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NUMERICAL INVESTIGATION OF HEAT TRANSFER CHARACTERISTICS OF PULSATING TURBULENT FLOW IN A STRAIGHT CIRCULAR PIPE

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Abstract -A numerical study has been carried out for convective heat transfer in a pipe subjected to pulsating turbulent flow.The flow is thermally and hydro-dynamically fully developed and the pipe wall is subjected to a uniform heat flux and water is used as working fluid. Prediction of heat transfer characteristics is done at Reynolds number 10000 under pulsating frequency of 0.2 Hz, 0.3Hz and 0.4 Hz and amplitude of 0.1, 0.2 and 0.3. The primary motives for this research is to enhance the knowledge and understanding of the behavior of pulsating heat transfer under steady and pulsating flows including the effect of various parameter like effect of change in pulsating amplitude and frequency of sinusoidal velocity function. The work incorporates computational analyses and its validation. It is noticed that change in amplitude does not affect the heat transfer while in case of change in pulsating frequency local time-averaged Nusselt number either increases or decreases than steady flow values depending on the frequency parameter.

***Key Words*:**Convective heat transfer, Pulsating turbulent flow, Pulsating amplitude, Pulsating frequency.

1.INTRODUCTION

By virtue of enhancement of the heat transfer coefficient, oscillating flow has received vital attention in thermal engineering. The rate of heat transfer amend since oscillation changes the thickness of the thermal boundary layer and hence the thermal resistance [1]. Convective heat transfer, or simply, convection, within the study of heat transport processes is influenced by the flow of fluids. The field of Convective heat transfer has been very important answer to the fundamental question of how a fluid flow acts as a “carrier” or “conveyor belt” for energy and matter. The convective heat transfer is at the convergence between two streams viz. heat transfer and fluid mechanics. Hence, the studies of any convective heat transfer problem rest on a thorough understanding of basic heat transfer and fluid mechanics principle [2].

Many engineering applications are significantly affected by the performance of heat transfer. For example, heat transfer in the engine manifolds both during intake and exhaust occur under pulsating condition the reason for this unsteadiness of the flow is due to pulses coming from cylinder ports. Such flows experience the difficulty of the phenomena analysis. The term ‘pulsating’ or ‘pulsatile’ is used for the class of cycle stationary flow during which oscillations occur around a time-average non-zero value [3].

Pulsating flow can be defined as a steady time mean flow with super imposed regular cyclic variations. The severity of pulsating flow depends on pulsation amplitudes, frequency and waveform. A reversed flow can occur under severe pulsating conditions. The measurement of both compressible and in-compressible flow can be affected when carried out under pulsating conditions. Pulsating flow occurs in pipelines fed by rotary or reciprocating compressors and pumps, and inlet and exhaust ducts of reciprocating engines [4]. Oscillating valves and regulators can cause some periodic variations [5].

In the present research, investigations are carried out for the effect of various parameters with reference to enhancement of heat transfer. The important parameters consideredare pulsating frequency (*f*), amplitude of pulsation (*A*). These parameters are considered for reporting a comprehensive comparison in increasing heat transfer with respect to these parameters. In this section, objectives of the numerical simulations have been made.
Nomenclature:

A = *Amplitude of pulsating flow*
f = *Frequency of pulsating flow*
Pr= *Prandtl number*
D = *Diameter of the pipe*
L = *Length of the pipe*
μ = *Dynamic viscosity*
V = *Pulsating velocity*
Nu = *Nusselt number*
U_0= *Non-pulsating velocity*
Re = *Reynolds number*
ρ = *Density of fluid*
C_p= *Specific heat capacity*
K = *Thermal conductivity*
$El_{turbulent}$ = *Entrance Length Number for Turbulent Flow*
T =*Time*
Q = *Heat flux* (W/m^2)

2. PROBLEM DEFINITION

The main objective of the present study is to investigate the effects of the changes in pulsating frequency and pulsation amplitude for pulsating flow of water in a circular tube for heat transfer enhancement. All the numerical simulations are carried out using CFD software ANSYS Fluent (V-16) in a 3D configuration. The heat transfer enhancement is calibrated in terms of mean Nusselt number.

