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Experimental investigation of heat transfer in oscillating circular pipes: High frequencies and amplitudes

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Heat transfer characteristics of oscillating turbulent air flow in a circular pipe heated at uniform heat flux were experimentally examined. The experiments were performed over range of Reynolds number 10×10^3 to 5×10^4 and oscillating frequencies from 5 to 100 Hz. Thermocouple, the temperature control system and the other measurement systems were installed on the oscillating section. For both steady and oscillating flows, the bulk and wall temperature, pressure drop and frequency were measured. Installing oscillating downstream of tested tube exit, result showed that Nu is strongly affected by the oscillating frequency and Reynolds number. The variation is more pronounced in the entrance region than in the downstream fully developed region. In oscillatory flow, a heat transfer enhancement of up to 28% at constant pumping power was achieved.

Key words: Heat transfer, oscillating flow, mixing.

INTRODUCTION

Oscillating flow has received significant attention in thermal engineering because of enhancement of the heat transfer coefficient. The rate of heat transfer is altered since oscillation changes the thickness of the thermal boundary layer and hence the thermal resistance. A wide literature investigation flow heat and fluid flow characteristics is reported by Zhao and Cheng (1998). They examined that two different groups are pulsating flow and reciprocating flow. The studies related to heat transfer augmentation in an oscillating flow in tube have been studied experimentally and analytically (Unal and Feridun, 2009; Lambert et al., 2009; Yan et al., 2012). Walsh et al. (1993) experimentally investigated forced convection cooling in micro-electronics boxboard via oscillating flow techniques. Their results show that electronic component running temperature may be decreases by means of as much as 30 to 40% when oscillating flow devices are placed.

An experimental study on related oscillating and pulsating flows was done by Liao et al. (1985). According to this study, heat transfer augmentation could occur only when the oscillating frequency was higher than a fixed value.

Sarpkaya (1986) investigated the fluid force acting on a cylinder and a sphere placed in an oscillating flow. Ishiwata and Ohashi (1990) have studied the fluid force acting on a cylinder in an oscillating flow condition. Okajima et al. (1997) have carried out flow visualization oscillating flow conditions for both of circular and square cylinders. Tanaka et al. (1990) investigated an experimental study on the fluid flow and heat transfer characteristics; different objects placed in an oscillating

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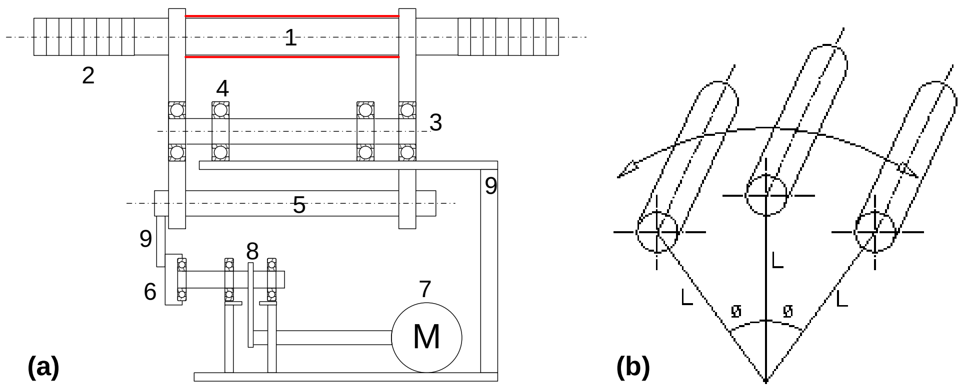

Figure 1. (a) The oscillation mechanism of the test pipe, (b) oscillating amplitude. 1-Test tube, 2-Flexible tube, 3-Oscillating rod, 4-Bearings, 5-Balance weight, 6-Rotating disc, 7-AC Motor, 8-Belt, 9-Krankshaft.

flow. Another experimental study was done by Cooper et al. (1994): heat transfer enhancement was observed in short channel at low frequencies and large amplitudes.

