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Research Article

An Experimental Investigation of Heat Transfer Characteristics of Pulsating Flow in Pipe

Juber T. Patel†* and Manish H. Attal†

†Department of Mechanical Engineering, Sinhgad College of Engineering, Vadgaon (Bk). Pune-411041, India

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Abstract

The heat transfer characteristics of pulsating turbulent air flow in pipe under different conditions of Reynolds number, pulsation frequency, pulsator location are investigated experimentally. A tube wall of uniform heat flux condition is considered for this case. Reynolds number varies from 7000 to 16500 while the frequency of pulsation is ranging from 1Hz to 3.33Hz. With installing the pulsation mechanism downstream of tested tube exit, results shows that Nusselt number is strongly affected by both pulsation frequency and Reynolds number. The maximum enhancement obtained in heat transfer coefficient is 44.4% at downstream and 17.7% at upstream at pulsation frequency of 3.33Hz. It is also observed that relative mean Nusselt number increases depending upon frequency range. The main implication of these results is that flow pulsation can be used in industrial heat exchangers to improve heat transfer coefficient and reduce operating cost.

Keywords: *Pulsating flow, Heat transfer enhancement, Turbulent flow, Pulsator.*

1. Introduction

The effect of pulsation on heat transfer remains a problem of interest to researchers due to its wide existence in industry. The operation of modern power-producing facilities and industrial equipment used in metallurgy, aviation, chemical and food technology and other technologies are governed to a large extent by pulsating flows. Cavitations in hydraulic pipelines, pressure surges and flow of blood are some of familiar instance of pulsating flows. The pulsating flow parameters affect the performance of many thermal engineering applications. These applications include refrigerating systems, reciprocating compressors, internal combustion engines, pulsing combustion systems. Therefore, there has been a growing interest in the effects of pulsating flow on convective heat transfer. This type of flow is characterized with fluctuations in both mass flow rate and pressure which have a great effect on heat transfer .Pulsating flows can be produced by reciprocating pumps or by steady flow pumps together with some mechanical pulsating devices. It may normally be expected that the heat transfer to or from the flow would be changed because the pulsation would alter the thickness of the boundary layer and hence the thermal resistance.

Pulsating flow is assumed to be consisted of a steady poiseuille flow and purely oscillatory. The amplitude of the time mean velocity is greater than the oscillatory velocity and flow direction never reverse. The pulsating flow is defined as continuous mass flow variations with a repeating waveform. Variables affecting the pulsating flow include frequency of pulsation, amplitude, Reynolds number and Prandtl number and pulsator location.

Most of the previous investigators considered a small number of the operating variables (such as Reynolds number, amplitude and pulsation frequency) in their studies and usually confined their studies to relatively narrow range of these variables. As a result, some investigators reported an increase in the heat transfer from pulsating flow, and others reported little increase, no increase, and even decrease in the heat transfer. These conflicting results showed that the heat transfer phenomenon in pulsating flow is still not clearly understood. The literature on pulsating internal flows inside tubes reveals that very little is known about their heat transfer characteristics. On the other side, there are many difficulties to find a theoretical solution to problems of hydrodynamic and heat transfer in the turbulent pulsating flows due to the complicated nature of turbulent unsteady flows. Therefore, the experimental investigation of pulsating flows is the most reliable way of understanding the phenomenon of the unsteady flows.

The characteristic of laminar pulsating flow inside tube under uniform wall heat flux have been experimentally investigated by Habib. It is reported that an increase and reduction in Nusselt number are observed, depending on the values of both the

*Corresponding author: **Juber T. Patel**

frequency and Reynolds number. They focused their work on laminar pulsating air flow in a pipe in the ranges of 780<Re<1,987 and 1<f<29.5Hz. Their experiments were performed under the condition of uniform heat flux, and they used rotating ball valve as a pulsator mechanism. They reported that for f<3Hz there was heat transfer enhancement due to pulsation but a reduction in heat transfer occurred as f increased above 3Hz. However, when f was raised above 14Hz, Nu began to increase again. They also stated that for laminar flow, Nu was not affected by Re as much as it was by f.