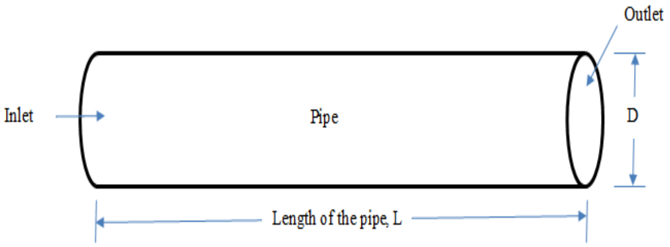

Fig -1: Geometry of specimen (pipe)

The flow domain consists of an inlet, an outlet, and the wall. The pipe diameter, D is 0.025m and length of the pipe, L is 1m. The fluid at a pulsating velocity 'V' enters through the pipe inlet with temperature 293K with frequency of 0.2 Hz, 0.3 Hz and 0.4 Hz and amplitude of 0.1, 0.2 and 0.3. The pipe wall is subjected to a constant heat flux 'Q' = 15000 w/m2. For studying the effect of change in pulsating frequency and amplitude, Reynolds number (Re) is kept constant at 10000, and is based on the diameter of the pipe. Other parameters used for the simulations are as follows:

Table -1: Parameters used for simulations

V	$U_0(1+A\sin 2\pi f T)$
Re	$\rho v D/\mu$
Pr	$\mu Cp/K$
Nu	$0.023 Re^{0.8} Pr^{0.4}$
$El_{turbulent}$	$4.4\ Re^{1/6}$
μ	0.001 Pa-s
U_0	0.4m/s
Cp	3.732 kJ/kgK
K	0.6 w/mk
ρ	998.2 kg/m3

The governing equations used for the simulations are 3D Navier-Stokes equations, as described:

Continuity equation:

$$\frac{\partial p}{\partial t}+\frac{\delta \rho u}{\delta x}+\frac{\delta \rho v}{\partial y}\rho+\frac{\partial \rho w}{\partial z}=0\ldots\ldots\ldots\ldots(1)$$

X- momentum:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)\ldots\ldots\ldots\ (2)$$

Y- momentum:

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)\ldots\ldots\ldots\ (3)$$

Z- momentum:

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)\ldots\ldots\ (4)$$

The two equations k-ε model uses the following transport equations for k and ε:

For turbulent kinetic energy k:

$$\frac{\partial p(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right]+2\mu_t E_{ij}E_{ij}-\rho\varepsilon\ \ldots\ldots\ldots\ldots\ldots\ (5)$$

For dissipation ε:

$$\frac{\partial p(\rho k\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t E_{ij}E_{ij}-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}\ldots(6)$$

Where, ui- velocity component in corresponding direction, Eij - component of rate of deformation, and μt - eddy viscosity.

Energy equation:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+q_v=\rho c_p\frac{\partial T}{\partial t}\ldots\ldots\ldots\ (7)$$

Where, k - materials conductivity (W/mk), qv - rate at which energy is generated per unit volume of the medium (W/m^3), ρ - density (kg/m^3), and cp - specific heat capacity (J/kgk)

2. BOUNDARY CONDITIONS

Table -2: Boundary conditions

Inlet	Velocity Inlet (V m/s)	0.4 m/s
Wall	Constant Heat Flux	15000 w/m^2
Outlet	Pressure Outlet	0 bar

3. METHODOLOGY

The methodology is adopted during the present study. Geometry is created in the ANSYS modeler workbench for the geometric parameters considered. The pipe is divided into two zones, laminar and turbulent zone. This is done to take care of the entrance length of the pipe, so that the flow considered here is fully developed. A fine grid is generated in the flow domain. Care is taken to capture the viscous boundary layer and thermal effects. The minimum wall normal distance is of the order 10-5, which satisfies the condition of y+ < 1. Figure 2 shows a grid generated for the simulation.

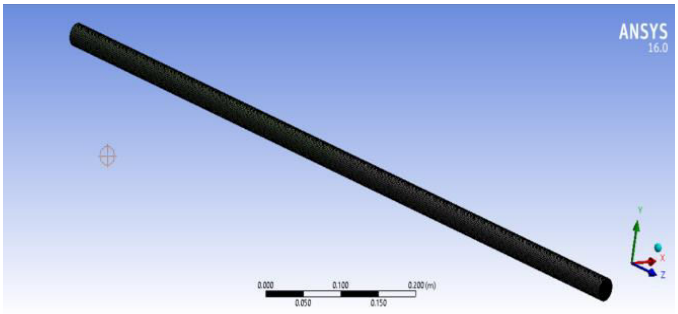

Fig -2a): Grid generated in the flow domain

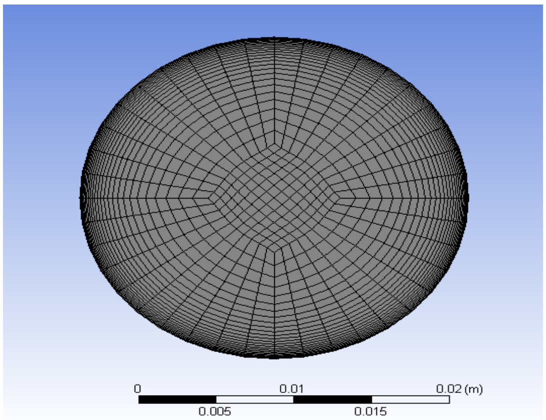

Fig -2b): Zoomed views of the grid generated on a normal plane of the pipe.

