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Experimental Investigation of Heat Transfer Enhancement by Pulsating Flow in a Minichannel

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Abstract. The increasing power density requirements of next generation high performance electronic devices has resulted in ever-increasing heat flux densities which necessitates the evolution of new liquid-based heat exchange technologies. Pulsating flow in single-phase cooling systems is viewed as a potential solution. In this study, an experimental analysis of thermally developed pulsating flow in a rectangular minichannel is conducted. The channel test setup involves a heated bottom section approximated as a constant heat flux boundary. Asymmetric sinusoidal pulsating flows with a fixed flow rate amplitude ratio of 0.9 and Womersley numbers (Wo) of 0.51 and 1.6 are investigated. The wall temperature profiles are recorded using infrared thermography. It is observed that the transverse wall temperature profile is influenced by the sudden velocity variations of such characteristic waveforms. A heat transfer enhancement of 6% was determined for asymmetric flow pulsations of $Wo > 1$ over the steady flow with a potential augmentation for higher flow rate amplitudes.

1. Introduction

A pulsating flow is a non-zero mean mass flow which consists of an oscillating flow superimposed on a mean steady flow. The frequency dependent evolution of the inertial characteristics of pulsating flows is intrinsically linked to the local, transient heat transfer behaviour. Pulsating flows are therefore an active research area and several studies have indicated the potential for appreciable heat transfer enhancement. Unsteady pulsating flows have potential application in microelectronics cooling owing to their high near wall fluctuating velocities which leads to heat dissipation enhancements. This trend was first described in an experimental study by Richardson and Tyler [1], who described the phenomenon as an "annular effect" for several tube geometries. Similar trends were observed in oscillatory temperature profiles obtained by Zhao and Cheng [2] and Mehta and Khandekar [3].

There are a limited number of published experimental studies on pulsating flow heat transfer. Walsh et al. [4] utilized an oscillatory flow device to reduce operating temperatures in a microelectronic PC cabinet by as much as 40%, compared with steady flow temperatures. More significant heat transfer enhancement can be achieved either through the use of complex fluid channel geometries by Zhang et al. [5], or by modifying the pulsatile flow waveforms in a study by Roslan et al. [6].

Several dimensionless numbers are used to describe pulsating flows. The Reynolds number, defined as $Re = \rho V D_h/\mu$, represents the ratio of convective and diffusive time scales. The Womersley number, $Wo = (D_h/2)\sqrt{(\omega/\nu)}$, quantifies the ratio of pulsating and diffusive time scales, where $\omega = 2\pi f$ is the oscillating angular velocity [7]. A pulsation flow rate amplitude, defined as $A_0 = Q_{p,max}/Q_m$ and representing the ratio of oscillating flow rate to steady flow rate, also influences the heat transfer. The time averaged Nusselt Number ($\overline{Nu} = (\bar{h}D_h)/k$) defines the relationship between fluid thermal conductivity and surface convective heat transfer rate, averaged over one pulsation cycle. The heat transfer enhancement is quantified and compared to the steady flow, described as $dNu = (\overline{Nu} - Nu_s)/Nu_s$. The overall uncertainty of Nu is about 7%, owing to the higher uncertainties for wall and bulk temperatures. Early studies at small amplitude oscillations ($A_0 < 0.2$) carried out by Patel et al. [8] found little alteration of the time-averaged heat transfer rate in a pipe flow for $1.86 \le Wo \le 8.57$. However, Gupta et al. [9] focused on larger amplitude fluctuations ($0.06 \le A_0 \le 4$) and ($2.29 \le Wo \le 3.79$), and measured a heat transfer enhancement of up to 21% when the flow experienced bulk-mean reversal. A time-dependent analytical analysis of bulk fluid temperature carried out by Blythman et al. [10] predicted, a reduction in heat transfer for the first half-cycle and an enhancement in heat transfer for the second half-cycle of a sinusoidal flow pulsation for a $1.4 \le Wo \le 22.1$. Additionally, a resemblance of transverse thermal profiles with the fluid displacement profiles was seen.

The current study focuses on experimental investigation of unsteady asymmetric sinusoidal flows defined by a special case of Clausen function integral (Cl_2) [11]. The waveform phase is defined by θ in the range $0 \le \theta \le 360°$, and t is the time period of the waveform. Leading (*-ive*) and lagging (*+ive*) asymmetric profiles are obtained from Equation (1).

$$Cl_2(\theta) = \pm \int_0^{\theta} ln\left[2sin\left(\frac{1}{2}t\right)\right]dt \tag{1}$$

By applying infrared thermography (IRT) techniques to obtain time-resolved and space-resolved measurements in response to pulsating flows, the overarching aim is to determine the local time dependent variation of wall temperature for pulsating flows in a heated rectangular channel and to exploit the phenomenon for efficient heat removal without compromising net mass transport.