They showed that oscillation contributes to fluid mixing and thus bring about enhanced heat transfer. The heat transfer enhancement by means of sinusoidal oscillating flow in circular tube was investigated by Kurzweg (1985). He showed that there was enhancement of heat transfer by oscillating the flow. The following studies have been carried out to explore oscillating flow characteristics. Herrera et al. (2003), studied non-Newtonian flow rise, according to the temperature, in exit measured temperatures. They showed that the bulk temperature of the fluid at the exit of the oscillating section was increased by the oscillating frequency and amplitude.

Many investigations have been conducted on heat transfer to the wall of a channel filled with porous medium by Leong and Jin (2004). They showed that the surface temperature distribution in oscillating flow is more uniform than the without oscillating flow.

The present work submits, constant wall heat flux, an experimental study on heat transfer, and friction factor characteristic of oscillating duct which the frequency range from 0 to 20 Hz. Furthermore, friction loss was determined by measuring pressure loss along the test section.

EXPERIMENTAL SETUP AND MEASURING SYSTEM

The experimental facility shown in the Figures 1a-b is designed and constructed to investigate the effect of oscillating on the convective heat transfer from a heated circular pipe over range $10 \times 10^3 < Re\ 5 \times 10^4$. It is an open loop in which air as working flow is pumped and passed through the test section to the atmosphere after being heated. The mechanism basically consists of three part; the air supply unit and necessary adaption and measuring devices, the test circular pipe and oscillating mechanism. The oscillation mechanism has been achieved as follows: When electrical DC motor (7) is turned, the belt (8) which is fitted shaft is reverses with together disc (6). While crank shaft (9) on the surface of disc which can be placed different location certain distance of the centre disc reversing, then, the crank shaft pushes labelled 9 parts. This part (9) is pushing other the balance part (5) forward-backward at the certain value distance (L) and degree (θ). Thus the oscillating rod (3) is also shifted forward-backward, this is, and the test pipe is doing oscillations movement. The value of the amplitude can be varied as a function of the shifting distance of the rod (3), where connected to the rotating disc.

In this work, as in Figure 1 (b), the shifting spaces of the pipe with oscillation amplitudes were taken as L=25, 50 and 100 mm.

The experimental conditions adopted in the present experiment are $5 \le f \le 100$ Hz and $1 \le x_0 \le 12$. This corresponds to the range of the oscillating flow Reynolds number $10 \times 10^3 \le Re_{osc} \le 5 \times 10^4$ that is defined as $\mathrm{Re}_{osc} = V_{scale} D / \nu$. Here velocity scale is $V_{scale} = 2\pi x_o f$. In the experiments, the oscillating flow with different frequencies was facilitating by adjusting the DC motor speed and the frequency of oscillating flow ranged from 5 to 100 Hz. The test section was heated by adjusting the power supply voltage. By adjusting the power supply voltage to heater, the input power from 0.5 to 4.5 kW was obtained. The test sections were insulated and to obtain uniform heat flux, a 1 mm-thick mica plate was attached on the surface the film heater.

The total length of the test section is 250 mm, the tube inside diameter 23 mm, outside diameter 25 mm and hydrodynamic entry length is 10 times diameters. The heat transfer coefficient was measured over length up to 100 mm.

For the oscillating flow heat transfer test, surface temperatures along the pipe, inlet and outlet bulk temperatures, pressure drop across the test section and the air flow velocity were measured. The inlet air temperature of the pipe and wall temperature at the various stations were measured by means of copper-constantan thermocouples.

The distributions of the thermocouple along the test tube was installing of the beginning to measure the dramatic change of the temperature in the entrance region. The locations of these thermocouple relative to pipe length are as X/L=0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1. The thermocouples were mounted at different points on the surface test tube. The bulk air temperature at the inlet and outlet test region were measured by two k-type thermocouple inserted in two holes which drilled the flanges at the entrance and exit of this test section. The pipe wall temperatures are measured by 10 k type thermocouple distribute along the circular tube surface from outside. Thermocouples were adjusted

