Numerical Investigation on the Laminar Flow in a Vertical Pipe with Elliptic Cross Section

Saleh Etaig[1], Gamal Hashem[2]

[1, 2]University of Benghazi, Faculty of Engineering, Benghazi, Libya

Abstract: ***The presented paper reports the analysis of the flows characteristic and heat performancein a horizontal pipe with elliptic cross section area. The flow is investigated by CFD techniques using a finite volume method. A range of Re number is tested in the present study. Various velocity ranges were used as constant wall heat flux boundary conditions. The increase of the Re number was found to increase the heat transfer rate; the skin friction factor was found to increase with the increase in Re number. The increase in Re number promoted Nu number at both top wall and side wall of the elliptic pipe, however, the temperature distribution on top wall and side wall was found to be different. The velocity in the elliptic pipe is calculated, and the results are shown and discussed***

Keywords: Heat Transfer, Fluid Mechanics, Elliptic pipe, CFD**.**

1. Introduction

Heat transfer improvement attracted the attention of many researchers for many decades. The heat transfer can be enhanced by many approaches, one of which is the configuration of the geometry. Many geometries have been tested by many scientists [1-6]. The circular cross section pipes were one of the most configurations tested among researchers [7-12]. Rectangular cross section pipes were also explored by a quite number in the literature [13-16].

The elliptical cross section pipe tested by Velusamyet al [17]studied the fully developed laminar flow of semi elliptic duct, they considered isothermal and uniform axial heat flux on the walls.They found that the ratio of Nusselt number to friction factor is higher for semi-elliptical ducts compared to that for other ducts, such as sinusoidal, circular segmental, and isosceles triangular ducts with the same height to base ratio.

The same authors [18] studied later the laminar mixed convection in vertical elliptic ducts. They highlighted that he ratio of Nusselt number to friction factor is higher for elliptic ducts compared to that for a circular duct, regardless the value of the Rayleigh number. Shariat et al [19] presented a numerical study on the laminar mixed convection in elliptic tubes using two phase mixture.They founded the usage of the elliptic pipes with AR 0.75 instead of the circular pipe is recommended.Dong and Ebadian[20] studied the thermally developing flow in elliptic ducts with internal fins, their results showed a high heat transfer coefficient, expected in the entrance region.The same authors [21] investigated the laminar flow in curved elliptic ducts.

Cain and Duffy [22]conducted an experimental investigation on the turbulent flows in elliptical ducts. They measured the friction factor for fully turbulent flow of air at a range of Re number, they highlighted that theturbulent core Reynolds similarity was incomplete.

Papadopoulos and Hatzikonstantinou[23] studied laminar Incompressible flow inside a curved duct of elliptical cross-section with internal longitudinal fins, their results showed that the heat transfer rate is improved by the internal fins and it depends on the aspect ratio.The fully developed turbulent flow in elliptical ducts was investigated by Nikitin and Yakhot [24], they highlighted that The variation of Reynolds stresses and turbulence intensities along the minor axis of the elliptical cross-section are found to be similar to plane channel data.

Voronova and Nikitin[25] investigate the turbulent flow in an elliptic pipe by DNS scheme, They made their simulation based on Re 4000 only. Topakoglu and Ebadian[26]analysed the laminar flow of viscous fluid in a curved elliptic pipe, they considered two different geometries, one with the major axis of the ellipse placed in the direction of the radius of curvature; and the other, with the minor axis of the ellipse placed in the direction of the radius of curvature.

The steady laminar flow of an elastico-viscous liquid in a curved pipe of varying elliptic cross section was studied by Sarin [27], He found that the absolute value of shearing-stress increases with Dean number, The shear stress is found to be more at the major axis and at the outer bend than at the minor axis and at the inner bend.

The steady laminar flow in a curved pipe of varying elliptic cross-section problem was investigated by Jain and Jayaramn[28], They calculated the secondary flow, shear stress and also the effect of constant curvature of the centre line.

The aim of the present work is to investigate the heat transfer performance and fluid flow characteristics of a flow in an elliptic pipe with a range of Re number.

2. Problem Description

The problem geometry considered in the present work is illustrated in Figure 1. It represents in a horizontal pipe with an elliptical cross section,the dimensions are shown in the figure with hydraulic diameter, where h, w and the hydraulic diameter are: 12 mm, 24 mm and 31.129 mm respectively.

