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Axial conduction in single-phase simultaneously developing flow in a rectangular mini-channel array

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ABSTRACT

Thermo-hydrodynamic performance of hydrodynamically and thermally (simultaneously) developing single-phase flow in an array of rectangular mini-channels has been experimentally and numerically investigated. The test section consists of fifteen rectangular parallel mini-channels of width 1.1 ± 0.02 mm, depth 0.772 ± 0.005 mm (aspect ratio = 0.7, hydraulic diameter = 0.907 mm), inter-channel pitch of 3.1 mm, machined on a copper substrate of thickness 8.0 mm and having an overall length of 50 mm. Deionized water used as the working fluid, flows horizontally and the test section is heated by a thin surface-mountable, stripe heater (constant heat flux boundary condition applied at the bottom of the substrate; top face being adiabatic). Reynolds number (Re) between 150 and 2500 and Prandtl number between 3 and 4, at an inlet pressure of about 1.1 bar, are examined. The laminar-to-turbulent transition is found to commence at Re ≈ 1100 for average channel roughness of 3.3 μm ($\varepsilon/D_h = 0.364\%$). Poiseuille (Po) and local Nusselt number (Nu_x) are function of flow Re in the entire range of experiments. Experimental data for Po and Nu_x are compared with available correlations for simultaneously developing flows in rectangular channels. A 3D numerical CFD model, exactly corresponding to the geometry and boundary conditions of the experimental setup, has also been developed. Conservation equations have been solved in the conjugate domain to explore conjugate heat transfer effects leading to deviation from true constant heat flux conditions. It is observed that at higher value of the axial conduction number (M), the experimental setup is prone to conjugate effects as a consequence of axial back conduction in the substrate. Due to this, local experimental Nusselt numbers are not only smaller than the actual counterparts predicted by the model, but also their axial variation is affected. Apart from the fact that transition occurs early, no new physical phenomena or effects are observed in the data. Most parallel channels connected to a common inlet header will have fully or partially developing flows. In addition, depending on the geometry and flow conditions (i.e. parameter M), conjugate heat transfer effects become predominant; therefore, the data should be carefully interpreted in this context and background.

1. Introduction

In recent years, there is a rapid growth of applications which require high heat transfer rates and fluid flows in relatively small passages. Some examples, which demand such flow conditions, are electronics cooling, space thermal management, MEMS devices for biological and chemical reactors, etc. The development of new applications requiring cooling of components in a confined space has motivated researchers to focus on the prediction of the thermo-hydrodynamic performance of mini and microchannels.

Though the words *minichannel* and *microchannel* appear frequently in the literature, there is no generally accepted demarcation of their regimes. The hydraulic diameter ($D_h = 4A/\zeta$) of the channel array used in this experimental study is 0.907 mm. Looking into the recent literature, this will be categorized as a 'mini-channel' [1], although alternate available definitions may also classify this hydraulic diameter as a 'microchannel' [2]. Despite the fundamental simplicity of laminar flow in straight ducts, experimental studies of mini/microscale flow have often failed to reveal the expected relationship between the transport parameters (e.g., friction factor and Reynolds number, flow transition limits). Furthermore, data for simultaneously developing flows, which inherently provide high species transport coefficients and therefore of practical interest, are not very abundant. Specific correlations for simultaneously developing flows for non-circular channels for the entire range of Pr and geometrical parameters, have also limited availability. In this context, before proceeding to describe the nuances of the present study, the relevant literature is reviewed in the next section.

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