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Infra-red thermography of laminar heat transfer during early thermal development inside a square mini-channel

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ABSTRACT

Infra-red thermography (IRT) has been employed to experimentally scrutinize the thermo-hydrodynamics of very early part of hydrodynamically fully developed, but thermally developing, internal laminar flow of water ($850 \geqslant Re \geqslant 100$) in a mini-channel of square cross-section (5 mm × 5 mm; aspect ratio = 1.0; D_{hyd} 5 mm). The channel is machined on that face of an aluminum substrate whose dimensions are 11 mm × 140 mm; the total width of the substrate being 45 mm. A constant heat flux boundary condition is provided on the substrate face which is opposite to that on which the mini-channel is machined. Thus, the mini-channel receives heat from three sides; the fourth side being covered by an insulating poly-carbonate material. IRT provides non-intrusive and high-resolution spatial measurement of local wall temperature in the streamwise direction. By assuming a one-dimensional heat transfer model in the transverse direction, the local value of heat flux and therefore the Nusselt number, in the thermally developing region, can be estimated. Moreover, a 3D conjugate heat transfer numerical model, exactly corresponding to the real experimental conditions, has also been developed. The conjugate effects in the experiment arising due to the substrate, as well as the high heat transfer coefficient in the early thermal development zone, are analyzed. The errors and discrepancy in the *in situ* boundary conditions which may creep in due to such effects, especially in the estimation of transport coefficients in the developing flow region, are scrutinized and delineated. It is concluded that experimental estimation of local heat flux is a primary requirement for minimizing the errors in estimating local Nusselt number in developing flows. This in turn, necessitates the use of non-intrusive field measurement techniques, such as IRT.

1. Introduction

In recent years, there is a rapid growth of applications which require high heat flux removal from confined geometries. To meet this requirement, miniaturization of species transport devices, which leads to high surface to volume ratio, is required. However, miniaturization of the thermo-fluidic systems has some inherent disadvantages. For example, in small geometries, generation of turbulence is not feasible and cannot be generally used as a means for heat transfer enhancement. Transport enhancement techniques in the laminar region thus need to be understood and implemented. Hydrodynamically and/or thermally developing flows are inherently suited for passively achieving high transport coefficients. Common examples of such flows occur in electronics thermal management, cooling of laser devices, space thermal management, MEMS devices for biological and chemical reactors, micro-scale chemical reactors and heat exchangers, etc.

Laminar flows, for a range of specified boundary conditions, are quite well understood in the macroscopic domain, both experimentally and analytically [1]. Extrapolating these ideas to micro or mini scales poses several challenges, such as: (a) the ratio of area of cross sections for the heat flow in the solid substrate encompassing the flow channels to that of the fluid flow domain (A_{sf}) is usually either comparable or can even be quite large. Due to this, the ensuing conjugate nature of heat transfer cannot be ignored. The heat transfer boundary condition which the fluid actually experiences at the solid fluid boundary significantly deviates from the conventional UHF (Uniform Heat Flux) or UWT (Uniform Wall Temperature), as mathematically or experimentally conceived [2–4], (b) intrusive point measurements for determining flow characteristics and transport coefficients, for example conventional thermometry and velocimetry, also defeat the purpose as they disrupt the thermal and hydrodynamic flow behavior, (c) localized 3-dimensional effects get manifested more profoundly in these small scale systems leading to erroneous estimation of transport parameters, and, (d) developing flows, especially immediately after entrance, provide very high heat transfer and therefore require higher resolution of temperature measurement for heat transfer estimation. These limitations necessitate that the metrology of such systems be, as far as possible, non-intrusive and preferably should provide

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Nomenclature

A	area (m^2)
c_p	specific heat at constant pressure (J/kg K)
D	diameter (m)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	length (m)
M	axial heat conduction number (–)
m	fin parameter $\sqrt{p \cdot h_{amb}/(k_{fin} \cdot A_{fin})}$ (1/m)
p	perimeter (m)
Q	Heat power (W)
q''	heat flux (W/m^2)
T	temperature (K)
T^*	non-dimensional temperature (–)
u	velocity (m/s)
Z	distance from inlet (m)
Z_h	hydrodynamic non-dimensional distance (=$Z/\mathrm{Re}{\cdot}D_h$)
Z^*	thermal non-dimensional distance (=$Z/\mathrm{Re}{\cdot}\mathrm{Pr}{\cdot}D_h$)