Elsayed *et al* investigated experimentally the heat transfer characteristics of pulsating turbulent air flow in a pipe heated at uniform heat flux. The experiments were performed over a range of 104< Re < 4 x104 and 6.6 ≤ f ≤ 68 Hz. This situation finds applications in modern power generation facilities and industrial processes. With installing the oscillator downstream of the tested tube exit, results showed that Nu is strongly affected by both pulsation frequency and Reynolds number. Its local value either increases or decreases over the steady flow value. The variation is more pronounced in the entrance region than that in the downstream fully developed region. It is observed also that the relative mean Nu either increases or decreases, depending on the frequency range. Although the deviations are small, it seems to be obvious at higher values of Reynolds number. The obtained heat transfer results are classified according to turbulent bursting model and looked to be qualitatively consistent with previous investigations. An experimental study on heat transfer characteristic of pulsating turbulent pipe flow using air in the ranges of 1<f<8Hz, 0.01<A<0.04m and 5,000<Re<29,000 was conducted by Habib *et al*. They kept the pipe wall at uniform heat flux, and used four bar slider crank mechanism driven by a variable speed DC motor as the pulsation mechanism. Their experimental results showed that for low Re there was enhancement in Nux at the entrance region for pulsating flow compared to steady flow and a reduction in Nux when flow was fully developed. However, the enhancement at the entrance region only occurred at low frequency (f<3Hz) and the effect was not significant (±1%). At high frequency (f>3Hz), there was around 8-13% reduction in heat transfer coefficient due to pulsation. The results also showed that for high Re, Nux decreased with increasing A. They observed an overall reduction of 13% in Nu for the whole range of Re in their study. They also concluded that resonance interaction occurred between bursting and pulsation frequency, which influenced augmentation of Nux at entrance region for Re=5,000.

Zohir *et al* continued the research by Habib *et al* and focused on the effect of the pulsator location and the diameter of the test section on the heat transfer characteristic. For their data, Re varied from 750 to 12,320 and f ranged from 1 to 10Hz, using a similar rig as their previous study. The results showed that for the upstream location of pulsator, the higher the amplitudes, the higher the heat transfer rate. On the effects of f, they concluded that in general for both upstream and downstream pulsation, the heat transfer was inversely proportional to f in the range of 1 to 10Hz. However, the downstream pulsation demonstrated more heat transfer enhancement compared to the upstream pulsation. They stated that for the downstream pulsation, when the pulsator valve was opened it allowed pressure inside the test section to fall to nearly atmospheric pressure. When the pulsator valve was closed, the pressure inside the test section rose to a high value. The rapid periodic rise and fall of pressure has a greater effect on the boundary layer.

For higher flow rates in a tube producing turbulent flow, Karamercan and Gainer studied the effect of pulsating water stream in double pipe heat exchanger in the following ranges of parameters: f<5Hz and 1,000<Re<50,000. They used five different displacement amplitudes at each flow rate. The transitional flow regime showed the highest heat transfer enhancement with increasing f. Their results showed that the effect of pulsation on heat transfer becomes less at higher flow rate because f disturbances that had been created by pulsation must compete with a higher level of turbulence that already exists in the fluid. Experimental investigations on pulsating turbulent pipe flow have been conducted by many authors. The results showed an increase and reduction in the mean Nusselt number with respect to that of the steady flow.

Many parameters have an influence on heat transfer characteristics of pulsating turbulent flow. Among those pulsation frequency, its amplitude, axial location, Reynolds number, Prandtl number and pulsator type and its location. In order to understand the phenomena of the effect of pulsation on the heat transfer coefficient and to resolve these problems of contradictory results, different models of turbulence for pulsating flows were considered. Two of these models are well known and mostly applied; the quasi-steady flow model and the bursting model.

Experiments were carried out to study the heat transfer performance of an inclined heated cylinder in pulsating flows by Guoneng Li. An empirical equation was developed that correlates the heat transfer enhancement factor to the infrasonic pulsating frequency (f = 6–20 Hz), Reynolds number (Re = 71–282), pressure amplitude (prms = 9–22 Pa), and inclination angle (Θ = 0–900). The heat transfer enhancement factor was found to decrease with the Strouhal number, and increase in trend with the inclination angle. In addition, a critical frequency (fcr= 14–18 Hz) was observed, below which the heat transfer enhancement factor decreases in trend with the Reynolds number, but it increases in trend with the Reynolds number when the frequency is above the critical frequency.

