dry cooling techniques [30], Queensland Geothermal Energy Centre of Excellence started to look into the application of such compact heat sinks as air-cooled heat exchangers/condensers with the main goal of reducing parasitic losses. The size of such microchannel heat sinks can be as small as the molecular mean free path. Hence, the Knudsen number, defined as the ratio of molecular mean free path length to a representative physical length scale, $Kn = \frac{\Lambda}{L}$ can be in the range $0.001 < Kn < 0.1$. It is known that for flow of a gas through a microchannel when the Knudsen number falls in this slip-flow range, the Navier–Stokes equations should be solved subject to a set of modified boundary conditions (see our Eqs. (1) and (2)) so that the results can match those obtained by experiments [11–14]. Implementing these boundary conditions can be an easy task for microconduits of regular cross-section [26] but those of arbitrary cross-sections see [1–3,13,14] for instance, can be hard to deal with. It is well-documented that the cross-sectional shape of a microchannel strongly depends on the technology used to build it [27]. For example, producing microchannels by chemical etching directly on the silicon wafers, the cross-sectional shape depends on a number of factors like the crystallographic nature of the silicon [27]; whereas it is possible to have microchannels of any cross-section. Therefore, more work on convection through microducts of arbitrary cross-sections is called for.

In view of the above, this paper presents numerical simulation of heat and fluid flow through a microchannel of semicircular cross-section with the walls being subjected to H1 boundary conditions following Shah and London's [31] terminology. Theoretical results are then compared with numerical predictions for the fully developed region.

2. Theoretical analysis

Fully developed, both thermally and hydrodynamically, forced convection slip-flow in a duct of semi-circular cross-section as shown by Fig. 1. This kind of problem occurs in circular tubes with a full baffle or twisted tape or welded conduits composed of a flat plate and a curved plate [32].

By assuming the incompressible fluid with constant properties, the slip velocity u_s^* is given by

$$u_S^* = \frac{F-2}{F}\ Kn\ D_H \frac{\partial u^*}{\partial n^*}\Big|_{wall} \tag{1}$$

where F is the tangential momentum accommodation coefficient, n* denotes the coordinate which is normal to the wall, Kn, is the Knudsen number with hydraulic diameter D_H as the length scale. The difference

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