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Numerical Investigation of pulsating Flow in 2-Dimensional Channel to Enhance the Heat Transfer Rate

Shital G. Nerkar[1,] Ramesh Rudrapati[2]
[1] Mechanical Engineering Department, MMIT, Lohgaon, Pune-411047, India
[2] G.H. Raisoni College of Engineering and Management, Pune-412207, India
Corresponding Author: Shital G. Nerkar

ABSTRACT

In this research, the numerical analysis of pulsating flow in 2D channel has been carried out with appropriate boundary and initial condition to maximize the heat transfer rate. The wall temperature is kept constant to observe the behavior of air fluid flow in a channel. The time average Nusselt number (Nu_{avg}) is used to study the effect of heat transfer on fluid flow. The user define function (UDF) file has been introduced to define the pulsating inlet velocity fluctuation. The governing parameters like Strouhal number (St) and Amplitude ratio (A/D) which ranges $2 \leq St \leq 20$ & $0.1 \leq A/D \leq 1$ are used to measure the effect on heat transfer. Simulations has been carried out on channel considering variable length with grid sizes 50×5000,50×7500,50×10000 and 50×125000. From the analysis, it is found that as the Strouhal number (St) and Amplitude ratio (A/D) increases the time average Nusselt number (Nu_{avg}) also increases. The Tecplot software is used to draw the plots and from it is found that the fluctuation of axial velocity near the wall surface is more, hence the heat transfer rate is high at that particular region. From result it is concluded that large amplitude ratio provides higher heat rate transfer as compare to the Strouhal number.

Keywords: Amplitude ratio(A/D), Channel, Heat transfer, Nusselt number (Nu), Pulsating flow, Strouhal number (St), Time average Nusselt number (Nu_{avg})

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I. INTRODUCTION

The pulsating flow is define as the unsteady flow characterized by repeated variation in pressure and mass flow around non-zero mean value which affect the heat transfer [1]. An analytical solution was obtained by Shigeo Uchida for circular pipe with pulsating laminar flow superposed on steady motion with the parallel flow to the axis of pipe as a assumption, and observed that the phase lag for velocity variation from that pressure gradient increases from 0-90° for pulsation of infinite frequency [2]. Pulsating incompressible flow in a straight, rigid, circular tube or channel are canonical phenomena of classical fluid mechanics. The heat transfer with pulsating flow is concern to researchers as heat transfer increases or decreases or no change according to fluctuation in different governing parameters and hence it is yet to be clear. As the heat transfer rate increases it alters the thickness of thermal boundary layer and thermal resistance [3]. The Pulsating flow in a pipe or channel is used in many industrial applications like IC engine, refrigeration system [5], reciprocating compressor [4], super charging system of reciprocating engines also in circulating system of blood [2]. Due to its wide existent in various applications with variation in results it is topic of interest for study. The different governing parameters like frequency, amplitude, Nusselt no.(Nu) , Reynold no.(Re), Stanton no(St), Prandtl no(Pr), pulsation method [5] etc are used in various research with different methodology. The user define function is required to find the solution of problem of fluid flow in Ansys Fluent program. The proper boundary conditions help to solve the problem exactly. The pulsation can be create due to pulsation mechanism as per requirement of pulse generation [5].

It was also-observed the heat transfer characteristics of pulsating flow in a pipe heated at uniform heat flux and resulted average Nusselt no. correlation between steady and pulsating flow [8]. Numerically convection heat transfer in pulsating turbulent flow with large velocity oscillating amplitudes in a pipe at constant wall temperature; their analysis results that larger velocity at some moments and the flow reversal during a period of the flow pulsation are the most important mechanism of the heat transfer enhancement [9]. Due to external imposed pulsations the hydrodynamic and thermal boundary layer of fluid flow disturbs. The pulsating flow with flow reversal helps to keep fluid in more contact with wall to increase the heat transfer rate [11]. The computational fluid dynamics is the one of the tool which used solve the problem of fluid flow, it gives appropriate results which matches the experimental results. The different studies was carried out on the laminar and turbulent pulsating fluid flow and observed different experimental, numerical or analytical results those given below. Haddad and Al-Binally [12] prove a general correlation between the heat transfer coefficient in a heating process for steady and pulsating flow of air through a rigid circular pipe. Hemida et al. developed an analytical solution of the fully developed thermal and hydraulic profiles under isothermal wall heat flux [14]. Experimentally observed velocity profiles in laminar oscillatory flow in tubes and resulted that at low frequencies the amplitude of the velocity is approximately parabolic with maximum at tube axis [16]. The Nusselt number at fully developed flow was not showing much variation for steady and pulsating flow. In transverse case the heat transfer enhancement was observed.