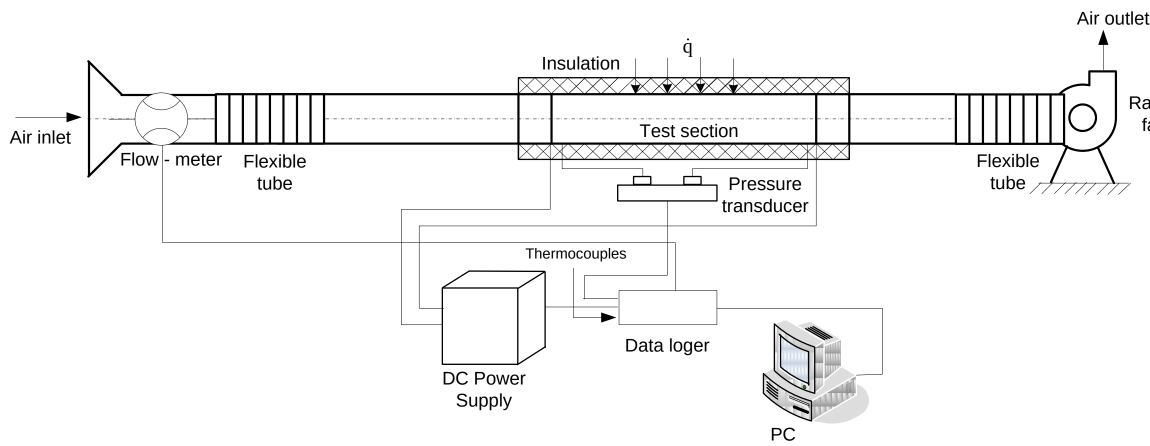

Figure 2. The schematic illustration of the experimental rig.

into 10 holes along outer surface of the test section, each of 1.8 mm in diameter and 2 mm in depth. Pressure drop across the test section was measured by differential pressure label cell and transducer "843 DP d/p" is which connected to two pressure taps along the test section on the surface. The total flow rate of the test section was measured by a flow meter label "Boaleeco flowmeter."

All data; temperature, DC current and voltage, differential pressure, frequency and flow rate over test section were recorded on "data acquisition". All flow properties were determined at the average bulk temperature. The local bulk temperature, ($Tb_x = \dot{q}_x / h_x - Tw_x$), was calculated from the linear relationship between Tb_x and the inlet and exit air temperatures. This linearity results from a constant heat flux condition so negligible heat transfer along the tube wall.

Before experiments, all thermocouples, pressure sensors and flow meter were fully calibrated. The frequencies of oscillating flow were adjusted by controlling motor speed. For fixed amplitude the experiments were carried out by increasing the oscillating frequency. As the experimental set-up regularly oscillates, it has certain amplitude. It has first been carried out as heat transfer experiments without oscillation conditions, $f = 0$. Then the results were compared with oscillation frequency.

RESULTS AND DISCUSSION

In this experimentally study a program is used to study the heat transfer characteristics of steady and oscillating turbulent pipe air flow. A lot of parameters affect the performance of heat transfer of such a flow among the amplitude and frequencies of oscillating. Reynolds number and the location of oscillating mechanism to the test section may have great effect. Experiments in both cases, steady and oscillating flow were executed while circular pipe wall were heated with fixed uniform heated flux of overall range: 500 to 4500 W/m^2 and the pulsation mechanism was located along a tube. The mass flow rate air was adjusted and frequencies varying from 5 to 100 Hz. The in experiment covered different degree of Reynolds number.

Calculation of heat transfer and friction factor

We consider the smooth circular pipe with constant cross section shown in Figure 2. The constant heat flux q'' is imposed on its surface pipe wall. Air was used as working flow and the mass flow rate $\dot{m}$ and the inlet temperature $T_{i.}$, the duct of length L, density of air ρ, thermal conductivity k. The rate of heat transfer is

$$Q = hA(T_w - T_b) \quad (1)$$

Heat transfer coefficient,

$$h = \frac{Q}{T_w - T_b} \quad (2)$$

Local heat transfer coefficient can be calculated:

$$h_x = \frac{Q_{net}}{A(T_w - T_{bx})} \quad (3)$$

Where (h_x) is the local heat transfer coefficient, (Q_{net} / A) is the local heat transfer rate per unit from the wall to air inside of tube. T_w is the local wall temperature of the tube, and T_{bx} is the bulk mean air temperature. The inside tube wall temperature was obtained by correcting the measured outside wall temperature by solving the cylindrical heat conduction equation from measured outside wall temperature; the one dimensional steady-sated heat conduction equation with variable thermal conductivity was solved numerically. The local air bulk temperature was calculated from the heat balance and local Nusselt number was calculated as

