ISLAMIC UNIVERSITY OF TECHNOLOGY

ORGANIZATION OF ISLAMIC COOPERATION

3D NUMERICAL INVESTIGATION OF FLOW AND HEAT TRANSFER CHARACTERISTICS IN SMOOTH WAVY FIN AND ELLIPTICAL TUBE HEAT EXCHANGERS USING ARW VORTEX GENERATOR

Prepared By:

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CERTIFICATE OF RESEARCH

The thesis title "3D NUMERICAL INVESTIGATION OF FLOW AND HEAT TRANSFER CHARACTERISTICS IN SMOOTH WAVY FIN AND ELLIPTICAL TUBE HEAT EXCHANGERS USING ARW VORTEX GENERATOR" submitted by Shah Mohammad Sabbir (131454) & Sadat Hasan Chowdhury (131443), has been accepted as satisfactory in partial fulfillment of requirement for the Degree of Bachelor of Science in Mechanical and Chemical Engineering on November, 2017.

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DECLARATION

THIS IS TO CERTIFY THAT THE WORK PRESENTED IN THIS THESIS IS AN OUTCOME OF THE ANALYSIS, SIMULATION & RESEARCH CARRIED OUT BY THE AUTHOR THEMSELVES UNDER THE WATCHFUL SUPERVISION OF DR. ARAFAT AHMED BHUIYAN.

SHAH MOHAMMAD SABBIR	**SADAT HASAN CHOWDHURY**
(AUTHOR)	**(AUTHOR)**

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ABSTRACT

3D computational analysis was performed to investigate heat transfer and pressure drop characteristics of flow in SWFET (Smooth Wavy Fin-and-Elliptical Tube) heat exchanger with VGs (vortex generators). The numerical model was well validated with the available experimental results. Numerical results illustrate that adding vortex generators and changing the shape of tube can bring about further heat transfer enhancement. Through careful adjustment of the position with respect to the elliptical tube, type and attack angle of vortex generators. Numerical study shows that adding vortex generator and elliptical shape of tube enhances heat transfer characteristics.

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Chapter 1: Introduction

A Finned Tube Heat Exchanger (FTHE) is designed for transferring heat between fluids using finned chambers and tubes. It is usually renowned as compact heat exchanger because of relatively higher heat transfer efficiency for its greater surface area to volume ratio. This type of heat exchangers are used in both commercial and engineering applications such as HVAC systems, power plants, photochemical, automobile radiators, aerospace etc.

Finned Tube Heat Exchangers are mostly employed when the heat transfer co-efficient of the process fluid is very low than other fluids. The extended surface area increases the heat transfer capacity and provide a better transmission quality. For Finned Tube Heat Exchanger, the design of fin characteristics are very important as the thermal resistance is very high on the air side which may vary from approximately 75% or more. For increasing the energy efficiency, enhanced fin configuration is being used recently.

Smooth Wavy Fin and Elliptical Tube Heat Exchangers are considered as next generation heat exchangers because of the corrugated fins which can provide extra surface area enlarging the length of air flow mixture path. The enhancement of heat transfer co-efficient is done by geometrically better air flow channel. As described, to increase efficiency of the Finned Tube Heat Exchanger elimination of thermal resistance on the air side is required. This can be done by either modifying the fin pattern or use of the Vortex Generators. Smooth Wavy Fin pattern can meet the first condition of modifying configuration of geometry. Vortex Generator is commonly known as flow manipulator used for producing stream wise vortices intentionally. Vortex Generator creates vortices and pressure drop due to friction on the edges.

1.1. Impact of Wavy Fin Patterns

Wavy fin patterns improve the heat transfer as the wavy surface enhances flow path of air and the wave pattern causes forced mixing of air stream. The surface area to volume ratio is also increased by doing so which results in better heat transfer than plate fins. Beecher and Fagan (1) first investigated the effects of air velocity and the pattern of fin arrangement by testing 21 wavy fin-tube heat exchanger. They arranged the wavy fins in a triple row staggered layout. The research of Beecher and Fagan was re invested by Webb (2) using multiple regression method where the value of heat transfer efficiency is measured based on multiple variables. Webb variable relationship was able to predict 88% of wavy fin data within ±5% and 96% of data within ±10% error range successfully. The research on wavy fin patterns carried out by different scholars then. Among them Lozza and Merlo (3) are recognized for their experimental study on the heat transfer and pressure drop performances of 15 various fin types heat exchangers. According to their findings wavy fins performance is comparatively satisfactory. After that, Yan and Sheen (4) evaluated plate, wavy and louvered fin patterns based on the Performance Evaluation Criteria (PEC) techniques during their experimental research. They also found the same output as Lozza and Merlo. The smooth wave pattern additionally helps the air stream to mix effectively and also stable the frictional losses within a controlled range.

1.2. Tube Pattern Selection

Usually circular tubes are most expected for finned tube heat exchanger. But the elliptical tube reduces the total drag force as it contains a better aerodynamic shape comparing to the circular one. Webb (5) shown that the performance of elliptical tubes are far higher for the low pressure drop due to the limited wake region on the fin behind the tube. Schulenberg (6) renowned for his pioneering study emphasizing the potential of implementing elliptical tubes in heat exchangers for industrial purpose. Saboya et al (7) invented a Naphthalene sublimation method for the calculation of the average convective heat transfer co-efficient of an elliptical tube heat exchanger. They stated that the overall performance for the elliptical tubes are better than circular. The use of elliptical tube with a wavy shape fin pattern can overcome the thermal resistance on air side for a better geometric configuration.

1.3. Effects of Vortex Generator

Vortex Generator or Flow Manipulator has become an essential component of compact heat exchanger. The generation of vortices increases heat transfer by developing boundary layers and flow destabilization. This also create an extra friction which causes pressure drop and thus energy loss. The geometry of vortex generator can control the augmented heat transfer. Recently researches on vortex generators are happening intensively. Fiebig and Chen (8) investigated the characteristics of heat transfer surface geometry with vortex generators. They found that a reduction of about 50% surface area can be done employing vortex generators comparing to a plain fin heat exchanger based on heat duty and pressure drop, as well as the efficiency of heat transfer. Jacobi and Shah (9) published their review about the employment of stream wise vortices for the improvement of air flow surface. A second law analysis of heat exchanger using cross flow was performed by Kotcioglu et al. (10) with an invention of new winglet type vortex generators. Torii et al. (11) experimentally studied the heat transfer and pressure loss of finned tube heat exchangers with inline and staggered set of tubes with delta winglet

1.4. Purpose

The purpose of the present work is to compare between the performance of smooth wavy fin heat exchanger using elliptical tube with Angle Rectangular Winglet (ARW) type vortex generator and without vortex generator. A numerical study is carried out to explore the effects of geometric shape of the tubes and presence of vortex generator. At first, a comparison of the performance of same pattern fin using elliptical and circular tube without vortex generators is invested. Then the performance level of smooth wavy fin elliptical tube heat exchanger with vortex generator and without vortex generator are evaluated. Angle Rectangular Winglet was selected as vortex generator pattern.