The Various results were observed by researcher and it is yet to be clear the effect of Pulsation on laminar fluid flow in pipe or channel and there is need of proper assessment of Impact of pulsating flow on heat transfer from circular 2D channel at constant wall temperature. To solve this problem a 2D channel is selected with constant wall temperature and the numerical method is used to solve the problem approximately. The flow is thermally and hydraulically developed in a channel. The Strouhal number and Amplitude ratio with variable ranges has been selected to observe the behavior of fluid. The two dimensional governing equations are used to solve the problem in the Ansys fluent 15 program. The effect of Strouhal number (St) and Amplitude ratio (A/D) on axial velocity and temperature profile is observed within the parameters range of $2 \leq St \leq 20$ & $0.1 \leq A/D \leq 1$ respectively. Also these two parameters are used to measure the effect of Time Average Nusselt no. (Nu_{avg}) on heat transfer rate.

II. PROBLEM FORMULATION

A 2-Dimensional channel has been considered to solve the problem of pulsating flow with interpreted UDF profile at the inlet of channel. The channel wall is kept at constant temperature to simulate approximate results. The air is used as a fluid to flow in a channel. The approximate boundary conditions are applied. The X co-ordinate represents the length of channel (L) and the Y co-ordinate represents the radius of channel (r) as shown in Figure 1. The working fluid air having density ρ=1.225 kg/m^3 and dynamic viscosity μ=0.00001789 kg/ms with all other thermo-physical properties considered as constant. The Maximum length to diameter ratio (L/D) considered as 250 as L/D=0.05Re.

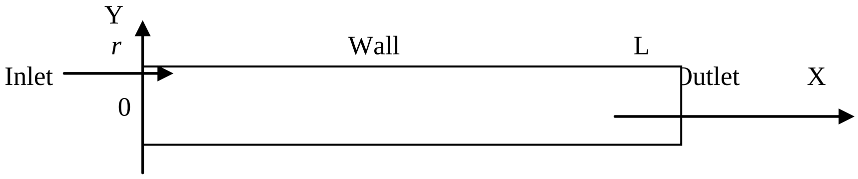


Figure:1 2D channel Geometry for simulation

2.1. Governing Equations

To solve the problem numerically it is necessary to used the governing equations and solve it by Ansys Fluent 15 program. The types of governing equations which was used are conservation of mass , conservation of momentum and energy equations given below. These equations are solved systematically with the help of solver.

Continuity Equation

$$\nabla . u = 0 \tag{1}$$

Momentum Equation

$$\frac{du}{dt} + u.\nabla u = -\nabla p + \frac{1}{Re}\nabla^2 u \tag{2}$$

Energy Equation

$$\frac{dT}{dt} + u.\nabla T = \frac{1}{Re.Pr}\nabla^2 T \tag{3}$$

Where Re is Reynold number and Pr is Prandtl number. In the research The length has been non-dimensionalized by pipe diameter (D), velocity by steady inlet velocity U_{steady} and time by D/ U_{steady} and temperature is non-dimensionalized as $(T-T_{in})/(T_w-T_{in})$.The UDF contains the inlet velocity profile and the other parameters values. Convective terms in the equations are discretized using second order upwind (SOU) scheme. The pressure term is discretized using a standard scheme and the pressure and velocity terms are coupled using SIMPLE (Semi-Implicit method) scheme. The heat transfer coefficient for this type of configuration is generally calculated using bulk temperature Tb. In that case, the local heat transfer coefficient h is given by q=h(Tw−Tb). However, as under the present circumstances, different inlet conditions (e.g. amplitude and frequency) are to be imposed, it is more meaningful to compute Nu with respect to inlet temperature instead of the bulk temperature is given below in equation (5).