2. Experimental Set Up and Instrumentation

2.1 Test Rig

An experimental set up is designed and constructed to study the heat transfer characteristics of the pulsating airflow through pipes for the turbulent flows. The details of the test rig are shown in Fig. 1. It is an open loop in which air as a working fluid is pumped and passed the test section to the atmosphere after being heated. The rig basically consists of three parts; the air supply unit with necessary adoption and measuring devices, the test section and the pulsating mechanism. The air supply unit and its accessories consist of a blower, flow control valves, orifice meter. The proposed pulsating mechanism consists of the variable speed rotating butterfly valve connected to motor with the help of belt-pulley to create flow pulsations. The whole mechanism is kept in front of the pipe outlet which repetitively opens and closes the flow through butterfly valve and thus imparts pulsations to the air.

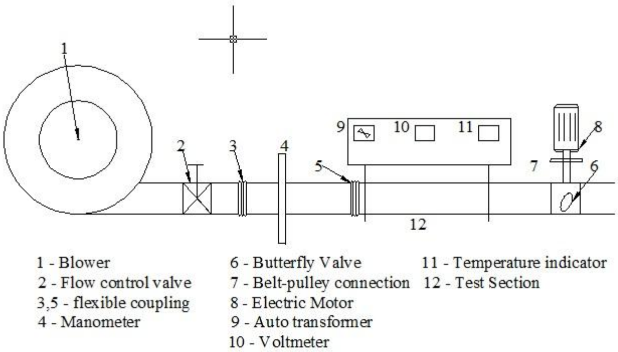

Fig.1 Schematic of Experimental Set Up

2.2 Air Supply Unit

Air is pumped by a centrifugal blower of capacity 1.28 HP rotating at 2000 rpm and having static pressure of 50mm of water column. The air flow rate is controlled by a flow control valve placed upstream of a calibrated orifice meter which measures the flow rate of the air using a U-tube manometer connected to a two static pressure taps. Besides controlling the flow, the control valves also served as a major pressure drop in the system. Afterward the air is passed over the test section via the upstream clamping joint and then exhausted to the atmosphere after being passed through the pulsating valve. The flow measuring sections as well as rest of test loop were completely isolated from vibrations source by two flexible connections. The flow enters the test section at uniform temperature and fully developed turbulent after being stabilized and adjusted.

2.3 Test Section

The test section is as shown in Fig.1. It is a copper tube of 25 mm inner diameter, 28 mm outer diameter. The test section is clamped from both sides by flexile joints. The pipe wall temperatures are measured by 4 k-type thermocouples distributed along the tube surface from outside. Thermocouple junctions are fitted into 4 holes along the outer surface of the pipe, each of 2 mm in diameter and 2.5 mm in depth. The thermocouple wires are then embedded inside the grooves drilled in the outer pipe surface parallel to its axis by epoxy collected out of the test section and connected to a multi-channel temperature recorder via a multipoint switch. The main heater of 0.4 m total length is a nickel chromium wire which has a resistivity of 15.5 Ω/m is divided into two equal lengths to heat up the test section tube. The tapes of the heaters are electrically insulated by fitting them inside very ductile Teflon pipes of 0.1 mm thickness and 2 mm in diameter and wrapped uniformly along the outside tube surface. These heater tapes are sandwiched by aluminum foils of 0.2 mm thickness for achieving a uniform heat distribution. An auto-transformer is used to supply and control the power of the two electric heater sections, which are connected in parallel with the required voltage. A layer of glass wool insulation of 35 mm thickness is applied over the heater, followed by a thin sheet of aluminum foil. The bulk air temperatures at inlet and outlet of the test section are measured by two k-type thermocouples inserted in two holes drilled through the flanges at the entrance and exit of this test section.

2.4 Pulsating Mechanism

The pulsating mechanism shown in Fig. 1 is located downstream at the exit of the tested pipe. It is constructed of three main parts; an AC electric variable speed motor, a variable speed transmission mechanism, and a rotating butterfly valve of 25 mm inner diameter. The valve spindle is connected to the motor through one stepped pulley and a belt. The output of the transmission mechanism, which is connected to the pulsator valve spindle through a sleeve, could be adjusted manually to rotate the butterfly valve with variable speed within the range of 30 to 100 rpm. Pulsation in the air stream is generated by the butterfly valve. The pulsator valve can be adjusted to rotate to give different frequencies, which are measured by a digital tachometer. The valve has the same inner diameter of the test section pipe and was located at downstream the end of the test section tube.