Other grid details are:

Min. grid size: 0.1mm, Max. grid size: 2 mm, No. of nodes: 1283136, and No. of elements: 1241529

Solver details:
The methodology given in literature [6] is employed for all the simulations. The pressure velocity coupling method is used and the gradients are calculated by Green Gauss method. For all the computations, a convergence criterion adopted is 1×10^{-6}. Also, viscous k-ε, realizable turbulence model with enhanced wall treatment is used.

4. RESULTS AND DISCUSSIONS

In the present work, various frequencies and amplitudes of pulsating flow have been considered for investigation of heat transfer enhancement. The results of the various cases considered in this work are presented.

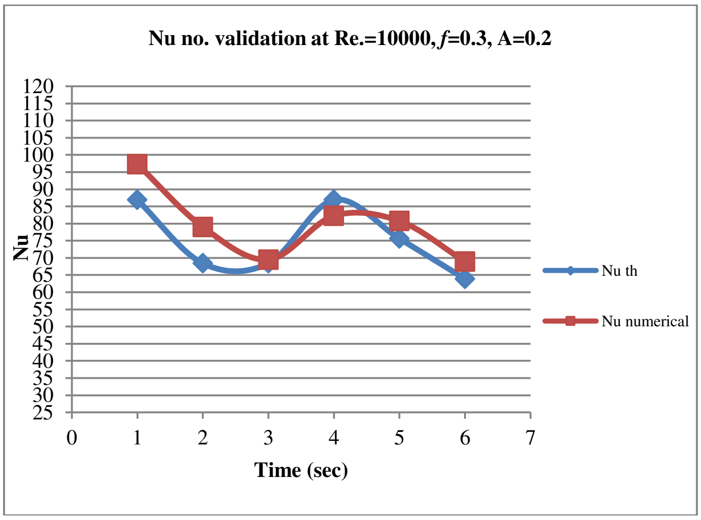

Fig -3:Comparison of present results with the theoretical results.

Fig. 3 shows comparison of theoretical values of Nusselt number at Reynolds number 10000, f = 0.3 Hz and A = 0.2. Nusselt number is computed at area averaged in fully developed region. It is noted that, initially there is difference of 12 % between theoretical value and numerical computed value. The computation has been performed for more time, then the theoretical Nu matches with Numerical Nu. Initial time duration, there is more difference in values of Nu theoretical and Nu numerical this is due to fact that, Theoretically all conditions are in settled and hence do not change with time (steady conditions), while in numerical situation the flow is still to settle down. It is focused on transient growth and development of temperature distribution and velocity fluctuations, as seen from established research; it takes around more than 6 sec, if we continue computing further we may see fluctuations coming down.

EFFECT OF CHANGE IN AMPLITUDE ON HEAT TRANSFER DUE TO PULSATING FREQUENCY:

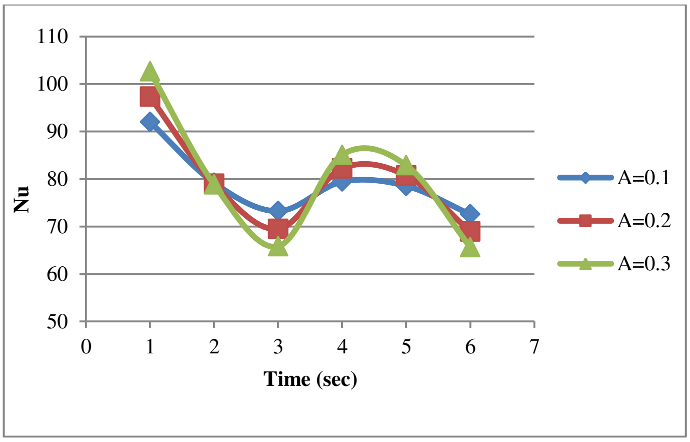

Fig -4:Effect on heat transfer due to change in amplitude at Re=10000 &*f*=0.3 Hz

Fig. 4 shows the effect of amplitude of pulsation frequency on heat transfer at Re = 10000 for pulsating frequency, f = 0.3 Hz. The computations are reported for dimensional time t = 6 sec. After 6 sec, it is noted that there is no significant change in the pattern in variation of Nu. It is evident from the figure that there is a slight difference in mean Nu as amplitude changes, at some point that is at 2 sec we can see that it is overlapping, it is due to effect of pulsation. With increase in amplitude, time instant Nu increases, indicating rise in the heat transfer rate instantaneously. However, if average of all Nu number is taken, with respect to time at each amplitude, Nu is approximately same after comparing for all amplitudes. This is because the velocity pulses which are responsible for enhancement of heat transfer are not significantly altered as the amplitude changes from 0.1 to 0.3. This shows that there is no significant change in the time-averaged heat transfer rate for the amplitudes considered.