Chapter 2 : Model Description

2.1. Physical Model

The model adopted in this study of tubes having a semi major diameter R_a = 6.56 mm and semi minor diameter R_b = 4.265 mm for elliptical tubes and diameter R = 6.56 mm for the circular tubes. The ellipticity e is expressed by e = R_a/R_b = 0.65015. The longitudinal tube pitch P_l is 27.5 mm and the transverse tube pitch is 31.75 mm. The fin material is aluminum and two neighboring wavy fins from a channel with wavy fin height H = 1.5mm. Wavy fin pitch F_p = 4.0 mm, wavy fin thickness δ = 0.2 mm, wavy fin wavelength λ_w = 13.04 mm and primary wave curvature is 1.80 mm.

The basic length of winglet C_r = 4 mm, span of winglet C_t = 2 mm and leading edge sweep angle Λ_{le} of the winglet are kept 20°. The winglet vortex generators are mounted on the smooth wavy fin surface and placed symmetrically on both sides of each elliptical tube and in the forward orientation.

In this study, the angle of attack has a value of αvg = 45°. For that purpose, the winglets are rotated on a vertical axis located at the center of the winglet base. If it is angled outward, it is called common flow down (CFD) configuration and if it is angled inwards, it is a common flow up (CFU) configuration. The position of the center of the VG base is given by $\Delta X = \pm R_a \cos(\pi/3) = 3.28$ mm and $\Delta Z = \pm 2R_b \sin(\pi/3) = 7.387$ mm.

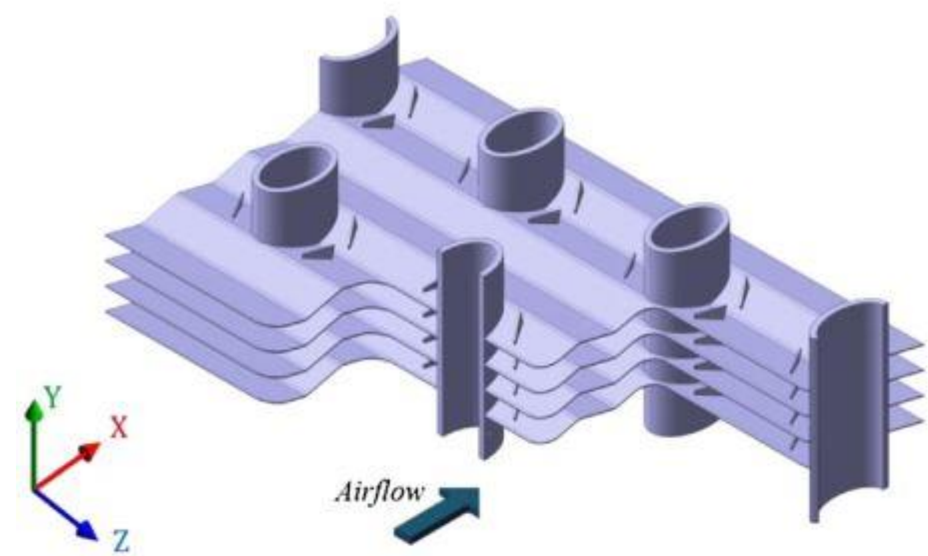

Figure 1. Isometric aligned section of core region of a smooth wavy fin-and-elliptical tube bank with mounted VGs

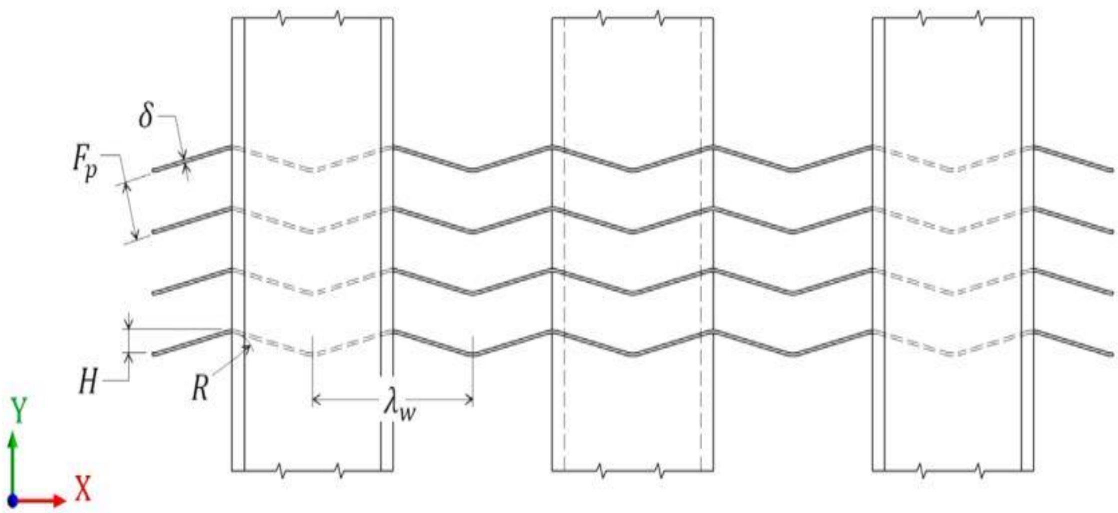

Figure 2. Geometric characteristics of a smooth wavy fin-and-elliptical tube heat exchanger