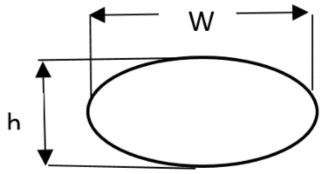


Figure 1: Geometry cross section

The pipe is exposed to an external constant heat flux, water enters the pipe with axial velocity and inlet temperature. Three Reynolds numbers were tested in the present work, 900, 1000 and 1200.

2.1 Governing Equations

The governing equations solved in the present study are the continuity equation, momentum equation, and energy equation. The continuity equation can be written as:

$$\nabla(\rho\vec{v}) = 0 \qquad (1)$$

The momentum equation is expressed as:

$$\nabla(\rho\vec{v})\vec{v} = -\nabla p + \nabla(\tau) + \rho g + F \qquad (2)$$

The energy equation can be written as:

$$\nabla(\vec{v}(\rho E + P)) = \nabla\left(K_{eff}\nabla T - \sum h_j J_j + (\tau\vec{v}\right) \qquad (3)$$

The heat transfer coefficient can be written as:

$$h = \frac{Q}{(T_H - T_C)} \qquad (4)$$

Nu number is calculated as:

$$Nu = \frac{hL}{k} \qquad (5)$$

2.2 Numerical Procedure

The finite volume was used to solve the governing equations with the boundary conditions. The domain was divided into 32060 cells, the second order upwind scheme was employed to discretize all the terms. To solve the pressure-velocity coupled equations, the SIMPLEC algorithm was selected. The convergence criteria is to reduce the maximum residual below 10^{-5}. After solving the governing equations, quantities of fluid dynamics can be determined

3. Results and Discussion

In this section, the results will be introduced and discussed. A converging diverging nozzle is investigated for three Re numbers, the geometry tested in 3D, the fluid examined is water entering the pipe in a uniform temperature and axial constant velocity, the flow exits the pipe at zero gauge pressure.

The heat transfer rate was studied and the results for Nu number is illustrated in Figure 2. The Nu number dropped sharply at the entry region and decreased gradually till the exit of the nozzle, it is worth to mention the Nu number increases with the increase in Re number as shown in the Figure.

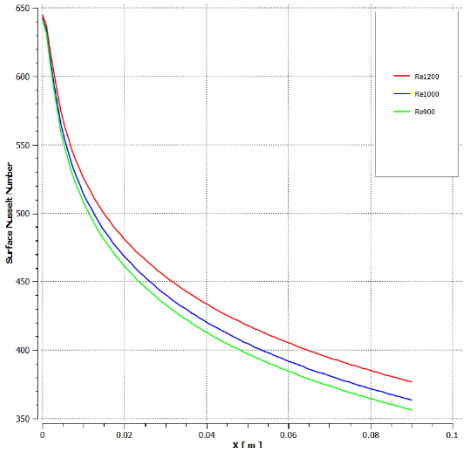


Figure 2: Variation of Nu number with Re number on the wall

The skin friction coefficient was also investigated and the results are depicted in Figure 3. The skin friction slumped significantly at the entry and decreased steadily afterward. The skin friction factor was found to increase with the increase in Re number, this is in line with relationship between skin friction factor and Re number, where the increase in the inertia force is expected to be accompanied with the increase in skin friction factor.

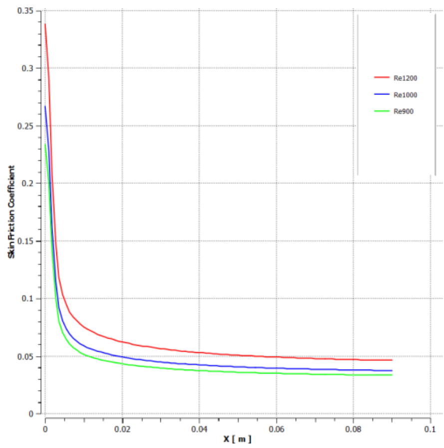


Figure 3: Variation of skin friction factor with Re number

In order to understand the variation of the temperature along the vertical pipe with the Re number, the results for temperature at top surface are introduced in Figure 4.

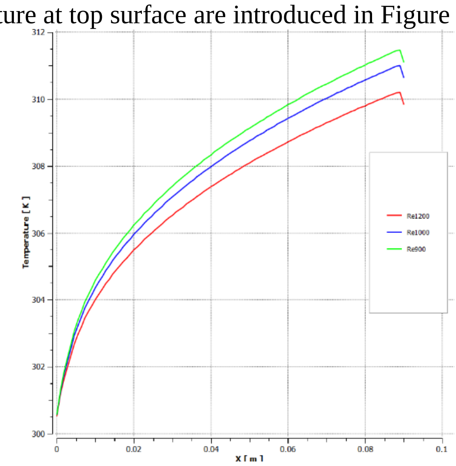


Figure 4: Variation of the temperature on the top surface

From the Figure, it can be seen that the temperature increased at the wall from 300 k to 311 k, this increase is attributed to the external heat flux applied to the wall. The temperature decreased with the increase in Re number, it is worth to mention that the temperature variation on the top surface is not symmetrical with that on the right surface. The trend of this variation is depicted in Figure 5.