EFFECT ON HEAT TRANSFER DUE TO CHANGE IN PULSATING FREQUENCY:

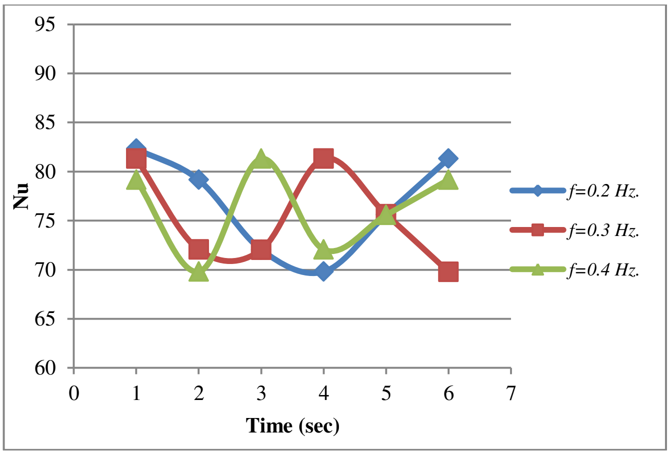

Fig -5:Effect on heat transfer due to change in pulsating frequency at Re=10000 & A=0.1

Fig. 5 shows variation in Nusselt number at Reynolds number 10000 for pulsating frequency 0.2 Hz, 0.3 Hz, 0.4 Hz. It is noted that for f=0.2 Hz, there is an instantaneous decrease of Nu till 4 sec, after which Nu gradually increases again, indicating increase in heat transfer. For f = 0.3 Hz, there is sudden decrease and increase of Nu with respect to time, whereas for f =0.4 Hz, there is drop in Nu till 2.5 sec and then up to 4 sec it increases, then again it drops till 6 sec. This variation in Nu with respect to change in frequency is bit intriguing, this is due to phenomena of frequency in which number of oscillation is less at 0.2 Hz, at 0.3 Hz number of oscillation is more compared to 0.2 Hz and at 0.4 Hz number of oscillation is more compared to 0.2 and 0.3 Hz which we can relate from Fig. 5 at each frequency. Nupulsating (time-averaged) increases than Nuuniform flow for f= 0.2 and 0.4 Hz. However, for f = 0.3, Nupulsating decreases than Nuuniform flow.

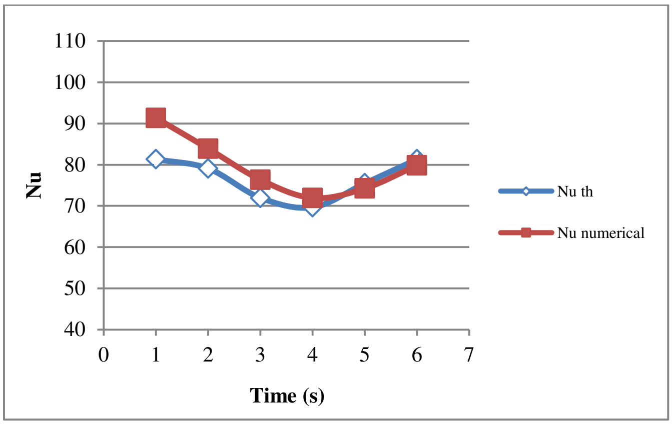

Fig -6:Nu no. validation at Re=10000, *f*=0.2Hz, A=0.1

Fig. 6 shows comparison of Nu obtained in present research work with the theoretical results for Re = 10000, f=0.2 Hz & A=0.1 case. It is noted that for initial time, there is deviation of around 12 % between theoretical value and numerical computed value (numerical results show enhanced heat transfer), but as for longer time computation the Nusselt number matches to the theoretical value. After a considerable time, Nu is much closer that is less than 2% (at 6 sec.) This is due to the transients in the flow, theoretically all conditions are in settled and hence do not change with time (steady conditions), while in numerical situation the flow is still to settle down. It is focused on transient growth and development of temperature distribution and velocity fluctuations. It is to be noted that the results compared here are from ab-initio state, purposefully taken into account to check effects of transients.