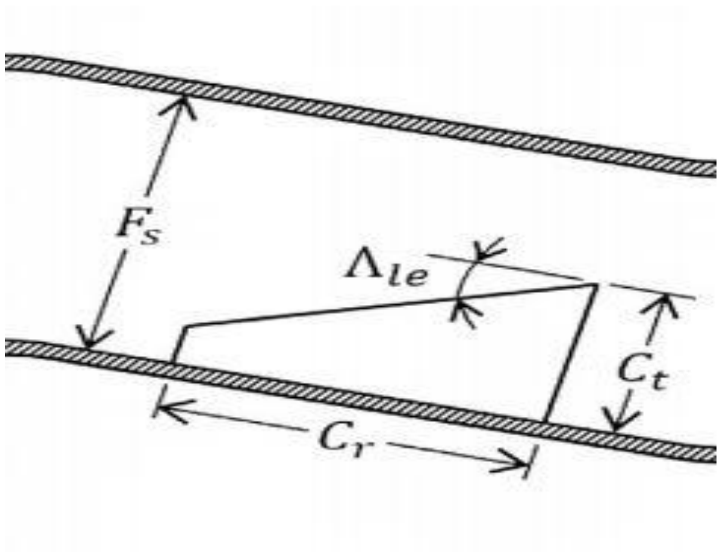

Figure 3. Schematic diagram showing vortex generator dimensions

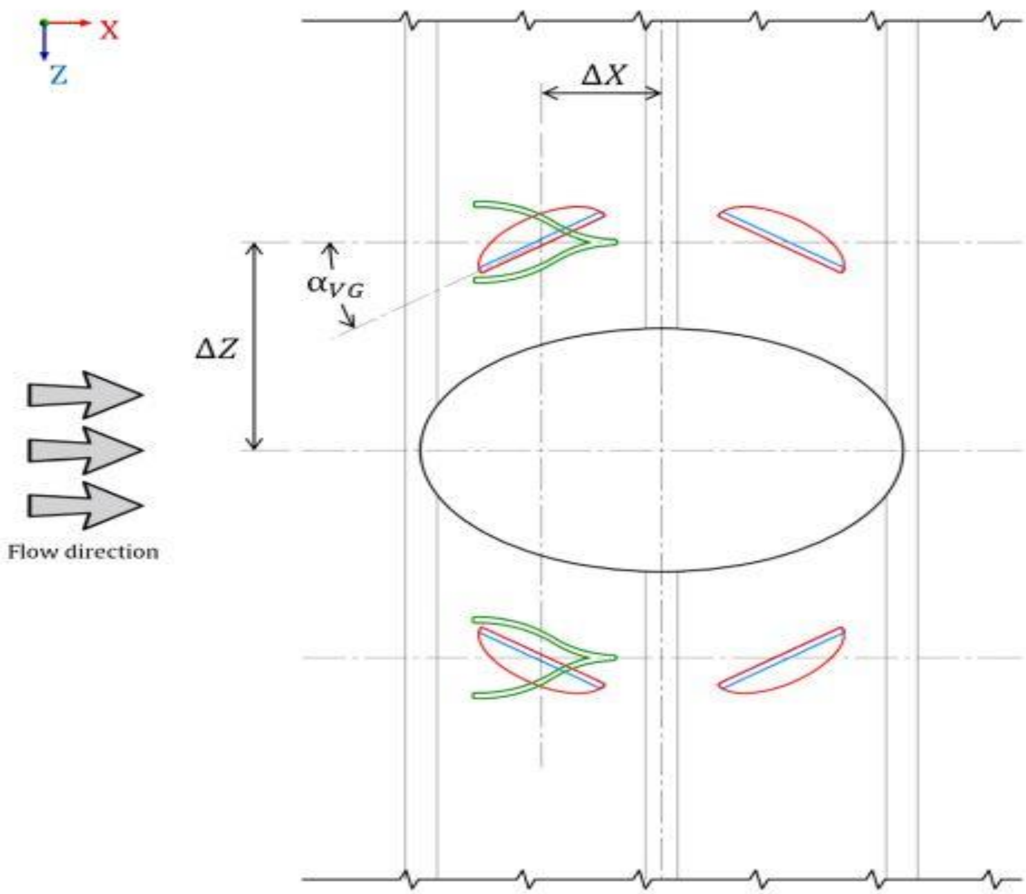

Figure 4. Positions of VGs and their placement with respect to the elliptical tube

The computational domain and the prescribed boundary conditions are illustrated in Fig. The neighboring two wavy fins' centric surface are selected as the upper and lower boundaries of the computational domain. The actual computational domain is then extended by 7 times of the fin spacing which is 28 mm at the inlet which ensure a uniform inlet velocity. It is also extended downstream 35 times of the fin spacing which is 140 mm for reducing recirculation at the computational domain outlet. By doing so, the outflow boundary condition was applied. As shown, the flow is performed in a co-ordinate system (X, Y, Z) where X is the stream wise co-ordinate, Y is the fin pitch co-ordinate and Z is the span wise direction.

2.2. Governing Equations

The 3D numerical simulations of the flow and heat transfer in the smooth wavy fin heat exchangers of different configurations were carried out by a turbulence model. The fluid is considered incompressible with constant physical properties and air flow in the computational domain was assumed to be three dimensional, steady and without viscous dissipation. Applying Einstein's notation, the governing equations used to describe the fluid flow and heat transfer including continuity, momentum RANS (Reynolds-averaged Navier-Stokes) equations and energy equation for the fluid domain can be expressed as follows:

- Continuity equation

$$\frac{\partial u_i}{\partial x_i} = 0$$

- Momentum equation

$$\rho\left[\frac{\partial u_i}{\partial t}+\frac{\partial u_j u_i}{\partial x_j}\right]=-\frac{\partial P}{\partial x_i}-\frac{\partial \tau_{ij}}{\partial x_j} \qquad \text{(i=1,2,3)}$$

- Energy equation

$$C_P\rho[\frac{\partial T}{\partial t}+\frac{\partial U_j T}{\partial x_j}]=\frac{\partial}{\partial x_j}[\lambda\frac{\partial T}{\partial x_j}]$$

where U_i and T are the Cartesian velocity components and the temperature, respectively.

For a Newtonian and incompressible fluid, the stress tensor is defined as follows:

$$\partial\tau_{ij}=-\mu(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i})$$

Several turbulence models are available, among these the SST (Shear Stress Transport) k-ω model developed by Menter(12) combines the use of the k-ω turbulence model near the walls and the capability of the k-ε model in the free-steam, and it has been demonstrated to have good behavior in adverse pressure gradients and separating flow. Therefore, the SST k-ω turbulence model is adopted in the present study.

2.3. Boundary Conditions

A synopsis of the boundary conditions applied in the computational domain can be found in Fig 5.