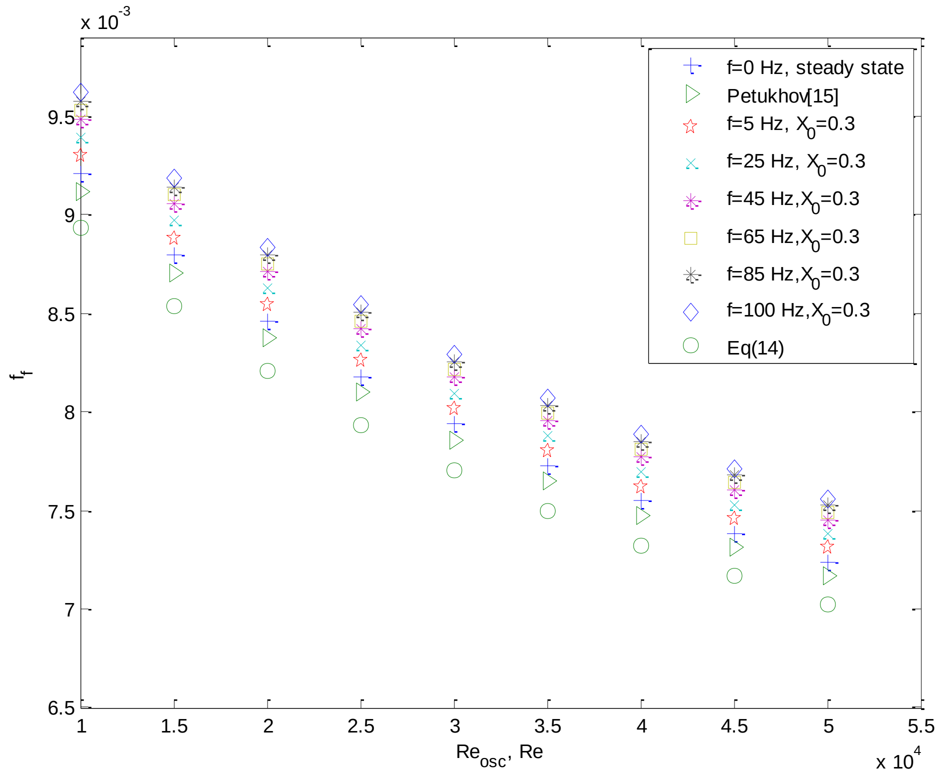

Figure 3. Friction coefficients in the test pipe as a function of Reynolds number for the different frequency rates.

$$Nu_x = \frac{h_x D}{k} \tag{4}$$

In oscillatory flows, Reynolds number can be characterised as

$$\mathrm{Re}_{osc} = \frac{2\pi f x_o D}{\upsilon}, \quad \dot{x}_{peax} = 2\pi f x_0 = V_{scale} \tag{5}$$

Where f is the frequency of oscillating, (cycles/s), x_0 is the centre to peak amplitude of oscillation and D is the tube diameter. The friction factor was determined from the measured values of pressure drop, ΔP, across the test length, L, and mass flow rate, $\dot{m}$ using the equation:

$$f = \frac{\Delta P}{\left(\frac{L}{D}\right)\rho \frac{v^2}{2}} \quad ; \; v = \frac{\dot{m}}{\rho \frac{\pi D^2}{4}} \tag{6}$$

Where v, the average velocity of air is, $\dot{m}$ is the air mass flow rate, D is the diameter of the test section tube. Oscillating flow, Figures 4 to 7 present local Nusselt number distribution along the test section of different frequencies, heat flux values and different Reynolds numbers. Using the values obtained from the experimental data in the oscillating pipe, the changes in the Nusselt number with the Reynolds numbers were drawn for various frequencies and the results were compared against the Dittus-Boelter equation ($Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}$, which describes the smooth tube without oscillation) and Gnielinski (1987) modified the correlation.