2. Experimental Technique

An experimental study for sinusoidal flow pulsations was previously elucidated by the authors Kumavat et al. [12]. The test rig consists of several plate sections clamped together, as represented in Figure 1 (a). Two pairs of copper electrodes supply a constant current of 42 A to an Inconel 600 foil of 12.5 μm thickness. The 350 mm long and 90 mm wide foil is laterally tensioned using a spring-loaded bolt mechanism and forms the bottom section of the channel by approximating a constant heat flux boundary condition. The heat flux generation is 5.3 kW/m^2 $\pm 0.6\%$ measured along the foil surface till the extent up to the outer contact points of copper electrodes. A rectangular channel of dimensions 360 mm x 22 mm x 1.4 mm (length x width x height) is cut into an acrylic plate and placed on the upper surface of the foil. De-ionised water is circulated as a coolant in a closed loop. Heat removed from the foil by the water is subsequently extracted by a fan-driven heat exchanger before the water returns to the channel inlet. A membrane contactor connected with a vacuum pump is used to remove air bubbles and other impurities prior to the testing.

The oscillatory component of the pulsating flow is driven by a McLennan 34 HSX-108 stepper motor attached to a FESTO piston pump controlled with a ST5-Q-NN applied motion drive. This provides precise control of the pulse generation resolution (up to 25000 steps per rev.), resulting in a maximum frequency of 25 *kHz*. The steady underflow is generated by a TCS M400 centrifugal miniature pump capable of attaining pulseless maximum flow rates of up to 2 *L/min*. A National Instruments NI-DAQ 9269 is used in conjunction with LabVIEW to modulate the frequency and amplitude of the function generator. An Atrato 710 series non-invasive ultrasonic flowmeter records precise flow rates. Calibrated type-T thermocouples record fluid temperatures at the minichannel inlet and outlet.

The experimental configuration ensures a hydrodynamically and thermally developed flow in the minichannel test section. The thermal boundary layer development length is determined from given by Durst et al.[13] and is calculated at the maximum Reynolds number used in this study, $Re_{max} = 81$, where Re_{max} equals the sum of the steady (Re_s) and pulsating (Re_p) Reynolds numbers. For the configurations tested, the maximum predicted steady hydrodynamic and thermal developing lengths are 9.72 mm and 54.43 mm respectively. IR measurements are recorded 220 mm downstream from the channel inlet. A small section of the underside of the foil is exposed to enable infrared temperature measurements. This section of the foil is sprayed with a thin layer of matte black paint to enhance its surface emissivity. To prevent heat loss from the foil via natural convection, a 1 mm thick sapphire glass is placed approximately 13.5 mm beneath the foil. The local time-dependent variations of the foil temperature are recorded using a FLIR SC6000 high speed, high resolution, infra-red camera. It has a maximum 640×512-pixel focal plane array with sensitivity of 2.5-5.1 μm range. Prior to testing, a two-point non-uniformity correction (NUC) is performed with a black body calibrator and an in-situ temperature-counts calibration is performed. The camera is triggered from LabVIEW to facilitate phase-locked measurements. IR video files are exported to Matlab for postprocessing and analysis.

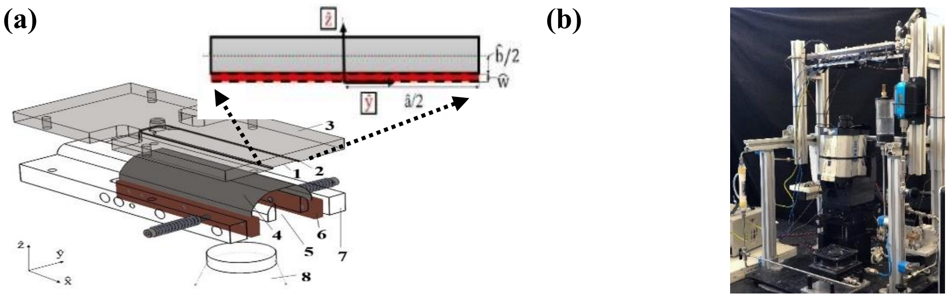

Figure 1. (a) Exploded sectional view of experimental rig showing: 1) channel profile, 2) o-ring, 3) channel plate, 4) foil, 5) air cavity, 6) electrodes, 7) heater plate, 8) camera. Inset view shows channel cross sectional view with dimensional notations, dashed lines mark the foil boundary. (b) Image of the actual experimental setup.