3. Experimental Procedure and Calculations

In this investigation, an experimental program is conducted to study the heat transfer characteristics of pulsating turbulent air flow through pipe. Several parameters affect the performance of heat transfer of such a flow. Among all the frequency of pulsation, Reynolds number and the location of pulsation mechanism relative to the test-section may have the great effect. Experiments in pulsating flow were executed while the pipe wall is heated with different heat input and the pulsation mechanism was located downstream and upstream of the test section. The mass flow rate of air was adjusted and held unvaried while varying the pulsation frequency from 0.0 up to 3.33 Hz. The investigation covered different values of Reynolds numbers in the range of $7000 < Re < 16500$.

3.1 Calculations

Discharge through orifice is calculated as

$$q = \frac{C_d A A_0 \sqrt{2gh_a}}{\sqrt{A^2 - A_0^2}} \quad (1)$$

The maximum Reynolds number of air flowing in a pipe of diameter D is given by

$$Re = \frac{4\dot{m}}{\mu \pi D} \quad (2)$$

Axial heat loss by conduction from both ends of the tested tube was eliminated by a two Teflon washers located between the test section flanges. The heat loss in radial direction through insulation was checked and found to be about 2% of heat input that can be ignored.

$$Q_{trans} = \dot{m} C_{pm} (T_{bo} - T_{bi}) \quad (3)$$

$$Q = hA(T_s - T_a) \quad (4)$$

The mean heat transfer coefficient is determined by

$$h = \frac{Q}{A * (T_s - T_a)} \quad (5)$$

The mean value of Nusselt number is determined by

$$N_u = \frac{h * D}{k_a} \quad (6)$$

The value of ka is detected at the mean bulk temperature of the flowing air.

The frequency of pulsation; f is determined by employing a digital tachometer. A photo electric probe emits light on to the flange that connected by the butterfly valve, which is taped at one side with a reflector. As the flange rotates, the reflection is counted by the probe. The number of reflections per minute is a measure of the speed of the motor, hence the frequency of pulsation.

$$f = \frac{2 * N}{60} \quad (7)$$

For the sake of validating the present experimental data, it has been compared with that reported in literature (Dittus and Boellter, 1930) for the steady flow, which is given by

$$N_u = 0.023 * Re^{0.8} * Pr^{0.4} \quad (8)$$

4. Results and Discussions

The effect of pulsation on the heat transfer characteristics are presented in terms of Nusselt number and average heat transfer coefficient for pulsated flow to the corresponding ones for steady flow at the different Reynolds numbers. The average heat transfer coefficient and Nusselt number is calculated by varying heat input and pulsation frequency.

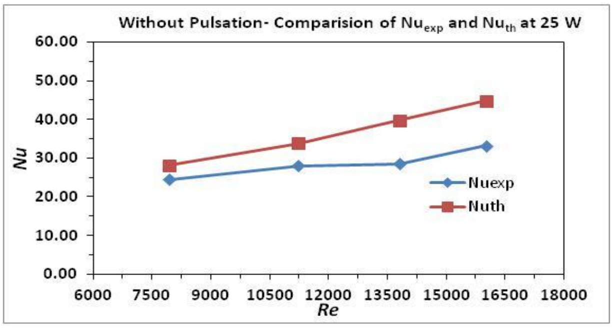

Fig.2 Comparison of Nusselt Number calculated experimentally and theoretically without Pulsation

Figure 2. shows the good agreement between experimental and theoretical values of Nusselt number at different Reynolds number. The variation in experimental and theoretical Nusselt number lies within 5-6 %.

