International Journal of Thermal Sciences 91 (2015) 157–166

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

# Local experimental heat transfer of single-phase pulsating laminar flow in a square mini-channel

Balkrishna Mehta, Sameer Khandekar*

*Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur, UP, 208016, India*

## ARTICLE INFO

*Article history:*
Received 12 June 2014
Received in revised form
1 January 2015
Accepted 4 January 2015
Available online 16 February 2015

*Keywords:*
Mini-channels
Pulsating flow
Local Nusselt number
Heat transfer enhancement
InfraRed thermography

## ABSTRACT

Disturbing a single-phase laminar internal convective flow with a particular pulsating flow frequency alters the thermal and hydrodynamic boundary layer, thus affecting the inter-particle momentum and energy exchange. Due to this externally imposed flow disturbance, augmentation in the heat transfer may be expected. Obviously, parameters like pulsating flow frequency vis-à-vis viscous time scales and the imposed pulsating amplitude will play an important role. Conclusions from reported literature on this and related problems are rather incoherent. Lack of experimental data, especially in micro-/mini internal convective flow situations, with imposed flow pulsations, motivates this study. Non-intrusive infra-red thermography has been utilized to scrutinize heat transfer augmentation during single-phase laminar pulsating flow in a square mini-channel of cross-section 3 mm × 3 mm, electrically heated from one side by a thin SS strip heater (70 μm, negligible thermal inertia); all the other three sides of the channel are insulated. The study is done at different pulsating flow frequencies of 0.05 Hz, 1.00 Hz and 3.00 Hz ($Wo = 0.8$, 3.4 and 5.9, respectively). These values are chosen because pulsatile velocity profiles exhibit different characteristics for $Wo > 1$ (annular effect, i.e., peak velocity near the channel walls) and $Wo < 1$ (conventional parabolic profile). Local streamwise heat transfer coefficient has been determined using the time averaged spatial IR thermograms of the heater surface and the local fluid temperature, linearly interpolated from measured value of inlet and outlet bulk mean mixing temperature. It is observed that for measured frequency range, the overall enhancement in the heat transfer is not attractive for laminar pulsating flow in comparison to steady flow with same time-averaged flow Reynolds number. The change is either marginal or highly limited, primarily occurring in the developing length of the channel. Thus, the results suggest that heat transfer enhancement due to periodic pulsating flow is questionable, and at best, rather limited.

## 1. Introduction

Single-phase fluid flow and heat transfer in pulsating flows are encountered in many engineering systems, ranging from industrial applications like electronics cooling, certain heat exchangers, pulse-tube cooling systems etc., to biological applications of arterial blood flow. The flow pulsations or fluctuations may sometimes be inherent to the flow situation (flow over tube bundles where vortex shedding from the leading tube induces fluctuations for subsequent tubes) or it may be externally superimposed on a steady flow (e.g., in a pulsed-jet situation). Cooling requirements in contemporary are significantly increasing due to the miniaturization of the engineering devices and increasing heat flux handling requirements. MEMS and Bio-fluidic systems are also gaining popularity, which may also encounter pulsatile flows with simultaneous heat/mass transfer. The explicit effect of pulsations on local and average heat transfer in internal convective is an interesting problem *per se* due to several complexities involved.

Several researchers have been working towards finding the insights of pulsatile flows from early decades of the last century. In a classical study Richardson and Tyler [1], experimentally discovered that pulsating flow field in circular, square and oval cross section tubes may lead to the ‘annular effect’ i.e., under certain operating flow conditions, the maximum velocity at the channel cross-section occurs near the tube wall and not at its center. Several others [2–4] studied oscillating flows in arterial systems to observe the differences in the manifested velocity distribution and viscous drag in comparison to a steady laminar flow. Uchida [5] theoretically studied the hydrodynamics of pulsating flow in circular tube for different non-dimensional frequencies and established that

---

* Corresponding author. Tel.: +91 512 259 7038; fax: +91 512 259 7408.
*E-mail address:* samkhan@iitk.ac.in (S. Khandekar).

http://dx.doi.org/10.1016/j.ijthermalsci.2015.01.008
1290-0729/

## Nomenclature

| | |
|---|---|
| A | amplitude ratio ($|U_t/U_{av}| = |Q_i^* - 1|$) (−) |
| Bi | Biot number ($h \cdot L_c/k_w$) (−) |
| D | diameter (m) |
| f | frequency of pulsation (Hz) |
| *Fo* | Fourier number ($\alpha \cdot t/L_c^2$) (−) |
| h | heat transfer coefficient ($W/m^2$ K) |
| k | thermal conductivity (W/m K) |
| L | length (m) |
| *Nu* | Nusselt number ($h \cdot D_h/k$) (−) |
| *Pr* | Prandtl number ($\upsilon/\alpha$) (−) |
| Q | volumetric flow rate ($Q_t + Q_{av}$) ($m^3/s$) |
| $Qi^*$ | instantaneous flow rate ratio ($Q/Q_{av}$) (−) |
| $q''$ | heat flux ($W/m^2$) |
| *Re* | Reynolds number ($U_{av} \cdot D_h/\upsilon$) (−) |
| St | Strouhal number ($f \cdot D_h/U_{av}$) (−) |
| $t^*$ | non-dimensional time ($t/\theta$) (−) |
| $T^*$ | non-dimensional temperature (−) |
| U | axial flow velocity ($U = U_{av} \pm U_t$) (m/s) |
| *Wo* | Womersley number ($d \cdot (\omega/\upsilon)^{0.5}$) = $(2\pi \cdot St \cdot Re)^{0.5}$ (−) |
| z | axial length (m) |
| $Z^*$ | non-dimensional axial length ($z/Re \cdot Pr \cdot D_h$) (−) |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | thermal diffusivity ($m^2/s$) |
| $\upsilon$ | kinematic viscosity ($m^2/s$) |
| $\omega$ | angular frequency (rad/s) |
| $\theta$ | time period (s) |