$$Nu_D = \frac{(f/8)(\mathrm{Re}_D - 1000)\,\mathrm{Pr}}{1 + 12.7(f/8)^{1/2}(\mathrm{Pr}^{2/3} - 1)}, \; \begin{bmatrix} 0.5 \le \mathrm{Pr} \le 2000, \\ 2300 \le \mathrm{Re}_D \; 5x10^6 \end{bmatrix} \tag{7}$$

Where, without oscillation, the friction factor given by Incropera and De Witt, (1987)

$$f = (0.79 \ln \mathrm{Re}_D - 1.64)^{-2} \tag{8}$$

The mean deviation of the predict Nusselt number is 10.8% and result of this study lies well among the results of the above mentioned correlations and shows the best agreement with the Modified Dittus-Boelter correlations, for the experimental conditions 5000 ≤ Re ≤ 5.10^4 and Pr=0.7. The results of the present work were correlated with Nusselt number as follow:

$$Nu_s = 0.2987\,\mathrm{Re}^{0.50} \tag{9}$$

Figure 3 shows the variation of friction coefficient with Reynolds number. As seen from the figure, the pressure

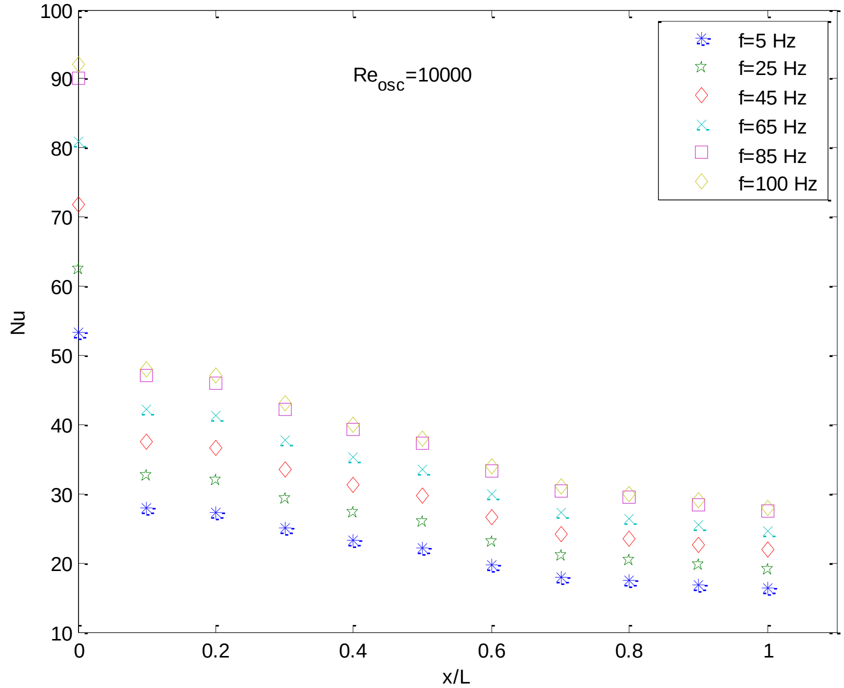

Figure 4. Local Nusselt number versus tube length.

friction coefficient increases when oscillating frequency increases.

Figures 4 to 5 show the trends heat transfer for different oscillating frequencies; oscillations promote fluid mixing and thus lead to enhanced heat transfer. It is seen that the increment of Nusselt number by means of frequency increases. From the Figure 4, it can be seen that the local Nusselt number decreases as dimensionless location x/L. The Nusselt number distribution are concave between, 0 ≤ L ≤ 0.85 and then nearly is constant all cases.

As seen in Figure 4, the heat transfer increases by an average of 28% with increased oscillating amplitude. This figure shows that Nusselt number has the highest value in the entrance region and approaches the minimum constant value for thermally developed flow at the end of the test section. The increasing in heat transfer with increasing frequency is due to oscillating which made the flow to be wavy which improves the heat transfer rate at the pipe wall. For a constant pumping power, it is useful to determine the effectiveness of the heat transfer enhancement of a heat transfer promoter in comparison with a smooth surface such that:

$$\dot{V}\Delta P_s = \dot{V}\Delta P_f \qquad (10)$$

Where $\dot{V}_s \, and \, \dot{V}_f$ are volumetric flow rate in the pipe, and ΔP_s and ΔP_f are pressure drops without and with oscillating, respectively. The heat transfer enhancement efficiency for constant pumping power can be expressed as follows:

$$\eta = \left(\frac{h_f}{h_s}\right)_p \qquad (11)$$

Where h_f and h_s are the convective heat transfer coefficient with and without oscillations, respectively.