The Nusselt number is define by,

$$Nu = \frac{hD}{k} \qquad (4)$$

Where, D=Pipe Diameter (m).
k= Fluid Thermal conductivity (W/mK)

The value of $Nu_i(x,t)$ is define by,

$$Nui = \frac{1}{(Tw - Tin)} \frac{\partial T}{\partial r} \Big| w = h \qquad (5)$$

2.2. Boundary Conditions

At the different section of channel the various boundary conditions are given to solve the problem and to find the appropriate results as follow,

At the inlet the UDF is introduced with inlet velocity condition as given in below equation (6);

$$U = U_{steady}(1 + A_0 Sin(2\pi Str)) \qquad (6)$$

Where,

$$St = fD/v$$

And v=0, $T=T_\infty$

At the wall; $T=T_w$, $u=0, v=0$

At the Outlet; $P_{gauge}=0$

Since quality, number and structure of grid are the three major parameters which will affect the accuracy label of a computational problem, grid generation presents one of the major steps in numerical solutions. The Grid sizes are chosen according to the Re range are 50×5000, 50×7500, 50×10000 and 50×12500 for L/D ratio 100, 150, 200 and 250 respectively. Zoomed view of the grid structure shown in Figure 2.

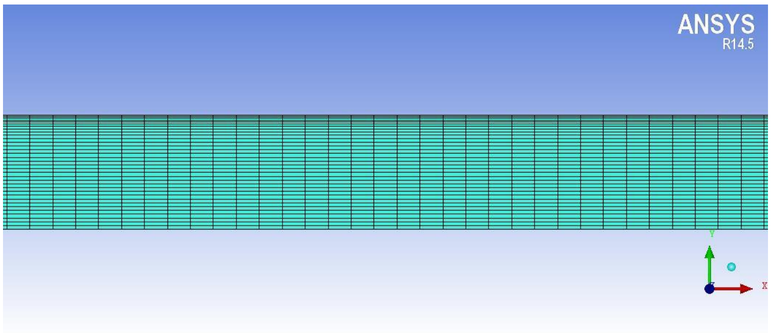


Figure 2: Structure of grid in computational domain

The numerical model is tested to observe the heat transfer characteristics of steady, incompressible flow without pulsation. The simulations are carried out in Ansys FLUENT program and resulted that the local Nusselt number for Reynolds number Re=200 and 1200 is found match with analytical result of 3.66 [3] as shown in Figure 3. The velocity profile for steady, incompressible flow without pulsation at Re=200 (5 ≤ L/D ≤ 50) and Re=1200 (5 ≤ L/D ≤250) was tested. Figure 4 shows the variation of velocity at different channel section and resulted that the maximum velocity was twice that of inlet velocity.