The required boundary conditions are elaborate for the three regions as follows :

- In the upstream extended region (domain inlet) :

  - At inlet boundary–

$U = U_{in} = 3.88$ m/s
$V = W = 0$
$T = T_{in} = 300K$

  - At top and Botton boundaries :

$\frac{\partial U}{\partial y} = \frac{\partial w}{\partial y} = 0$, v=0, $\frac{\partial T}{\partial y} = 0$

  - At side boundaries:

$\frac{\partial U}{\partial Z} = \frac{\partial V}{\partial Z} = 0$, w=0 , $\frac{\partial T}{\partial Z} = 0$

- In the downstream extended region :

  - At top and bottom boundaries :

$\frac{\partial U}{\partial y} = \frac{\partial w}{\partial y} = 0$, v=0 , $\frac{\partial T}{\partial y} = 0$

  - At side boundaries:

$\frac{\partial U}{\partial Z} = \frac{\partial V}{\partial Z} = 0$, w=0 , $\frac{\partial T}{\partial Z} = 0$

  - At outlet boundary:

$\frac{\partial U}{\partial x} = \frac{\partial v}{\partial x} = \frac{\partial w}{\partial x} = \frac{\partial T}{\partial x} = 0$

❖ *In fin coil region:*

- At top and bottom boundaries :

U=V=W=0

Temperature = periodic

- At side boundaries:

Fluid region:

$\frac{\partial U}{\partial Z} = \frac{\partial V}{\partial Z} = 0$, w=0 , $\frac{\partial T}{\partial Z} = 0$

Fin surface region:

u=v=w=0 , $\frac{\partial T}{\partial Z} = 0$

Tube region: u=v=w=0 , T = T_w=constant

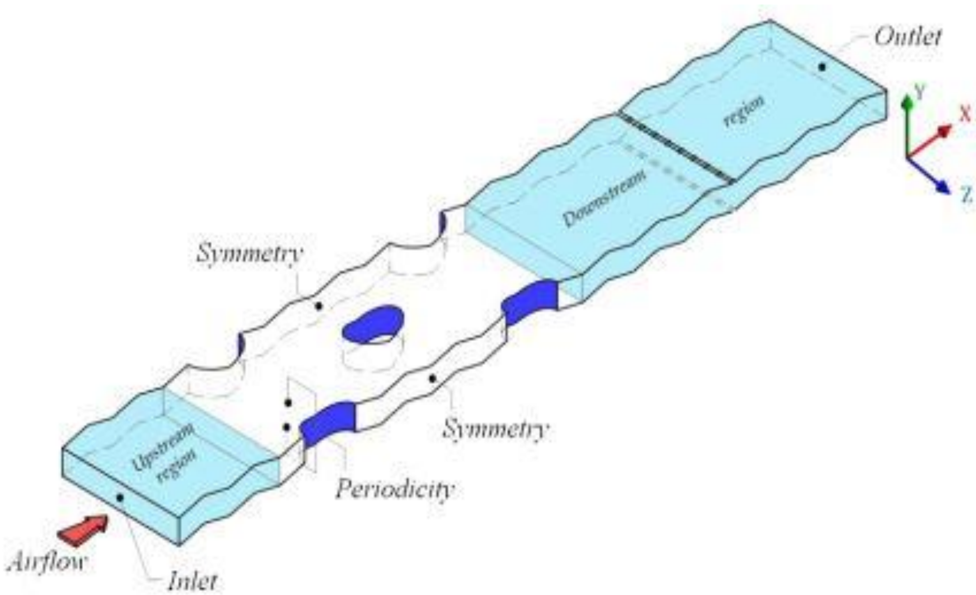

Figure 5. Three-dimensional illustrative diagram of the computational domain

Chapter 3: Methodology

3.1. Parameter definitions

In order to present the 3D numerical implications, the thermal performance of the heat exchanger is presented by employing nondimensional parameters as:

$$Re_{Dh}=\frac{U_{max}\,D_h}{\nu}$$

$$Nu=\frac{h\,D_h}{\lambda}$$

$$h=\frac{Q}{\eta_0\,A_t\,\Delta T_{lm}}$$

$$Q=\dot{m}C_P(T_{in}-T_{out})$$

$$\Delta T_{lm}=\frac{(T_{in}-T_W)-(T_{out}-T_W)}{\ln[(T_{in}-T_W)/(T_{out}-T_W)}$$

$$f=\frac{\Delta_P}{\frac{1}{2}\rho U_{max}^2}\cdot\frac{A_c}{A_t}$$

$$j=\frac{h}{\rho U_{max}C_p}\,Pr^{\frac{2}{3}}$$

where U_{max} is the fluid velocity at the minimum free cross-section, D_h is the hydraulic diameter for flow channel, $\dot{m}C_P$ is the heat capacity flow rate, $\Delta_P$is the pressure drop across the computational domain, T_W is the wall temperature and T_{in} is the bulk inlet temperature taken as constant. The temperature of the inlet air is higher than that of the tube wall. T_{out} is the bulk temperature at the outlet.