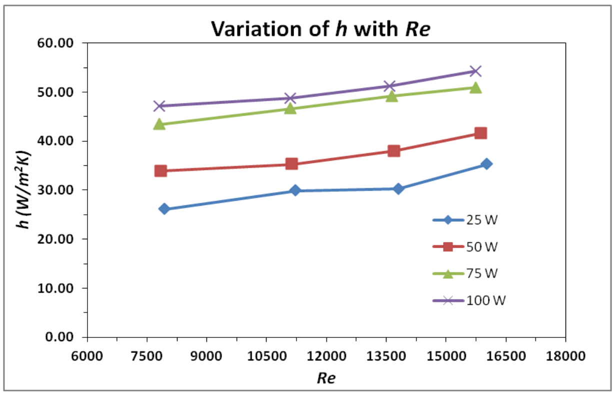

Fig.3 Variations in Heat Transfer Coefficient with Reynolds Number at different heat input

It can be seen from Fig. 3 that enhancement is found in mean heat transfer coefficient comparing with different heat inputs. It shows that the values of mean heat transfer coefficient slightly increase with increasing the value of Reynolds number and more with heat input. It is because when the Re increases, it causes turbulence and recirculation to fluid. The 30-34% enhancement in heat transfer coefficient is found at maximum heat input 100 W.

For increment in heat input, it can be seen from Fig. 4 that enhancement is found in mean Nusselt Number. It is because of the increase in the level of turbulence due to pulsation. At higher frequency, more frequent disturbances can be obtained depending upon Re. Hence, it gives improved turbulence and heat transfer rates. The 35-40 % enhancement in mean Nusselt Number is found at maximum heat input 100 W, when pulsation mechanism is at downstream. When the pulsation mechanism is at upstream, the17-20 % enhancement in mean Nusselt Number is found at same working parameters, as shown in fig.5.

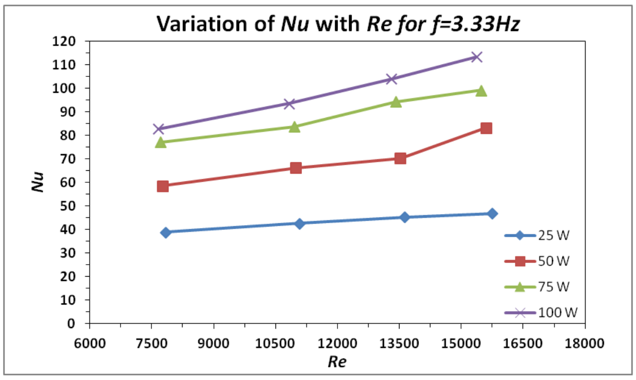

Fig.4 Variations in Nusselt number with Reynolds Number at different heat input with f=3.33Hz (Downstream)

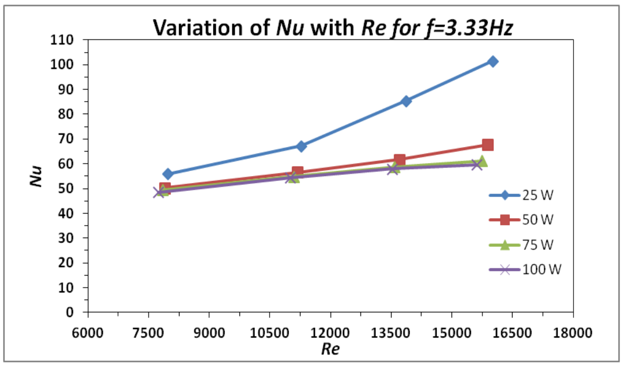

Fig.5 Variations in Nusselt number with Reynolds Number at different heat input with f=3.33Hz (Upstream)

It can be seen from Fig.6 that enhancement in mean Nusselt Number takes place and is higher compared to without pulsation for same heat input of 100W at downstream. It is because of the increase in the level of turbulence due to pulsation. At higher frequency, more frequent disturbances can be obtained depending upon Re. It shows that the values of mean Nusselt Number increases with increasing both the value of Reynolds number and pulsation frequencies. The 40-44 % enhancement in Nusselt Number is found at maximum pulsation frequency 3.33 Hz when pulsator is at downstream but when pulsator is at upstream it gives the 24-28 % enhancement in mean Nusselt Number at maximum pulsation frequency 3.33 Hz as shown in fig.7.