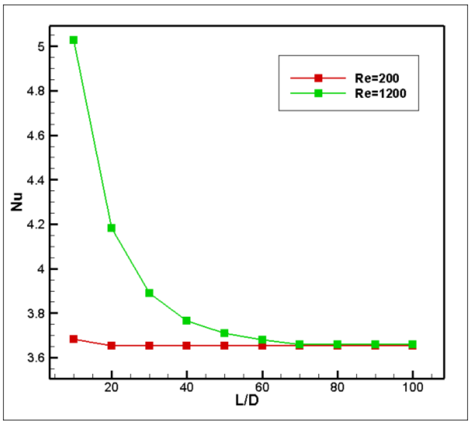
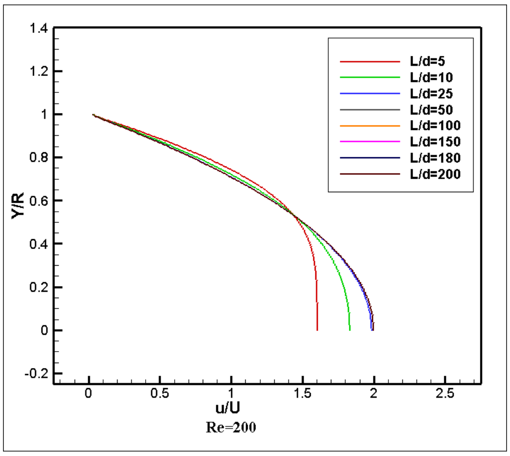
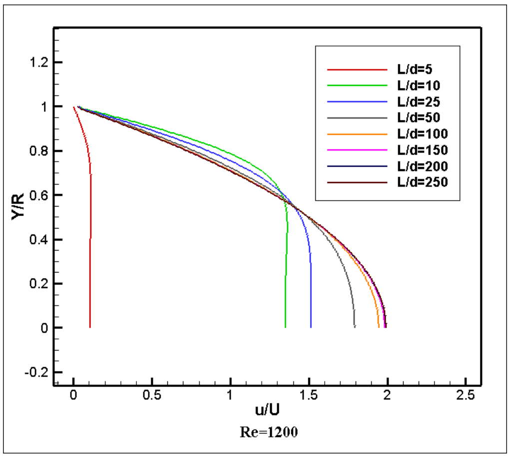


Figure 3: Local Nusselt number for steady flow at Re=200 and Re=1200



(a)



(b)

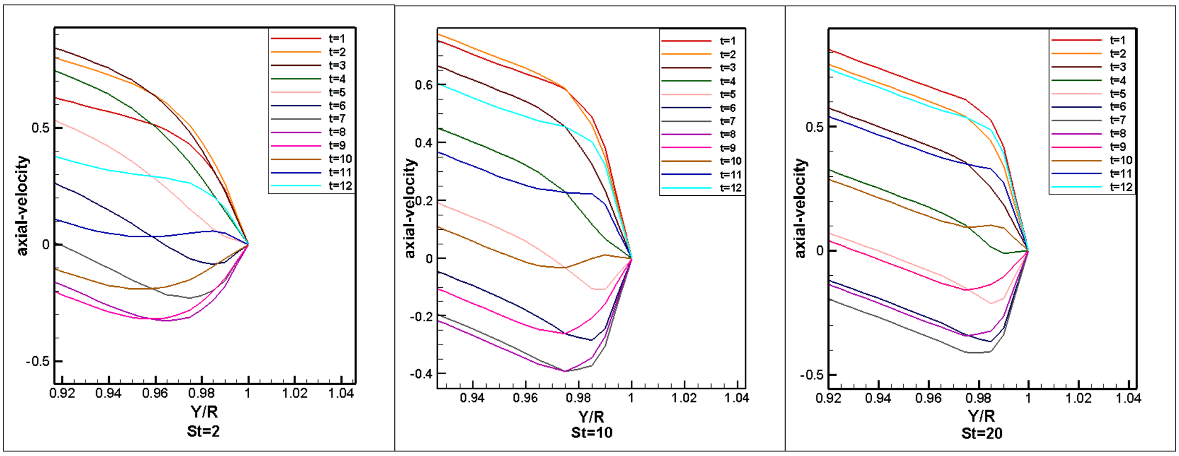
Figure 4: Sectional velocity profiles for steady flow at (a) Re=200 and (b) Re=1200

III. RESULTS AND DISCUSSION

To study the effect of variation of Strohl no and Amplitude ratio on heat transfer characteristics, it is varied in the range of $2 \leq St \leq 20$ & $0.1 \leq A/D \leq 1$ & Re=200 respectively in the step of 200. The effective length of the domain is used much beyond the minimum length requited to develop flow (L/D=0.05Re). As the effective length is the function of Re and it is selected as L/D ratio with the range of 100-250 for different Reynold no (Re). With reference to Analytical results the Grid sizes are chosen according to the Re range are 50×5000, 50×7500, 50×10000 and 50×12500 for L/D ratio 100, 150, 200 and 250 respectively. The study of effect of St and A/D on heat transfer characteristics, the variation of axial velocity and temperature along the channel radius are plotted accordingly.