*Subscripts*

| | |
|---|---|
| av | average |
| c | characteristic |
| f | fluid |
| h | hydraulic, hydrodynamic |
| i | instantaneous |
| in | inlet |
| r | relative |
| s | steady state |
| t | transient/unsteady component |
| w | wall |
| * | non-dimensional quantity |

phase-lag between the pressure gradient and velocity increases with frequency and this lag asymptotically approaches to 90° for infinite frequency of flow oscillations. Yakhot et al. [6] numerically analyzed pulsating laminar flow of a viscous, incompressible liquid in a rectangular duct. It was concluded that at low imposed frequencies, practically no phase-lag existed between the pressure gradient and resulting velocities, but, at higher frequencies, phase-lag increased.

More recently, Chang et al. [7] have made another attempt to analyze the phase-lag between the imposed pressure gradient and flow rate in low frequency laminar pulsating flow. This study concluded that phase-lag exists even at very low frequency (less than 0.5 Hz) in laminar pulsating flow through circular pipes and parallel plate. Phase-lag increases with increase in frequency and hydraulic diameter of the tube/duct, but decreases with increase in viscosity and remained unaffected by the applied pulsation amplitude. Ray et al. [8], carried out extensive numerical simulations and obtained a correlation to predict the development length for laminar, developing flow through pipes under sinusoidally varying mass flow rate. Computations were done for moderate to high mean flow Reynolds number region ($100 \le Re_{av} \le 2000$), dimensionless amplitude of mass flow rate pulsations of 0.2, 0.4 and 0.8 (i.e. ratio of amplitude of mass flow rate pulsations to the time averaged mass flow rate in the channel) values and non-dimensional frequency parameter was varied from 0.1 to 20 i.e., complete region from quasi-steady to inertia-dominant region was covered in this study. It was found that at low imposed flow frequency, variation in the instantaneous development length is sinusoidal and can be predicted from the steady state flow condition based on instantaneous flow *Re*. On the other hand, when frequency of pulsation is higher, amplitude of the development length decreases; therefore, estimation of maximum flow development length based on maximum *Re* will give the most conservative estimate. Normalized variation of development length has been found to be independent of average Reynolds number $Re_{av}$, but it depends on non-dimensional frequency and mass flow rate amplitude ratios.

Siegel and Perlmutter [9] have shown the dependence of overall heat transfer on the frequency of pulsations. Furthermore, when constant temperature wall boundary condition was used, the Nusselt number showed periodic fluctuations along the flow direction. In other subsequent studies [10–15], hydrodynamic ‘annular effect’, phase-lag and periodic axial fluctuation of fluid temperature and heat transfer were confirmed. However, Seigel [16] argued that, for forced convection in laminar flow in a channel, flow oscillations tend to reduce the heat transfer coefficient. Cho and Hyun [17], numerically investigated the effect of flow pulsations in a pipe using laminar boundary layer equations. It was observed that at the fully developed downstream region, Nusselt number may increase or decrease depending on the frequency parameter (*Wo*). Kim et al. [18] studied the thermally developing but hydrodynamically fully-developed pulsating channel flow and isothermal channel walls. They observed that flow pulsations hardly affected the thermal behavior. Guo and Sung [19] observed that for small amplitudes, heat transfer gets augmented within a band of operating frequencies but at higher amplitudes, heat transfer gets always augmented. Hemida et al. [20] observed that pulsations produced little changes in heat transfer, the change being always negative. In addition, this small change is limited to the thermally developing region only. Jun et al. [21], executed an experimental study to understand heat transfer characteristics of pulsating flow and concluded that by increasing the flow rate, heat transfer gradually increases and strong pulsations result in enhancement of heat transfer. However, in this study, there were some measurement ambiguities, e.g., (a) heat transfer estimations were averaged out in space and time (b) heat balance has been done based on local fluid measurements by thermocouples, which measure the local instantaneous temperature but not the bulk mean mixing temperature (c) Non-dimensional parameterization has not been done, which make the interpretation of results non-universal and confined to the reported study only. Yu et al. [22] and Chattopadhyay et al. [23] observed no change in time-averaged Nusselt number due to flow pulsations. Bouvier et al. [24], performed an experimental study to understand heat transfer in oscillating flow in a circular pipe. Parameters used in this study were maximum Reynolds number, non-dimensional frequency (*Wo*) and amplitude of oscillation. Temperatures were measured inside the fluid and at different radial locations at the wall and heat