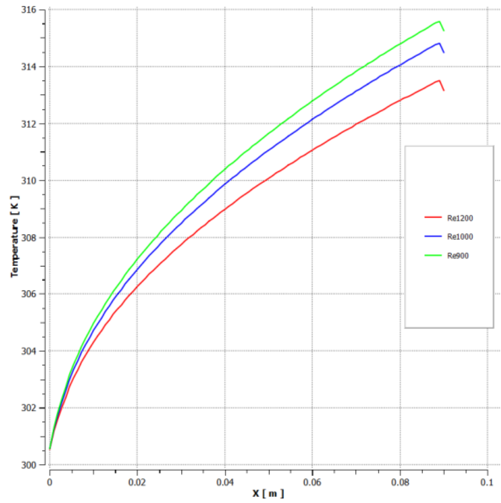


Figure 5: Variation of Temperature at right side of the pipe

The temperature at right side increased along the pipe wall, however this increase is 1.5% higher than that on the top wall. Re number has a negative effect on the temperature which explains the improved the heat transfer with the rise in Re number. To gain a better understanding to the flow characteristics, the flow velocity was investigated and the results are shown in Figure 6.

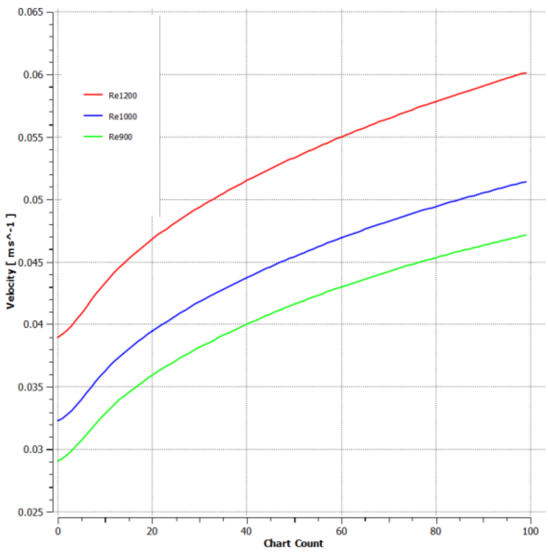
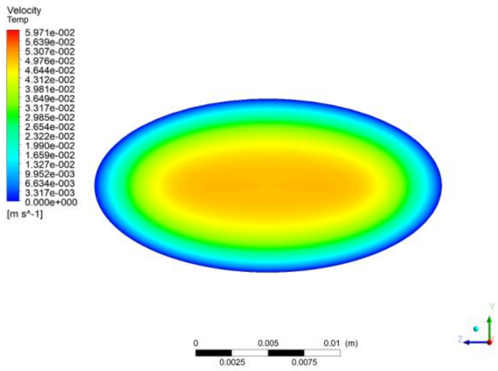


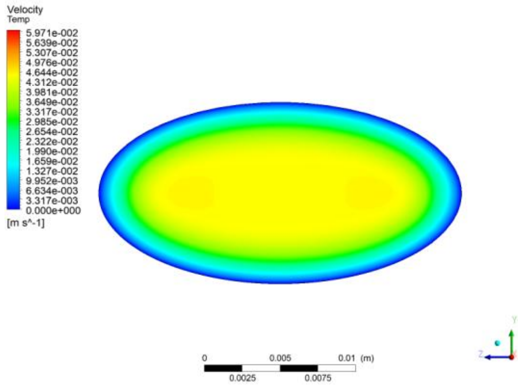
Figure 6: Velocity variation in the center of the elliptic pipe

It can be seen from Figure 6 that the velocity increases along the centerline of the pipe, the velocity is obviously increases with the increase in Re number.