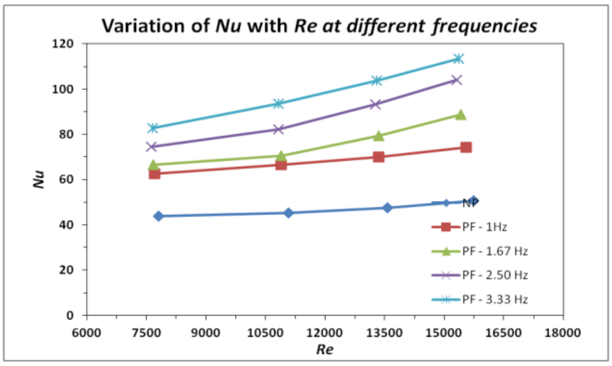

Fig.6 Variations in Nusselt number with Reynolds Number at different pulsating frequencies (Downstream)

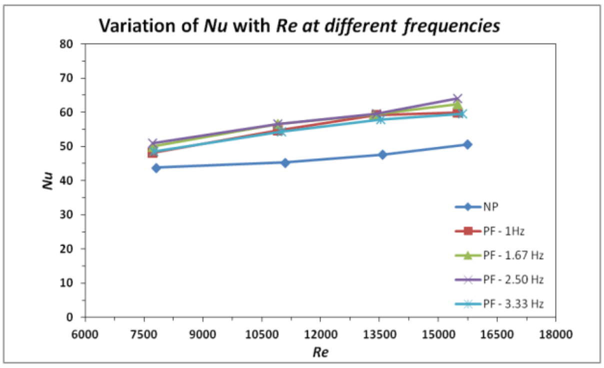

Fig.7 Variations in Nusselt number with Reynolds Number at different pulsating frequencies (Upstream)

Figure.8 shows the variation of Relative mean Nusselt Number $(\eta)_m$ with Reynolds Number at various pulsation Frequencies at 100 W, when pulsator is at downstream. This variation shows that when certain increase in frequency of pulsation is there then Relative mean Nusselt Number increases. In case of location of pulsator at upstream shown in Fig.9, it is clear that Relative mean Nusselt Number $(\eta)_m$ increases up to certain range of Re and then starts decreasing. It is also valid in case when frequency increases. It is because high Re and frequency produces damping of the turbulence so it leads to decrease in Relative mean Nusselt Number.

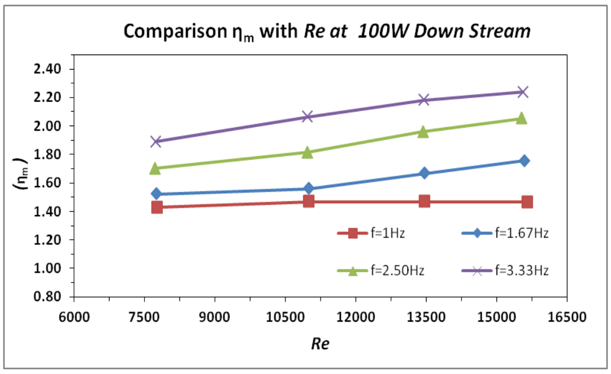

Fig.8 Variations in Relative mean Nusselt number with Reynolds Number at 100 W. (downstream)

Figure.10 shows that the variation in Nusselt Number without pulsation and with flow pulsation. It is clear from the plot that Nusselt Number when pulsating mechanism at down side have better results compared to the upstream and without pulsation. The variation in pulsating mechanism at downstream and upstream position of Nusselt Number lies within 14-17 %. Figure.11 shows that the variation in Nusselt Number without pulsation and with flow pulsation. The variation follows same pattern as that of above case but the enhancement in heat transfer coefficient seems very prominent in case of downstream as compared to upstream and no pulsation. This is because in downstream pulsation there is alternate opening and closing of the valve. When the valve is closed then pressure inside the test pipe increases (above atmospheric pressure) and when it is open pressure falls suddenly. This phenomenon happens periodically in the test section which causes more turbulence and eddies formation in the flow. But, in case of upstream flow the pressure inside the tube is all the time atmospheric pressure. Hence the heat transfer enhancement with downstream pulsation is more efficient than that of upstream pulsation at similar pulsator location. The variation in pulsating mechanism at downstream and upstream position of Nusselt Number lies within 16-20 %.