Greek symbols

δ	thickness (m)
μ	dynamic viscosity (Pa s)
ρ	mass density (kg/m^3)
φ	heat flux ratio ($= q''_z/q''$) (–)

Non-dimensional numbers

Bi	Biot number ($h{\cdot}\delta/k_s$)
Nu	Nusselt number ($h{\cdot}D_h/k_f$)
Pr	Prandtl number ($\mu_f{\cdot}c_p/k_f$)
Re	Reynolds number ($\rho_f{\cdot}u{\cdot}D_h/\mu_f$)

Subscripts

amb	ambient
b	base
c	characteristics
f	fluid
fd	fully developed
fin	related to a fin
h	hydraulic, hydrodynamic
hp	heated perimeter
i	inlet
m	mean
o	outlet
sf	solid–fluid
t	thermal
w	wall
z	local value

multi-dimensional high-resolution spatio-temporal information of the process parameters.

IRT is a rapidly developing technique for spatio-temporal thermal measurements for research purposes. As compared to other non-intrusive techniques like Liquid Crystal Thermography (LCT), it is much more versatile, repeatable and relatively easier to implement. Various issues which need to be addressed for quantitative estimation of process parameters from the measured IR energy spectrum include, amongst others, (i) calibration of the sensor (ii) determination of the correct emissivity of the radiating surface (iii) transmissivity of the participating media and IR optics (iv) isolation of noise during digitalization [5].

Klassen et al. [6] used IRT to obtain the transient surface temperature distribution in the neighborhood of an evaporating droplet. Hetsroni et al. [7] employed a hot foil IRT technique for the measurement of heat transfer in single-phase as well as two-phase flows. Use of IRT in applications involving convective flows e.g., jet impingements on rotating disks, jet in cross flow and internal flows etc., has been reported by Astarita et al. [8]. Exploiting the capability of IRT at small scales, Hetsroni et al. [9] have performed field measurements of surface temperature of a heated capillary tube. This method was based on the measurement of local temperatures on the air-side surface of a thin heater, whereas the other side of the heater was subjected to a liquid flow; the heat transfer coefficient between the wall and inner flow was determined. Montelpare and Ricci [10] investigated the convective heat transfer coefficient of liquid cooled short pin fins using IRT. In this study, lateral surface temperature was estimated from the top surface temperature distribution captured by IR camera. Kakuta et al. [11] used IRT for measuring the temperature of sub-millimeter-thick water; the temperature distribution due to diffusion in the water was measured and results were compared with the numerical simulation by using the conduction model. In another study, Buchlin [12] used IRT for the quantitative estimation of convective heat transfer of high enthalpy flows, multi-jet systems and systems with turbulators ribs. The author also highlights the critical data reduction parameters for correct temperature estimation from IR radiation data. Recently, Hetsroni et al. [13] have implemented IRT on micro-channel and micro-fluidic systems and have highlighted the major problems encountered in the process. Brutin et al. [14] investigated the thermal motion inside the sessile drop kept at the heated surface by using IRT. Transient measurements of evaporation process were done to experimentally capture the different phases involved in it. Hemadri et al. [15] have employed IRT for the measurement of spatio-temporal 2D temperature fields on a radiator plate embedded with a pulsating heat pipe. In this study, quasi-steady state spatial surface isotherms on the radiator plate were successfully captured and the results were in good agreement to those predicted by their numerical simulations.

In the recent past, the frequency of reports describing the utilization of IRT for studying convective flows is rapidly increasing. State-of-the-art camera systems available today can provide sufficient spatio-temporal information to elucidate quantitative conclusions regarding mini and micro-scale convective flow situations, provided of course, due diligence is exercised on sources of error generation in such systems [16].

In the present study, the primary aim is to experimentally determine the local laminar heat transfer coefficient along the streamwise direction in single-phase internal convective flows. The study focuses on the very early part of thermal boundary layer development wherein the transport coefficients, as well as their axial gradients along the streamwise direction, are very high and the measurement is challenging. As noted earlier, most practical systems having mini/micro dimensions will be subjected to conjugate effects. In recent years, many studies report the quantitative estimation of the effect of conjugate heat transfer on convective flows in mini/micro scale geometries on the convective transport. Lee et al. [17] and Lee and Garimella [18] conducted a 3-D conjugate laminar heat transfer analysis, including entrance effects, for single channels as well as micro-channel heat sinks, subjected to uniform heat flux imposed on the bottom of the substrate. Operating regimes and boundary conditions wherein conjugate effects become important were identified. Based on numerical simulations they have proposed correlations to predict local and average