The heat transfer ratios for constant pumping power have been given in Table 1 for the various Reynolds numbers and frequencies. The heat transfer ratios vary from 0.869 to 1.041 depending on the Reynolds number and the frequency. Oscillating flow, under the certain situation, can be considered favourable in terms of heat transfer enhancement and energy saving. The indication from Table 1 is that there will be a net energy gain only if $(h_f / h_s)_P \rangle 1$. For the oscillating flow, the relation is between η (heat transfer efficiency) and Re for the various oscillating flows. The value f ≤ 50, and, Re= 15000 has no energy gain. It is seen from Table 1 that η increases with increasing frequency and decreasing Re number.

The heat transfer rate strongly depends on oscillating frequency. Because of oscillation in the test section, the unsteady flow is changed its direction, by oscillation.

We now compare the experimental results of the

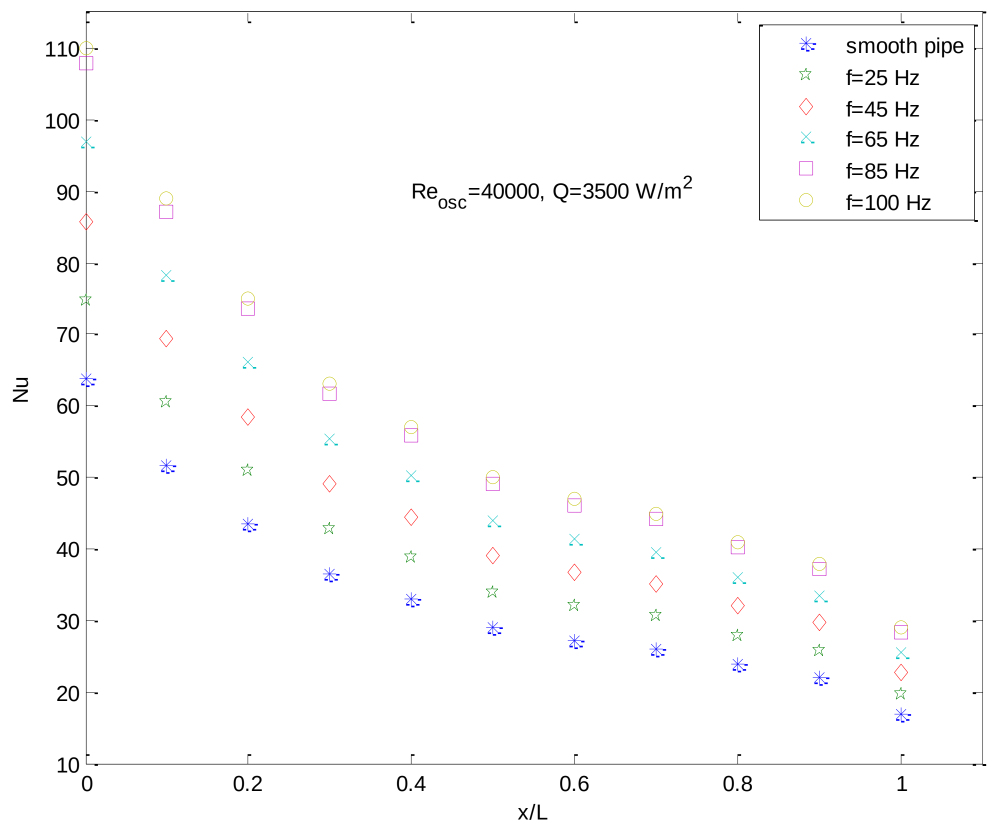

Figure 5. Local Nusselt number versus tube length.