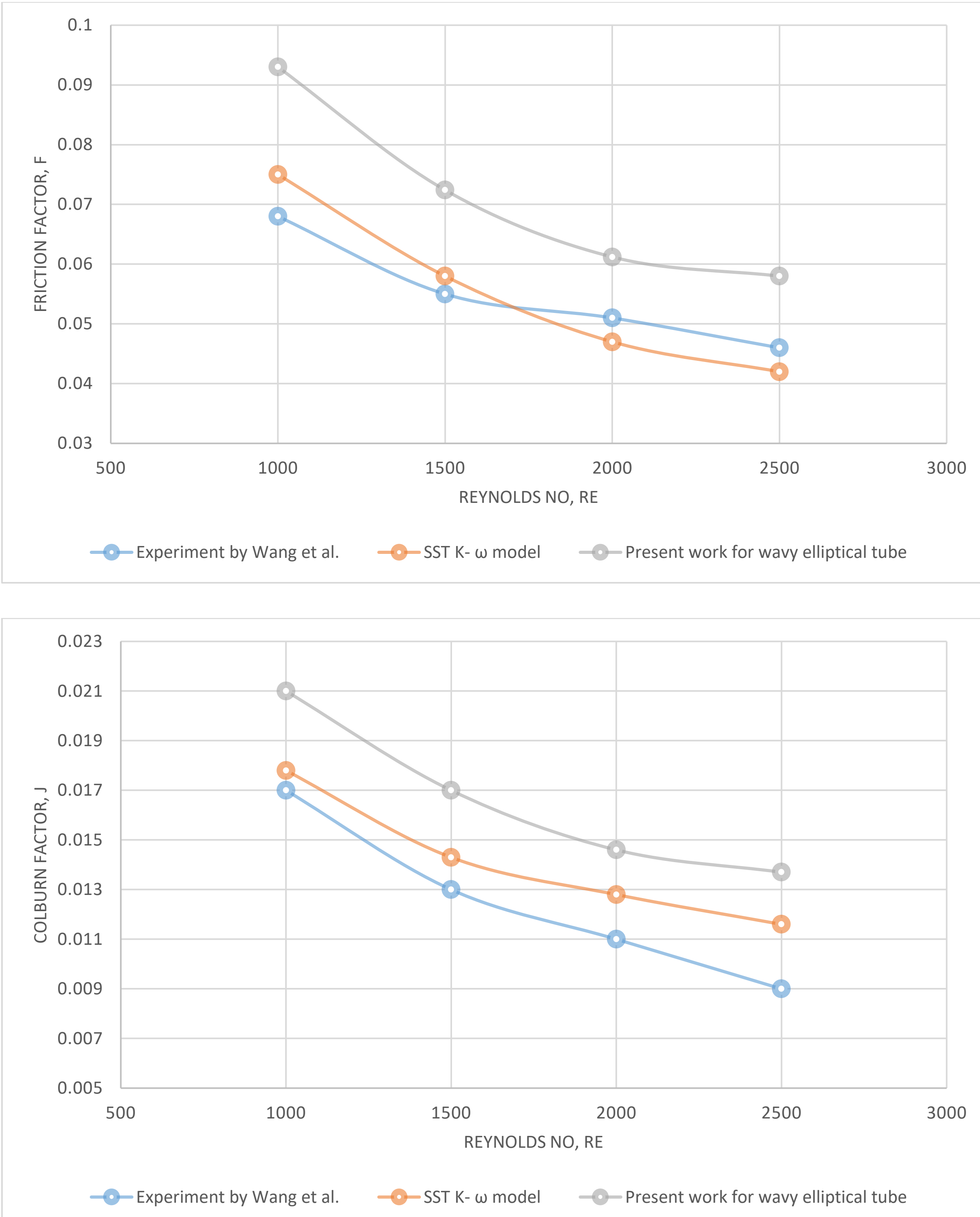

Figure 6. Experimental-numerical comparison of f and j for model validation

3.2. Grid generation technique

The aforementioned governing equations and the boundary conditions of the smooth wavy fin-and-elliptical tube heat exchanger are solved by the commercial CFD software ANSYS CFX® 14.5 (ANSYS, Inc.) based on the FVM (finite volume method) for the thermal and fluid dynamics analysis. The reliability of the results depends on the numerical model and special attention has to be taken in the selection of the numerical scheme. A high-resolution advection scheme is adopted. If the mean residuals of all variables, including mass, all velocity components and temperature, are less than 108, the iterative process is terminated. The 3D grid system for all the fluid domains is established using the commercial code ANSYS ICEM CFD® 14.5 (ANSYS, Inc.). The computational domain was divided into several subdomains. Then different strategies are employed for each subdomain to generate the mesh. For the extended domains, a structured hexahedral mesh is employed because of its simplicity. The central fin domain and VGs were meshed using unstructured tetrahedral elements. To improve the accuracy of the numerical results, the grid around the vortex generators and tubes is refined to resolve the secondary flows (horseshoe vortices, flow separations) where high gradients are expected.

3.3. Grid independence test and code validation

Prior to the computations, the grid independence of the numerical solutions was verified in order to ensure the accuracy and validity of the numerical results. The independent grid study on the SWFET heat exchanger with rectangular trapezoidal winglet VGs with an angle of attack $\alpha_{VG} = 45°$ was performed at Re_{Dh} = 2000. To keep a balanced trade-off between convergence time and solution accuracy, the adopted grid number in the computational domain is about 0.64 million.

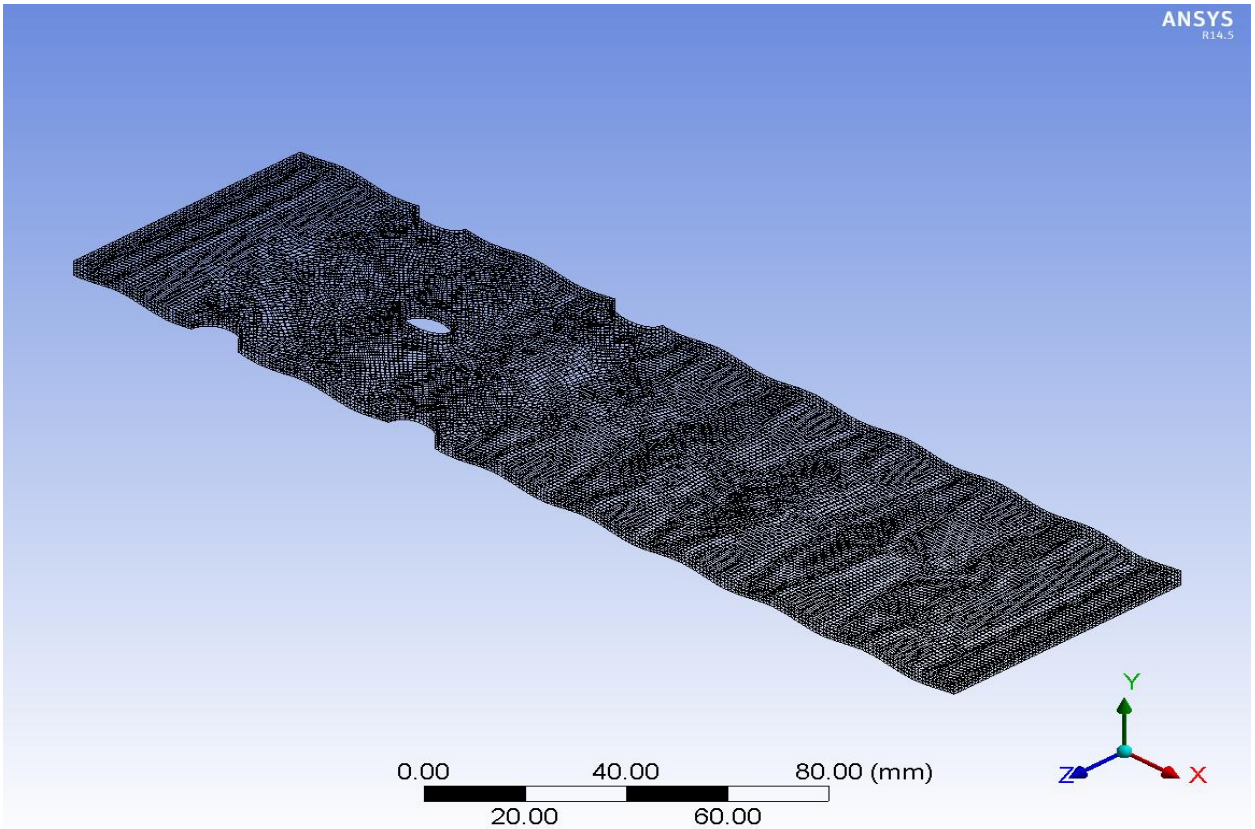

Figure 7. Meshing Geometry

In order to validate the accuracy of the current simulation method, preliminary computation results for a wavy-fin heat exchanger were compared with the experimental data reported by Wang et al.(13). The results of the SST k-ω model compare best with the experimental results over the whole Reynolds number region discussed in the present work. The maximum difference between the numerical results obtained by the current SST k-ω model and the experimental data for friction factor (f) and Colburn factor (j) were found to be about 11% and 16%, respectively. Thus, the agreement between the numerical results and experimental data indicates the reliability of the computational model.