3.1. Effect of Strohl number (St) :-

The Strohl number (St) was varied from 2 to 20 at Re=1000 and A/D=0.6 respectively. The variation of axial velocity and the temperature distribution is plotted with the respective angle instances (eg. t=1 for 30^{o}, t=12 for 360^{o}) as shown in Figure 5 and 6. The axial velocity plot resulted velocity fluctuation from positive to negative near the wall surface. Hence, the boundary layer thickness decreases which results heat transfer near wall surface. At the core region the velocity variation is positive so it is not affected as shown in Figure 6. The maximum fluctuation is within the range of 0.92 to 1 m length as shown in Figure 5. From plots at St=2 (figure 5(a)) the velocity changing from 0.92 m, at St=10 (figure 5(b)) it is 0.96 m and at St=20 (figure 5 (c)) it is changing from 0.965 to 1 m respectively.



(a) (b) (c)

Figure 5: Variation of Axial Velocity at (a) St=2 (b) St=10 and (c) St=20

The temperature plot as shown in Figure 7 resulted that the temperature decreases as the Strohl no.(St) increases. The heat transfer and boundary layer thickness is not affected by the temperature variation. The decrease in temperature was θ=0.87 at St=2 as shown in Figure 7.

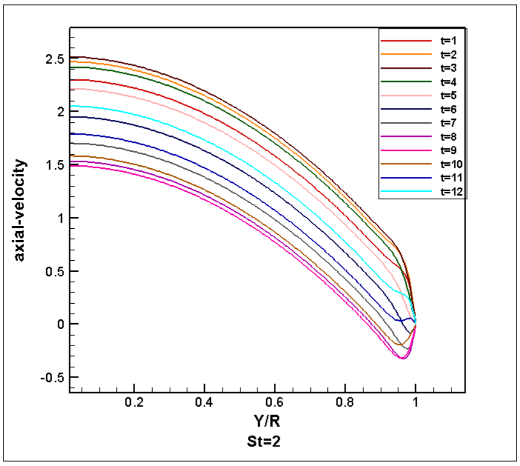


Figure 6: Variation of Axial Velocity at St=2

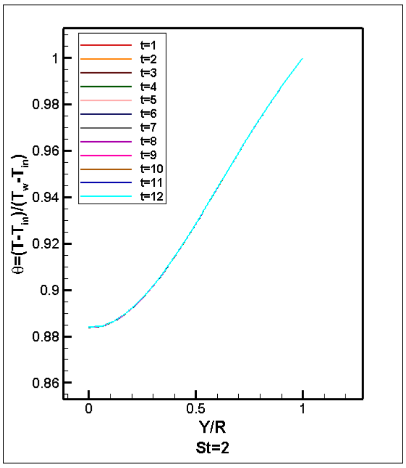


Figure 7: Variation of temperature at St=2

3.1.1 Variation of average Nusselt number (Nu_{avg}) at Different Strohl number (St)

The value of Nu for laminar flow is 3.66, which is validated earlier. From the results, it is observed that the value of Nu_{avg} are increasing as the St increases and hence it helped to increase the heat transfer rate as fluid comes more in contact to the surface. For fully developed flow the value is plotted at different St as shown in Figure 8. From the figure it is observed that the Nu_{avg} increases from 3.679 at St=2 to 3.697 at St=20 and 3.699 at St=10 as it is fluctuating continuously. This fluctuation helps to enhance the heat transfer rate due to pulsation variation.