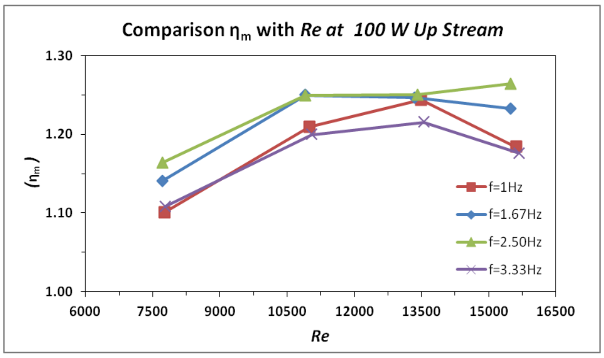

Fig.9 Variations in Relative mean Nusselt number with Reynolds Number at 100 W. (Upstream).

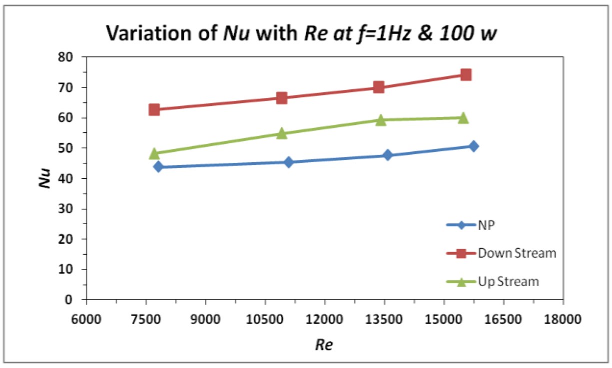

Fig.10 Comparison of Nusselt Number calculated for pulsating mechanism at both side

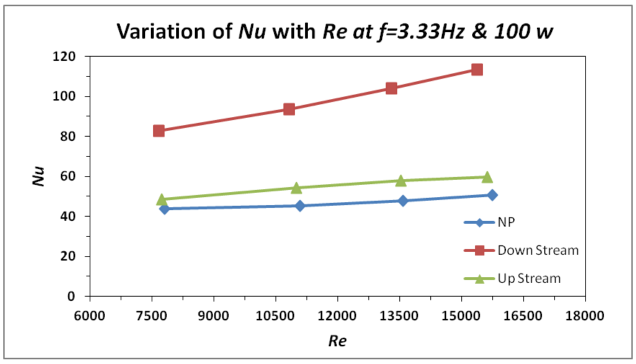

Fig.11 Comparison of Nusselt Number calculated for pulsating mechanism at both side.

Conclusions

The experimental investigation has been carried out to find out heat transfer characteristics for turbulent flow through pipe (with and without pulsation). The effect of pulsation frequency, Reynolds number and heat input on heat transfer coefficient and Nusselt number in case of upstream and downstream location of pulsation mechanism is experimentally investigated. The pulsation mechanism consists of butterfly valve connected to variable speed motor by belt-pulley.

By creating pulsation in flow, it enhances the convective heat transfer charactestics through tube. The average heat transfer coefficient increases with increasing the pulsation frequency and Reynolds number. The maximum enhancement obtained in heat transfer coefficient is 44.4% at downstream and 17.68% at upstream when pulsation frequency is 3.3 Hz. The Nusselt number increases with increasing the pulsation frequency and Reynolds number. The maximum enhancement obtained in Nusselt number is 43% at downstream and 11.2% at upstream when pulsation frequency is 3.3 Hz. With increase in heat input the enhancement in average heat transfer coefficient and Nusselt number were observed for pulsation mechanism at upstream and downstream position. Enhancement in mean heat transfer coefficient and mean Nusselt number is more prominent in case of downstream position in caparison to upstream position and no-pulsation case.

References

Al-Haddad A; Al-Binally N,(2006), Prediction of Heat Transfer Coefficient in Pulsating Flow,Int J Heat Fluid Flow, 10(2): pp.131–133.

Mostafa Hesham M., Torki A. M., .Abd-Elsalam K. M , (2005), Experimental Study for forced convection Heat Transfer of pulsating flow inside Horizontal Tube,4thInternational Conference on Heat Transfer, Fluid Mechanics and Thermodynamics,Cario, pp. 516-522.

Habib M.A; Said S.A.M; Al-Dini S.A; Asghar A; Gbadebo S.A, (1999), Heat transfer characteristics of pulsated turbulent pipe flow, J Heat Mass Transfer 34(5): pp. 413–421.

