Study of Laminar Micro-Convective Flow with Variable Fluid Properties

A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

'by'

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“Dedicated to my beloved parents & family”

For their love, endless support, encouragement & sacrifices

ABSTRACT

Over the last two decades, the rapid advances in micro-fabrication techniques have provided the capability to batch fabricate micro-devices quickly and inexpensively. Therefore, the use of high-density, high power, and high-speed micro-devices are increasing day by day that leads to widespread interest in the micro-fluid mechanics and the need for both comprehensive and systematic investigation of the fundamental aspects of these phenomena. Flows in such devices are subjected to high-temperature gradients and operate at low Reynolds numbers. These flows exhibit substantial variations in fluid properties, viz. Density (ρ), Dynamic viscosity (μ), Thermal conductivity (k), and Specific heat at constant pressure (C_p). The present study investigates the influence of variations in fluid properties (a Non-rarefaction effect) on liquid and gas micro-convection. Some deviations at the micro-scale flow from conventional theory have been reported in the past, but the causes of these deviations are not comprehensively and systematically explained or justified. Thus, the objective of this thesis is to understand flow deviations due to variations in fluid properties, which can help in the design of micro-channel heat sinks of micro-devices or cooling system of gas turbine blades. The present investigations can be summarized as follow:

The physical effects of fluid property variations on flow and thermal development in micro-channel are numerically analyzed. The effects of temperature-dependent density $\rho(T)$, viscosity $\mu(T)$, and thermal conductivity $k(T)$ variations on single-phase laminar forced convection are investigated. The problem is especially simulated for hydrodynamically and thermally developing water flow in micro-channel with no-slip, no-temperature jump, and constant wall heat flux boundary conditions. The present research, by means of numerical results, analyzes the influence of $\rho(T)$, $\mu(T)$, and $k(T)$ variations on Fanning friction factor (f_f), Poiseuille number (Po), dimensionless wall velocity gradient $(\partial\bar{u}/\partial\bar{r})_w$, static gauge pressure

drop (Δp_s) and Nusselt number (Nu). The effects of temperature-dependent viscosity variation on fully developed flow through a micro-channel are also numerically investigated in this thesis. The effects of $\mu(T)$ variation are able to couple the velocity and temperature fields. Therefore, the velocity and temperature profiles vary qualitatively along the micro-flow. Due to $\mu(T)$ variation, the concept of *flow undevelopment* (the reverse process of flow development) is observed in the flow regime.

The Chilton-Colburn analogy is very helpful for evaluating the heat transfer in internal forced flows. In the present thesis, the validity of Chilton-Colburn analogy between $St \cdot Pr^{2/3}$ and f_f is re-examined for laminar micro-convective flow with variable thermophysical fluid properties. It is observed that the Chilton-Colburn analogy is valid only for that portion of the flow regime, where $St \cdot Pr^{2/3}$ decreases with decreasing f_f. The validity of Chilton-Colburn analogy is also verified by the inverse dependence of Reynolds number (Re) with f_f. Two modified non-dimensional parameters *"$\Pi_{S\mu T}$ and Π_{SkT}"* are emerged from the non-dimensional form of 2D, steady state, incompressible, pure continuum-based, laminar conservation of momentum and energy equations respectively. Additionally, the role of $\Pi_{S\mu T}$ and Π_{SkT} in flow friction is also investigated.

The present study also investigates the frictional and heat transfer characteristics of water flowing through a circular micro-channel with variable fluid properties. The computational analysis reveals the importance of physical mechanisms due to variations in thermophysical fluid properties such as viscosity $\mu(T)$, thermal conductivity $k(T)$ and density $\rho(T)$ and also their contribution in the frictional and heat transfer characteristics. Various combinations of thermophysical fluid properties have been used to find their effects on fluid friction. It is observed that the fluid friction attains the maximum value in the vicinity of the inlet and diminishes along the flow. Reynolds' analogy helps to find the flow regime in which heat transfer increases while shear stress decreases for thermophysical fluid properties.

Therefore, the present study also numerically investigates the validity of Reynolds' analogy between Stanton number (St) and Fanning friction factor (f_f) for micro-convective water flow considering combined variations in fluid properties such as temperature-dependent density, viscosity, and thermal conductivity. It is proposed that the Reynolds' analogy is valid when St increases with a decrease in f_f for thermophysical fluid properties. Three modified non-dimensional parameters ($\Pi_{S\rho T}$, $\Pi_{S\mu T}$, and Π_{SkT}) appear from the non-dimensionalization of the governing conservation equations. The dependence of the friction factor on these parameters is examined with the help of dimensional analysis. It is also noted that the effects of variation in fluid properties on the convective heat transfer coefficient and Nusselt number are significant for micro-convective flow.

The physical effects of variable fluid properties on heat transfer and frictional flow characteristics of laminar gas-micro-convective flow are also investigated in this research. The physical effects induced due to variations in air density with pressure and temperature, and gas viscosity, thermal conductivity, and specific heat with temperature are analyzed. Numerical results reveal that the heat transfer and frictional characteristics of laminar gas micro-flow are drastically affected by these physical effects. Hence, the present research suggests that these physical effects need to be well considered in the applications of laminar gas-micro-convection based on large temperature gradients, e.g. the design of micro-channel heat sink, and the flow cannot be generally considered as constant property flow, as in conventional channels.

Keywords: Micro-channels, Fully developed flow, Heat transfer characteristics, Frictional flow characteristics, Variable property effects, Dimensional analysis

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LIST OF PUBLICATIONS

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3) **R. Kumar**, S.P. Mahulikar, Numerical reexamination of Chilton-Colburn Analogy for thermophysical fluid properties, *ASME Journal of Heat Transfer* 139(7) (2017) 071701-1–10
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5) **R. Kumar**, S.P. Mahulikar, Physical effects of variable thermophysical fluid properties on flow and thermal development in micro-channel, *Heat Transfer Engineering* 39(4) (2018) 1–17 doi: 10.1080/01457632.2017.1305841, in press.
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