Chapter 4: Results and discussion

4.1. Influence of new winglet VGs

In order to investigation the influence of new winglet VGs on the flow and heat transfer characteristics for smooth wavy fin-and elliptical tube heat exchangers, a comparative study for SWFET heat exchangers with new winglet VGs and without winglet VGs is performed. The angle of attack is set as 45°.The Reynolds number based on the hydraulic diameter ranges from 500 to 3000. The smooth wavy fin-and-elliptical tube heat exchanger without VGs will be referred to as “baseline” case. Several studies were carried out to investigate the effect of location of vortex generator pairs on heat transfer enhancement of fin-and-tube heat exchangers. Most of these studies considered one circular tube element and placed a pair of vortex generators near the side or downstream surface of the tube.

The present study reveals that combinations of smooth wavy fin, elliptical tube and the two winglet VG pairs improve the heat transfer significantly, especially in the dead water zone. Effect of position of the winglet vortex generator pairs (e.g., rectangular trapezoidal winglet) on the heat transfer enhancement in the smooth wavy fin-and-elliptical tube heat exchanger is shown in figure 8. Because the winglet vortex generator pairs are installed nearby up- and down-stream side of elliptical tube, heat transfer enhancement caused by horseshoe vortices and by longitudinal vortices are coupled. The increase in Nusselt number Nu by vortex generators is found to be much higher in the case of two winglet vortex generator pair than one winglet vortex generator pair cases at the same Reynolds number.

4.2Ansys simulation result

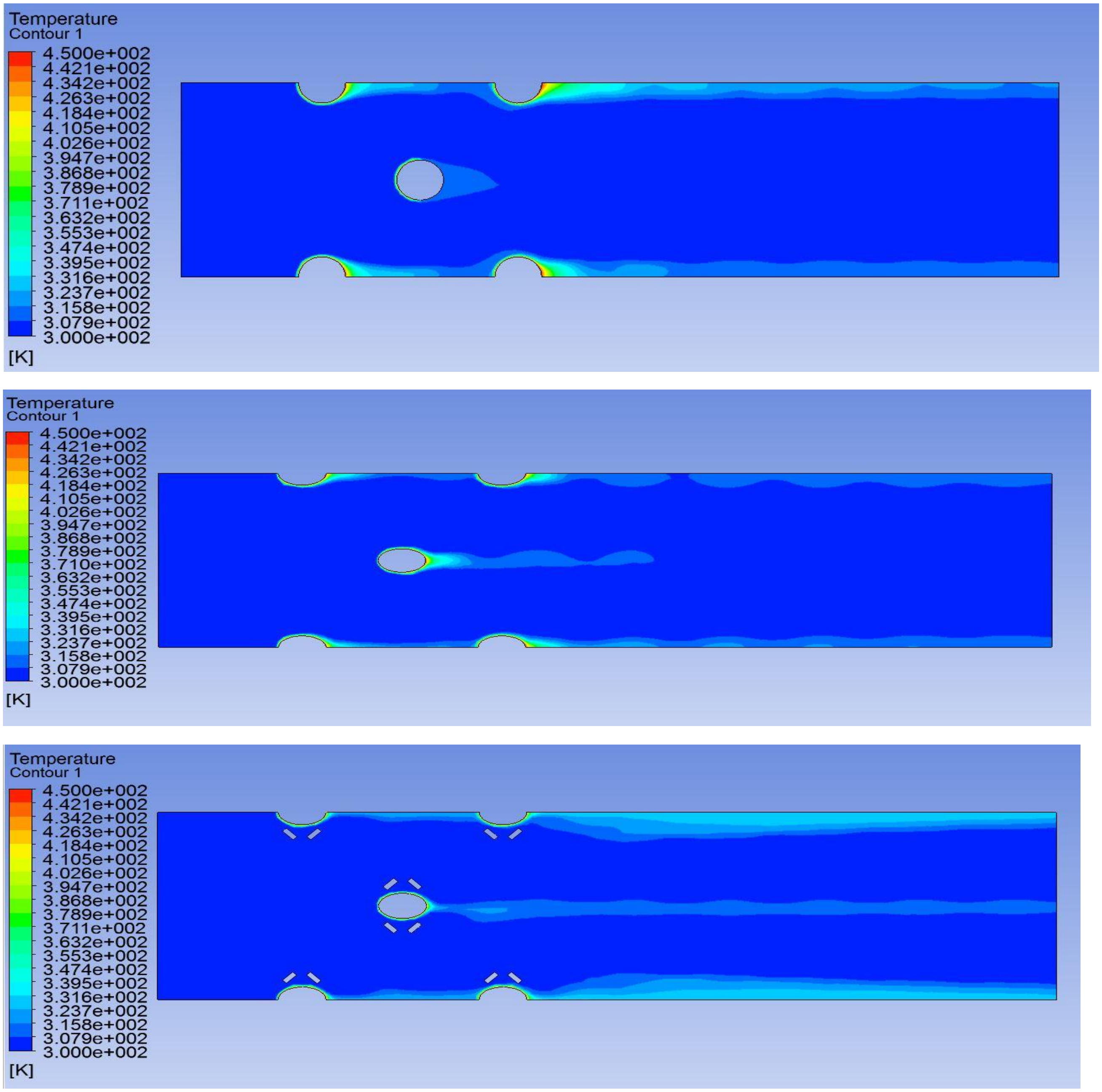

Figure 8. Temperature Contour of Circular tube wavy fin, Elliptical tube wavy fin & Elliptical tube wavy fin using ARW vortex generator respectively

From the temperature contour that was obtained by simulating in ANSYS it is clear that the temperature performance of elliptical tube with vortex generator is better than circular tube.