Gbadebo S. A. , Said S.A.M., SAM, Habbib M.A.,(1999), Average Nuseelt number correlation in the thermal entrance region of steady and pulsating turbulent pipe flows, J Heat Mass Transfer 35: pp. 377–381.

Zohir A. E., Habib M., Attya A. M., A.l. Eid,(2006), An Experimental Investigation of Heat Transfer to Pulsating Pipe Air Flow With Different Amplitudes, J Heat Mass Transfer 42 (7): pp. 625-635.

Habbib M.A. , Attya A.M. , S.A.M. Said, A.l. Eid, A.Z. Aly,(2004), Heat transfer characteristics and Nusselt number correlation of turbulent pulsating air flows, J Heat Mass Transfer 40, pp. 307-318.

Cho H. W. and Hyun J. M.,(1990), Numerical solutions of pulsating flow and heat transfer characteristics in a pipe,Int. J. Heat and fluid flow, 11,(4) pp. 321-330.

Moschandreou, T and Zamir,(1997), Heat transfer in a tube with pulsating flow and constant heat flux, J Heat Mass Transfer 35(10): pp. 2461-2466.

Chattopadhyay H., Durst,S.Ray F.,(2006), Analysis of heat transfer in simultaneously developing pulsating laminar flow in a pipe with constant wall temperature, J Heat Mass Transfer 33: pp. 475-481.

Xuefeng W., Nengli Z. ,(2005), Numerical analysis of heat transfer in pulsating turbulent flow in a pipe, J Heat Mass Transfer, pp. 48:3957-3970.

Hessami M.A. and Zulkifli N.,(2007), Experimental Study of Pulsatile Flows in a Heated Horizontal Tube For Various Flow and Pulsation Conditions, ICET07, University of Kuala Lumpur.

Elsayed. Elshafei A.M, Mohamed M. Safwat , Mansour H., Sakr M.,(2008), Experimental study of heat transfer in pulsating turbulent flow in a pipe International Journal of Heat and Fluid Flow,29 ,pp. 1029–1038.

Mamayev, V.V., Nosov, V.S. and Syromyatnikov N.I.,(1976), Investigation of heat transfer in pulsed flow of air in pipes, Heat Transfer-Soviet Research, Vol. 8, No. 3, pp. 111–116.

Ishino, Y.Y., (1996), Flow and heat transfer characteristics in pulsating pipe flows (Effects of pulsation on internal heat transfer in a circular pipe flow),Heat transfer: Japanese research, 25(5):pp. 323-341.

Karamercan, O. and J. Gainer,(1979), The effect of pulsation on heat transfer. Industrial Engineering Chemical Fundamental,18: pp. 11-15.

Incropera J; Dewitt M, (1996), Introduction to heat transfer, Wiley and Sons, Inc., New York.

Chapra.S.C, Canale.R.P, (1998), Numerical methods for Engineering with programming and softwere, Wcb/Mcgraw-Hill, first edition, pp 137-145.

White, Frank, M, (2003), Fluid Mechanics, Fifth edition, McGraw-Hill, second edition, pp 176-225.

Habib, M.A., A.M. Attya, A.I. Eid, and A.Z. Aly, (2002), Convective heat transfer characteristics of laminar pulsating pipe air flow,Heat and Mass Transfer, 38(3): pp. 221-232.

Guoneng Li, Youqu Zheng, Guilin Hu, Zhiguo Zhang,(2013), Experimental investigation on heat transfer enhancement from an inclined heated cylinder with constant heat input power in infrasonic pulsating flows, Experimental Thermal and Fluid Science 49, pp. 75–85.

Wanga Chang, Gaob Puzhen , Wanga Shaowu , Lia Xiaohui , Fanga Chengyue ,(2013), Experimental study of single-phase forced circulation heat transferin circular pipe under rolling motion, Nuclear Engineering and Design 265 , pp. 348– 355.

Guoneng Li, Youqu Zheng ,Yousheng Xu ,Guilin Hu, Zhiguo Zhang, (2014), Experimental investigation on heat transfer enhancement from a heated circular cylinder with constant heat input power in turbulent pulsating cross flows, Heat Mass Transfer, Springer-Verlag Berlin Heidelberg, DOI 10.1007/s00231-014-1355-8.