3. Results and Discussions

Experimental results for laminar steady flows of $U_z = 0.017\ m/s$ is validated against a conjugate heat transfer numerical model. Figure 2 presents phase-averaged wall temperature profiles for pulsating frequencies f = 0.02 Hz ($Wo = 0.51$) and 0.2 Hz ($Wo = 1.6$), maintained with a flow rate amplitude of $A_0 = 0.9$. The measurements are recorded for the heated bottom wall in the transverse direction ($\hat{y}$) set at an axial distance of 260 mm away from the inlet. The y-axis (T_w^*) represents the phase-averaged difference between asymmetric pulsating flow heated wall temperatures and steady flow heated wall temperatures, averaged over 20 pulse cycles. The asymmetric waveforms have been observed to generate high fluctuating velocity components compared to sinusoidal fluctuations, as shown by McEvoy et al. [14].

In Figure 2 (a), the time-dependent transverse wall temperature profiles show similar peaks at near wall locations for phases 1.4 π and 1.6 π, indicating a *reduction* in heat transfer, while minor heat transfer enhancement is observed for phases 0 to π. The reduction phenomenon is evident particularly for $Wo < 1$ wherein the excitation time scales are longer than the fluid convective time scales, thus transverse diffusion of heat from the wall to the fluid is dominant. Hence a reduction in heat transfer of 0.5% over a steady flow is observed, while an apparent reduction of 15% exists for square waveform pulsations [3] and 0.8% for sinusoidal flow pulsations [10]. For a convection dominant regime with $Wo > 1$ as presented in Figure 2 (b), the amplitude of the wall temperature fluctuations is greatest away from the side wall, i.e., towards the fluid core regions, for most phases (0.2 π – 1.2 π). This is a result of enhanced fluid mixing, which produces heat transfer enhancement in the range $4 \leq \hat{y} \leq 7$. The difference in Nusselt number indicates an enhancement of 6% over the steady flows as opposed to that of the square wave pulsations with a reduction of 0.25% [3] and 0.21% for sinusoidal pulsations [10]. The instantaneous flow acceleration leads to rapid fluctuations of fluid elements in the transverse direction and greater fluid inertia in the bulk regions. The viscous forces continue to prevail in the near wall region, hence smaller near wall temperature fluctuations are observed in this region for most phases.

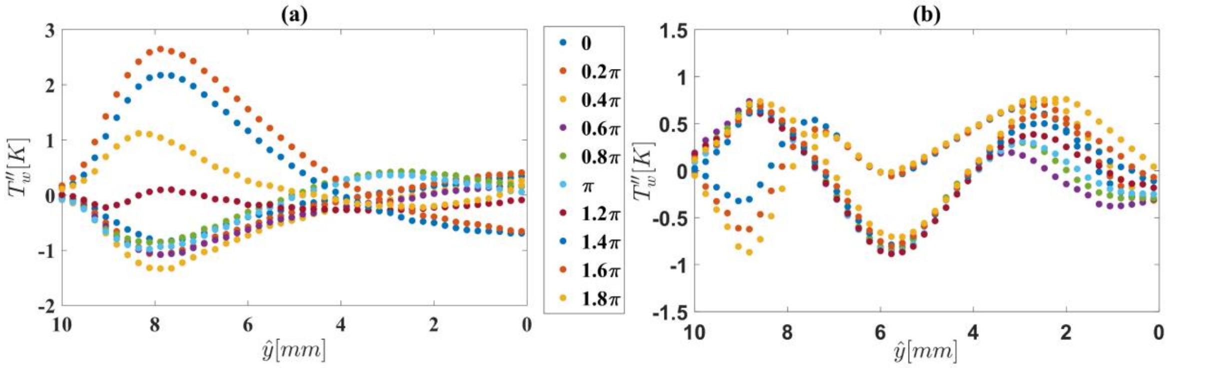

Figure 2. Phase-averaged difference between pulsating and steady components of wall temperature profile for f = (a) 0.02 *Hz* (*Wo* = 0.51) and (b) 0.2 *Hz* (*Wo* = 1.6) in the transverse direction. Colours indicate successive phase angles from 0 in increments of 0.2 π.

4. Conclusion

The study uses infrared thermography to examine the transverse wall temperature profiles for laminar pulsating flows at the bottom heated wall of a rectangular minichannel. Asymmetric sinusoidal pulsating flows of $Wo = 0.51$ and $Wo = 1.6$ maintained at $A_0 = 0.9$ are investigated to analyse the influence of pulsation frequencies on heat transfer. To the authors' knowledge, this forms the first reported analysis of heat transfer enhancement in rectangular minichannels due to asymmetric sinusoidal flow pulsations. As the asymmetric waveforms are driven by a sudden shift in fluid velocities, distinct wall temperature profile patterns are observed. Low Womersley number pulsating flows dominated by viscous effects showed a marginal reduction in heat transfer by 0.5% due to higher diffusion rates. While higher Womersley numbers indicated a comparatively appreciable heat transfer of 6% enhancement due to enhanced fluid mixing in the vicinity of the wall.

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