In order to find out how velocity change inside the elliptic pipe, a contour of the velocity is investigated and introduced in Figure 7.



a)

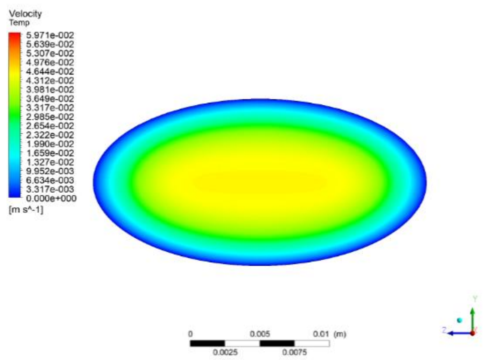


b)

Figure 7: Velocity contour for Re=1000 a)at the middle of the pipe b) at x=0.8 m

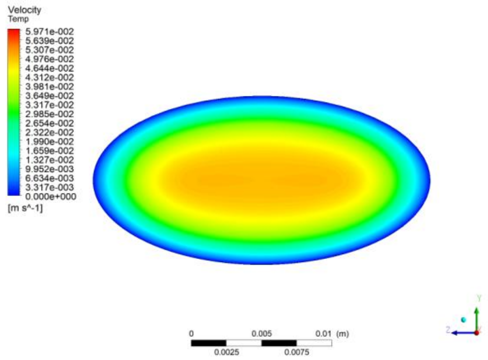
The Figure explains the contour of velocity in the elliptic pipe cross section and shows the developed flow and the maximum velocityin the core where the velocity is expected to decrease near the wall.

To capture the velocity variation for all Re numbers tested, Figure 8 represents the contours of velocity variation fore=900, 1000 and 1200 at distance x=0.8 m.

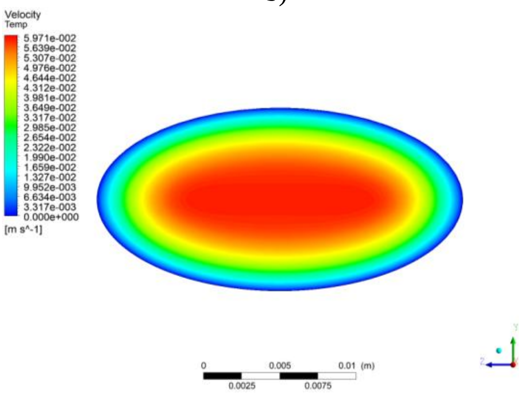


a)

It can be seen from Figure 8 the increase in Re indicates the increase in velocity as a developed flow. This is in line with the increase in Re promoted the heat transfer remarkably as discussed earlier.



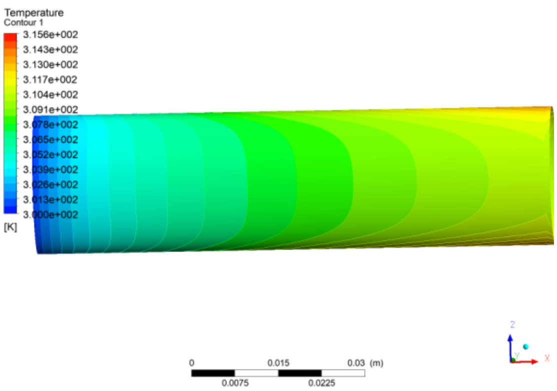
b)



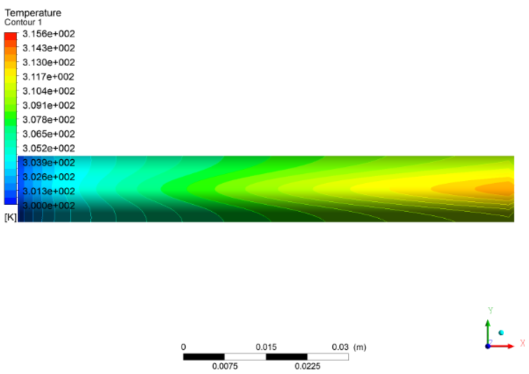
c)

Figure 8: Contours of velocity for a)Re=900 b)Re=1000 c) Re=1200

For a better understanding to the temperature distribution in the elliptic pipe, contours of the temperature are illustrated in Figure 9. The Figure shows the distribution of temperature on the wall for Re=1200 at a) upper wall and b) side wall.



a)



b)

4. Conclusions

Numerical simulations were successfully applied to model the heat transfer and flow characteristics in an elliptic pipe. The governing equations were solved using finite volume approach.

The heat performance and the flow characteristics were studied and the following notes were addressed:

- The heat transfer enhanced significantly with the increase in Re number.
- The skin friction factor increased with the increase in Re number.
- The Nu number is at peak value at inlet and decreases gradually along the wall.
- The temperature distribution varies between top wall and side wall of the elliptic pipe.

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