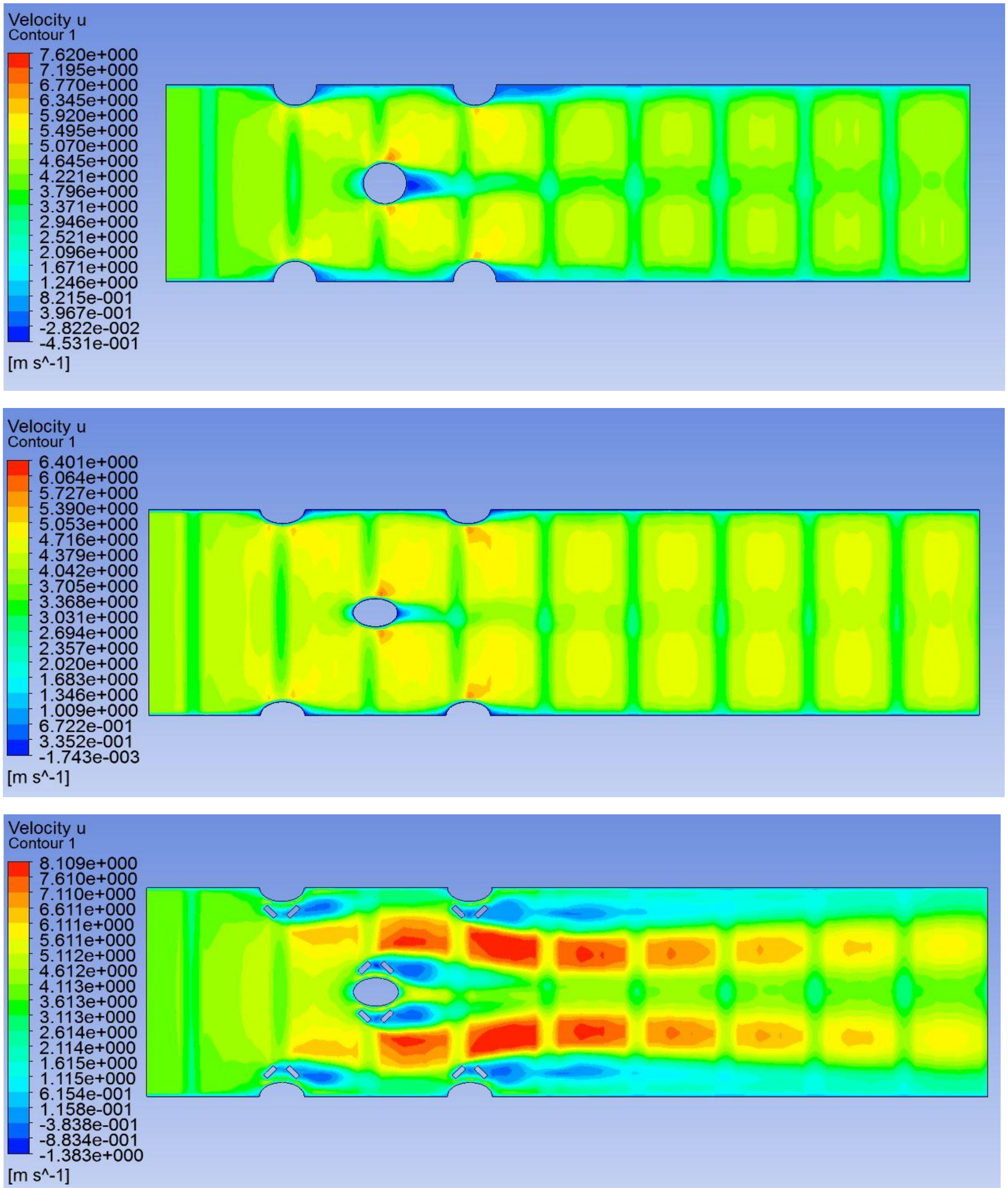

Figure 9. Velocity Contour of Circular tube wavy fin, Elliptical tube wavy fin & Elliptical tube wavy fin using ARW vortex generator respectively

From the velocity contour it is seen that the velocity increases significantly due to the presence of vortex generators.

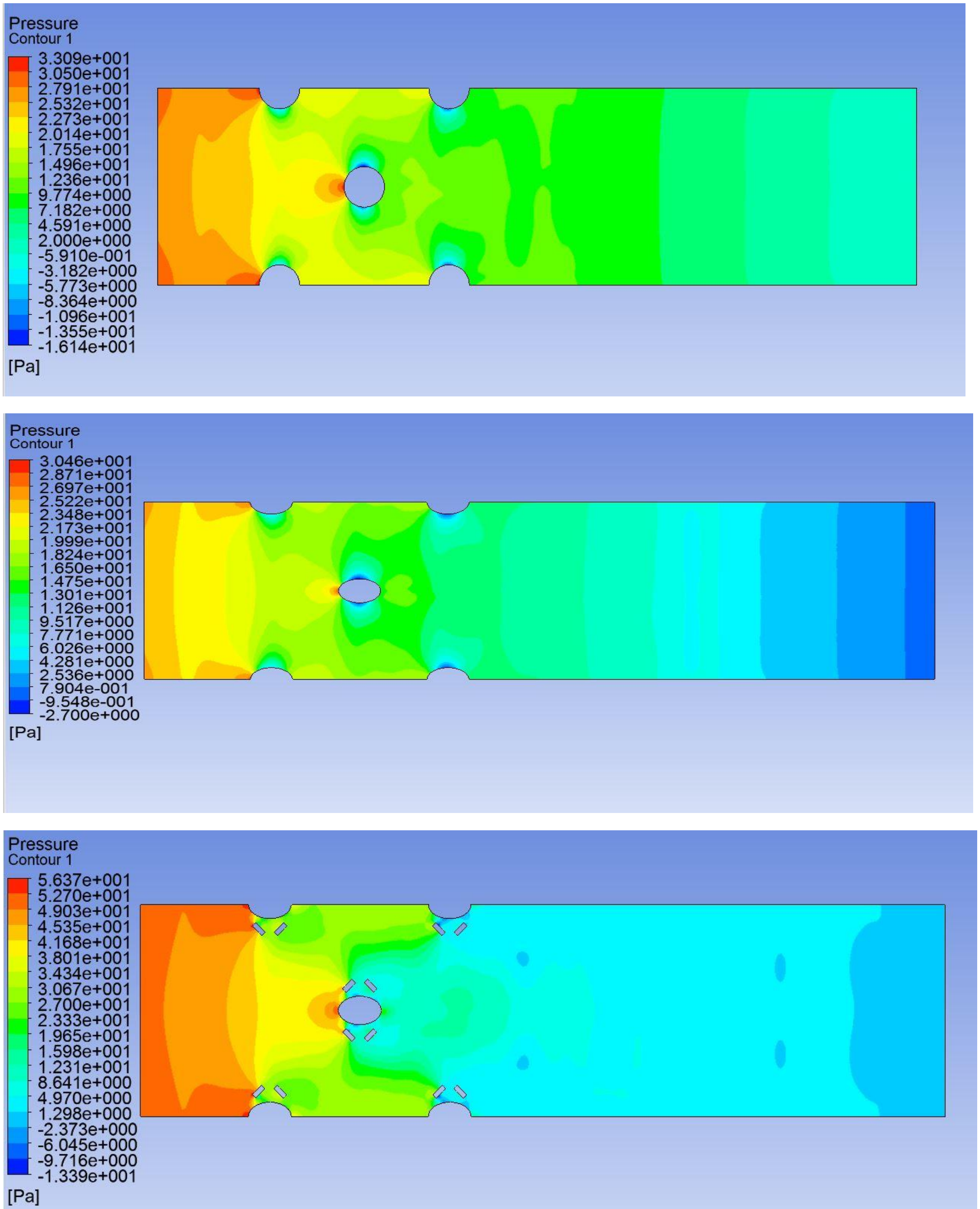

Figure 10. Pressure Contour of Circular tube wavy fin, Elliptical tube wavy fin & Elliptical tube wavy fin using ARW vortex generator respectively

The pressure reduces appreciable due to the presence of vortex generators. In circular tube the pressure drop is minimum.