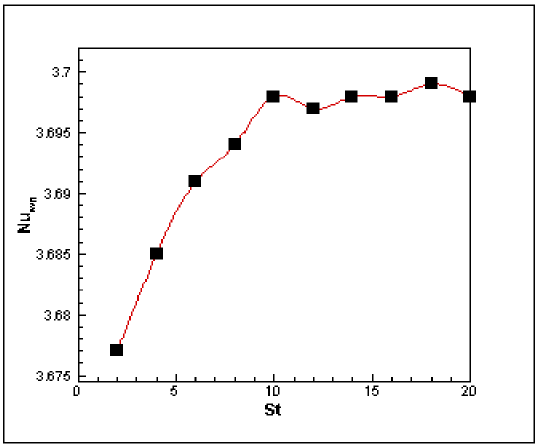
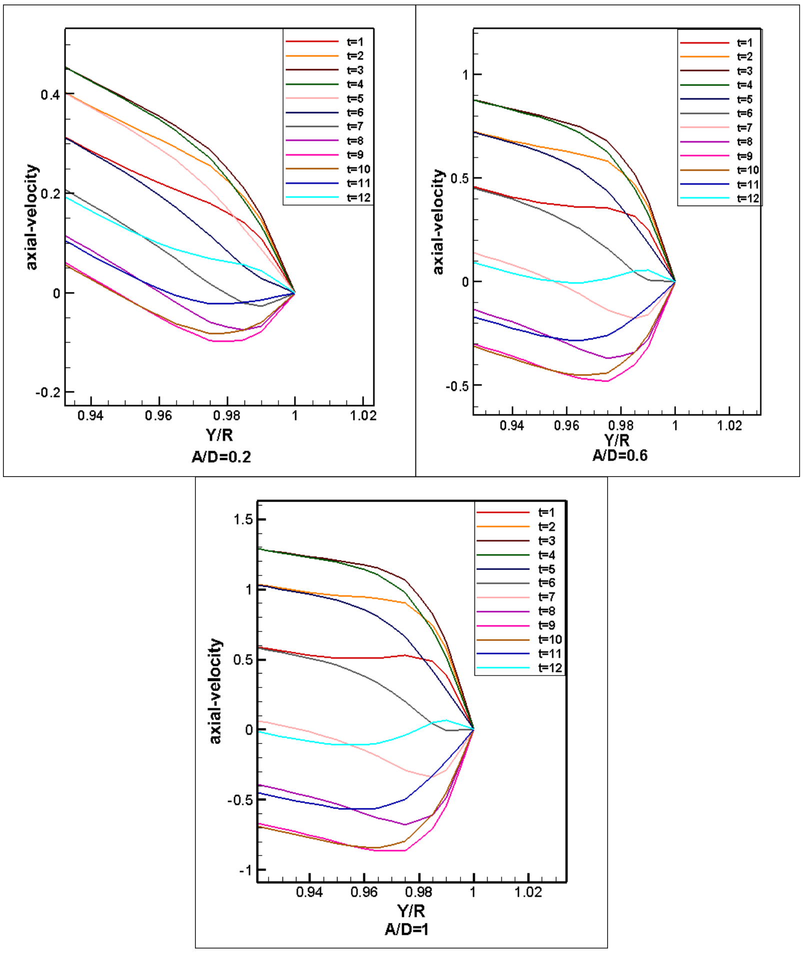


Figure 8: Variation of Nu_{avg} with St

3.2. Effect of Amplitude Ratio (A/D)

The Amplitude Ratio (A/D) is the function of area and diameter of channel. The value of Amplitude ratio is within the range of $0.1 \leq A/D \leq 1$ with constant Re=1000 and St=5 selected. The variation of A/D is distributed in the instances of 0.2. The simulations are carried out by changing the value of A/D in the UDF with approximate boundary and initial condition. The variation of axial velocity and the temperature distribution is plotted with the respective angle instances (eg. t=1 for 30°, t=12 for 360°). From Figure 9, it is observed that the thickness of the profile increases as the A/D ratio increases. The variation of axial velocity at different A/D ratio shows the continuous fluctuation near the wall surface is encountered. Hence it is resulted that the particular A/D ratio range is required to enhance the heat transfer in channel.