Table 1. $(h_f / h_s)_P$ for various Reynolds number and frequency values.

Frequencies/amplitude	Reynolds number			
	10000	20000	30000	50000
0.0 /0.0	0.954	0.937	0.908	0.869
10/25	0.962	0.948	0.923	0.880
25/25	0.964	0.958	0.948	0.900
65/25	1.018	0.965	0.964	0.913
85/25	1.041	1.020	1.09	0.961

steady and oscillating flows along the test section. In oscillating flow, the heat transfer coefficient is higher than the steady flow heat transfer coefficient under the constant flow conditions, Figure 6. Because it is thought that periodically varying coriolis accelerations produce secondary flows changing periodically in direction in the cross section perpendicular to the flow direction. It is argued that sudden pressure changes at the duct affect directly the flow direction and heat transfer behaviour in the channel.

Figure 7 which in all studied conditions, the value of Nu increases with an increase X/D and f. This figure shows that Nusselt number is maximum at the X/D=12 and f=50 Hz.

Conclusion

In this study, the heat transfer from heated surface in oscillating parallel amplitude circular tube was investigated experimentally. The experiments were figured out for different large frequencies amplitude (x) and heat fluxes while Reynolds number. All the calculations in analyzing the experimental data were based on measurement taken from the test section. Nusselt number was obtained from the experimental data. The heat transfer increases with frequency and amplitude of the oscillating. It was seen that the oscillating flow heat transfer strongly relate on the frequencies and amplitude. The local Nusselt number in

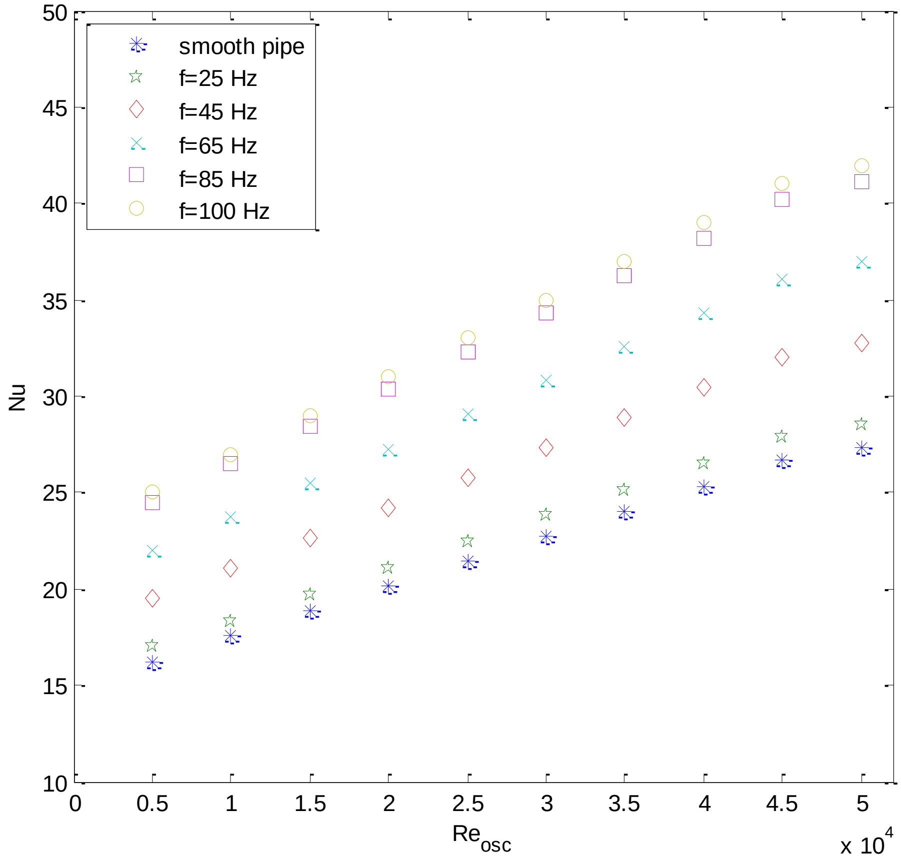

Figure 6. Variation of Nusselt number with Reynolds number for different frequency.