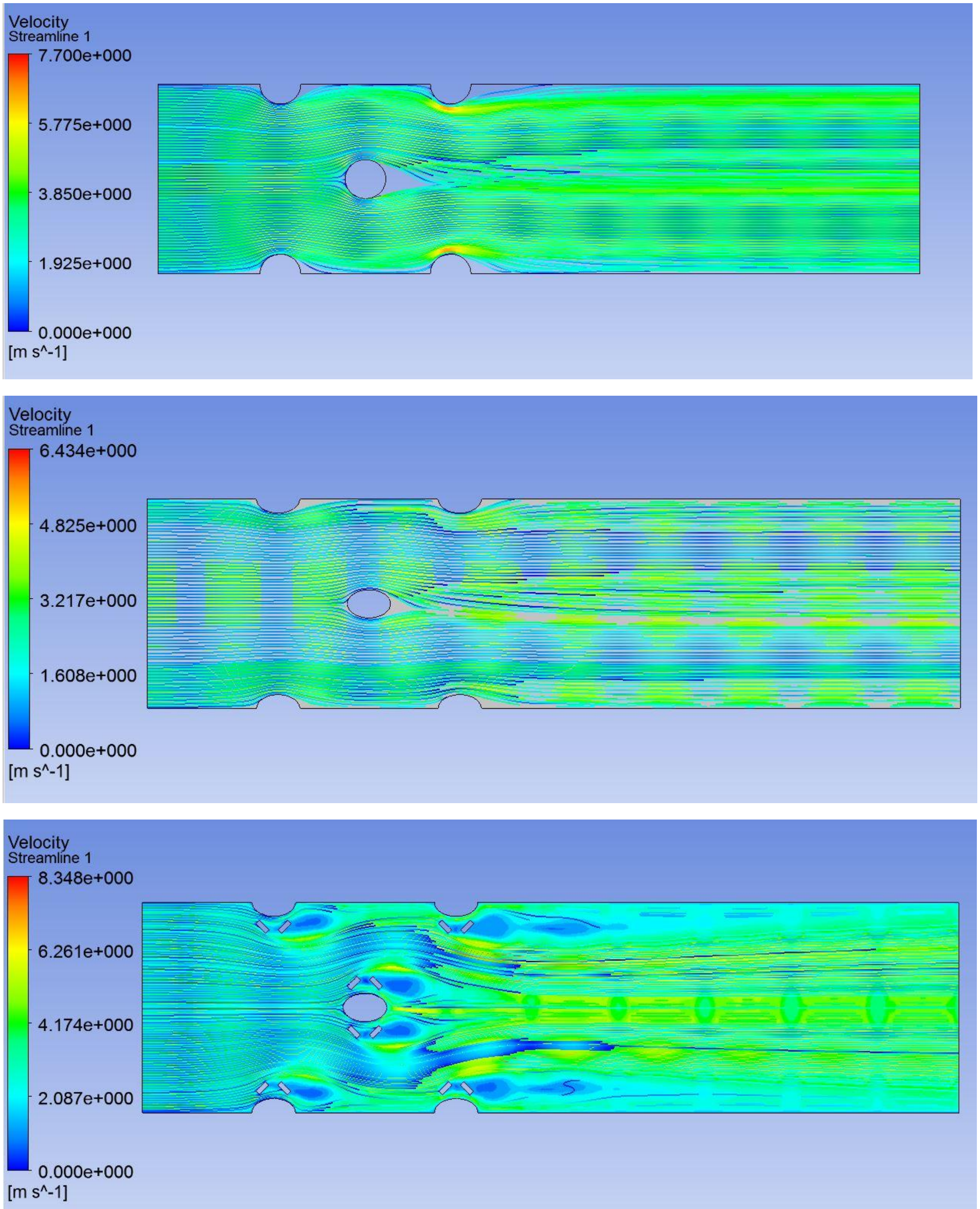

Figure 11. Velocity streamline of Circular tube wavy fin, Elliptical tube wavy fin & Elliptical tube wavy fin using ARW vortex generator respectively

Due to the presence of vortex generator the velocity of the stream line increases.

Data for pressure, temperature and velocity obtained from simulation is presented in tabular form below:

Circular Tube	Plane 1 (X = -0.0893)	Plane 2 (X = 0)	Plane 3 (X = 0.1566)
Pressure	28.6692 Pa	14.1943 Pa	0.249316 Pa
Temperature	300 K	321.74 K	317.089 K
Velocity	3.89454 m/s	5.94498 m/s	4.65807 m/s

Elliptical Tube	Plane 1 (X = -0.0893)	Plane 2 (X = 0)	Plane 3 (X = 0.1566)
Pressure	26.686 Pa	14.8846 Pa	0.24133 Pa
Temperature	300 K	324.825 K	316.113 K
Velocity	3.89437 m/s	5.32889 m/s	4.56061 m/s

Elliptical Tube With ARW VGs	Plane 1 (X = -0.0893)	Plane 2 (X = 0)	Plane 3 (X = 0.1566)
Pressure	52.291 Pa	31.3407 Pa	0.360595 Pa
Temperature	300 K	331.529 K	327.239 K
Velocity	3.89422 m/s	7.84575 m/s	5.81406 m/s

Figure 12. Comparison of Properties at different plane with different configurations

Chapter 5: Conclusion

3D numerical simulations were conducted to explore the effects of ARW vortex generators. The SST (Shear Stress Transport) *k-ω* turbulence model was applied in finding the heat transfer and fluid flow characteristics of the new smooth wavy fin-andelliptical tube heat exchanger. The overall performance of the SWFET heat exchanger is compared with VGs.

It is seen that ARW winglet at 45° has better heat transfer performance compared to the circular tube without vg. The result shows the importance of using ARW vortex generator at 45° for heat transfer enhancement.

Figure 13 : Nusselt number and Reynold number comparison of SST k-ω model and wavy elliptical tube with ARW VG.

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