(a) (b) (c)

Figure 9: Variation of Axial Velocity at (a) A/D=0.2 (b) A/D=0.6 and (c) A/D=1

The temperature variations are observed and resulted that the temperature curves are overlapping to each other. The temperature in channel decreases as the value af A/D increases as shown in Figure 11. It is also observed that the heat transfer rate is not affected by temperature variation as same like previously observed in St (figure 7).

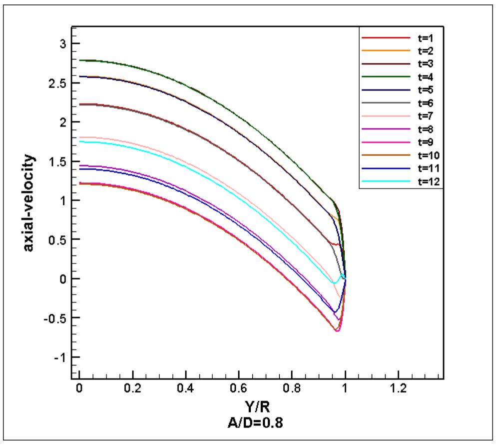


Figure 10: Axial Velocity at A/D=0.8

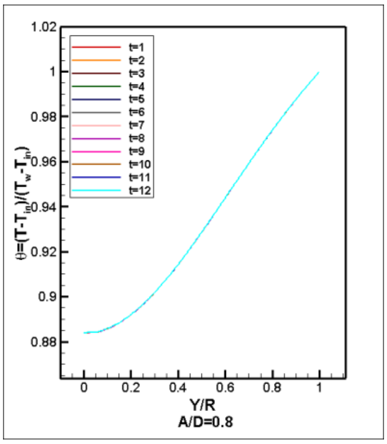


Figure 11: Variation of Temperature at A/D=0.8

3.3 Variation of Average Nusselt number (Nu_{avg}) at Different Amplitude Ratio (A/D)

The variation of the Amplitude Ratio has been resulted with different value of Average Nusselt no. (Nu_{avg}). The Nusselt no. (Nu) is the function of heat transfer hence the variation of Nu_{avg} resulted that the heat transfer rate increases as it is varying continuously from 3.65 at A/D=0.2 to 4 at A/D=1. From Figure 12 it is observed that the Nu_{avg} is increases slowly upto A/D=0.6 and at higher A/D ratio Nu_{avg} is increases rapidly. Hence these rapid changes in Nuavg affect the boundary layer thickness and also increase the heat transfer rate. From the results it is clear that the value of A/D is important to maintain in this range for St=5 and Re=1000.

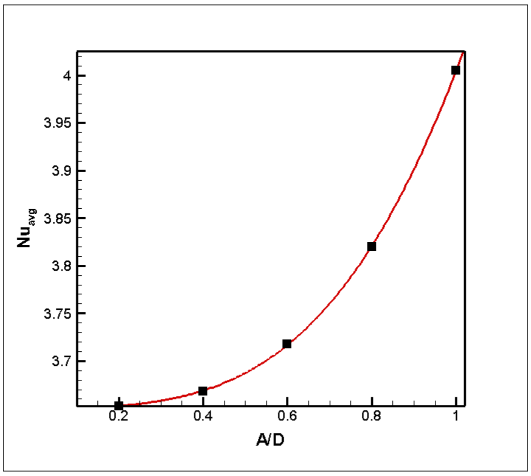


Figure 12: Variatiom of Nu_{avg} with A/D

IV. CONCLUSIONS

The 2D channel is simulated in ANSYS Fluent program and from the results it is concluded that;

- The variation of axial velocity near the wall surface is more and hence the heat transfer rate is maximum at that particular region.
- As the mass of fluid strikes the wall of channel due to changes of velocity from positive to negative results decrease in boundary layer thickness and hence enhanced the heat transfer.
- The Amplitude ratio (A/D) results in enhancement in heat transfer due to rapidly variation in Nu_{avg} as compared to Strohl no. (St).
- The heat transfer rate is not affected by temperature variation for Strohl no (St) and Amplitude ratio (A/D).
- The enhancement of heat transfer in pulsating flow is more as compared to the steady flow in 2D channel as observed.

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