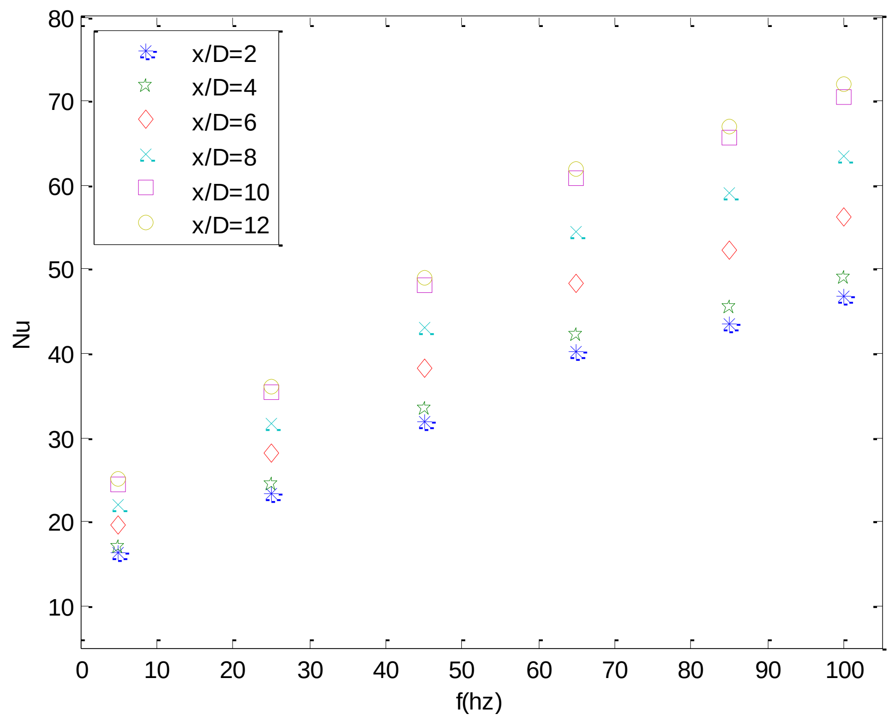

Figure 7. Variations of Nusselt Number oscillating amplitude and frequency.

steady flow decreases along the flow direction and approaches the thermally developed value. Both local and average Nusselt numbers increases with increases in the Reynolds number for steady and oscillating flows. The local Nusselt number increased with increasing oscillating frequency. The oscillating generator is to efficiently enhance the heat transfer in the duct flow but also in a significant pressure drop increase. The heat transfer is strongly ratio dependent - the oscillating amplitude.

NOMENCLATURE

A : heat transfer area, m^2

c_p : specific heat, kJ / kgK

D : test tube inside diameter, m

h : heat transfer coefficient, $W / m^2 K$

k : thermal conductivity, W / mK

L : total length of the test section, m

$\dot{m}$: mass flow rate, kg/sn .

Nu_f : Nusselt number for oscillating.

Nu_s : Nusselt number for smooth tube.

$\Pr$: Prandtl number, $\mu c_p / k$.

Q : heat flux based on test section surface area, W / m^2.

Re : Reynolds number, $u_{av} D / \upsilon$.

Re_{osc} : Oscillatory Reynolds number, $\mathrm{Re}_{osc} = 2\pi f x_0 / \upsilon$.

P : pressure N / m^2.

$\dot{p}$: pumping power to heat transfer rate.

ΔP : static pressure difference, N / m^2.

T : temperature, K .

ΔT : difference between wall and fluid temperatures, $T_w - T_b, K$.

u_{av}: the average velocity of air is, m/s.

V_{scale}: effective mean velocity of oscillating flow, m / s .

w: total uncertainty in the measurement.

ϑ : average velocity, m/s.

f : frequency, s^{-1}.

x_0 : center-to peak, oscillatory amplitude, m.

Greek symbols

ρ : density of fluid, kg/m^3.

δ : uncertainty.

μ : dynamic viscosity, $Pa.s$.

ν : kinematics viscosity, m^2 / s.

θ : angle, rad .

Subscripts

b : bulk.

i : inlet.

$loss$: loss.

s : smooth pipe.

w : wall.

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