CASE: Re = 10000, A = 0.1, *f* = 0.4

Fig -7:Temperature distribution near outlet of the pipe for Re = 10000, A = 0.1, *f* = 0.4

Fig. 7 shows temperature distribution near outlet of the pipe for Re = 10000, A = 0.1, f = 0.4 case. It is evident that the temperature assumes a profile of pulsation and the temperature distribution is in the form of puffs. Fig. 8 shows velocity distribution near inlet of the pipe for the same case. It is to be noted that the velocity pulses are evolving right from the entrance of the pipe. These pulses due to the imposed amplitude and frequency affect the flow. A fully developed parabolic profile with pulsation in noted here, whereas its net effect is in creating turbulence in the form of pulses (or puffs) as noted in Fig. 9.

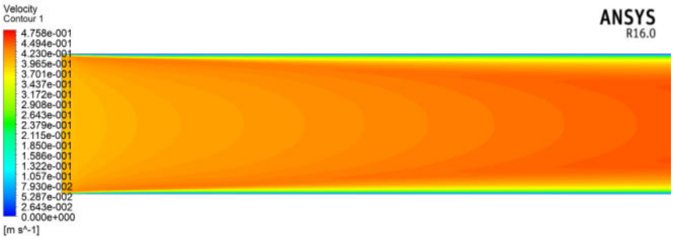

Fig -8:Velocity distribution near inlet of the pipe for Re = 10000, A = 0.1, *f* = 0.4

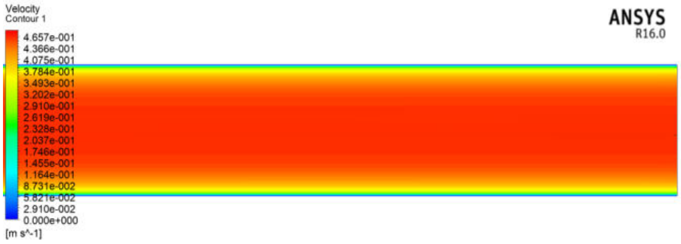

Fig -9:Velocity distribution near outlet of the pipe for Re = 10000, A = 0.1, *f* = 0.4

Fig. 10 show temperature distribution at various sections of the pipe and Fig. 11 show temperature distribution at outlet section of the pipe. It is noted that, as the flow develops, temperature increases from inlet towards exit. A Central core of lower temperature is observed right from inlet to the outlet and radially the temperature is found to be increasing, the maximum temperature being at the wall. It is worth noting that at every section, the temperature distribution follows a peculiar pattern, despite that the oncoming flow velocity is with pulsation. At section iii and onwards in figure 10, the symmetry pattern of temperature distribution is seen to be broken, which indicates the unevenness caused due to pulsation. Fig. 11 shows temperature distribution at outlet of the pipe for Re = 10000, A = 0.1, f = 0.4. The pulsation nature is quite evident.

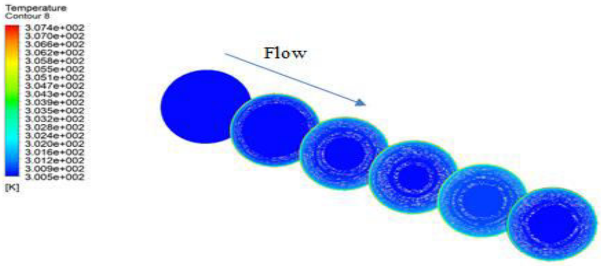

Fig -10:Temperature distribution at various sections of the pipe for Re = 10000, A = 0.1, *f* = 0.4

Fig -11:Temperature distribution at outlet of the pipe for Re = 10000, A = 0.1, *f* = 0.4

5. CONCLUSIONS

A detailed analysis is carried out on the heat transfer enhancement achieved by pulsating flow. Parameters considered are the pulsating frequency, amplitude of the pulsatile flow. The results obtained are very much in agreement with the theoretical results. The major outcomes of this study are as:

1. At specific pulsating frequency if time average velocity becomes more than non-pulsating flow or inlet velocity then heat transfer increases and if time average velocity becomes less than non-pulsating flow or inlet velocity then heat transfer decreases.
2. No significant change in the time-averaged heat transfer rate for the amplitudes considered.
3. Effect can be seen on heat transfer in presence of pulsating frequency in comparison with steady flow,local time-averaged Nusselt number either increases or decreases than steady flow values depending on the frequency.
4. Despite of imposing various amplitude and frequencies for pulsation, it is noted that a small change with respect to amplitudes, and different nature for different frequency cases.

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