

CHAPTER 1:

INTRODUCTION

1.1 What are Heat Exchangers:

Heat exchangers (HXs) are devices that transfers heat from one gas or liquid to another by mixing them together. HXs are commonly used in many industrial and commercial applications to efficiently transfer heat from one medium to another.

There are various types of heat exchangers used in the industries, but all of them work on the same basic principle: two fluids or gases flow through the heat exchanger in separate channels, and heat is transferred between them through a conductive barrier, such as a metal plate or tube.

One of the most common types of HXs is the tube and shell heat exchanger, which consists of a series of tubes surrounded by a shell. One fluid flow through the shell while other flows through the tube, while the other, and heat is transferred between them through the walls of the tubes.

HXs are used in a wide range of applications, including heating and cooling systems, refrigeration systems, power generation, chemical processing and many others. They offer a highly efficient and cost-effective way to transfer heat between fluids or gases, making them an essential component of many industrial processes.

1.2 What Are Vortex Generators:

Vortex generators (VGs) are small aerodynamic devices which are installed on the surface of an aircraft wing or other surfaces, such as a wind turbine blade, to improve airflow and increase lift or reduce drag. They work by creating vortices, which are swirling flows of air that help to energize the boundary layer, or the thin layer of air that sticks to the surface of an object.

Vortex generators typically take the form of small, angled fins or plates that are mounted at a slight angle to the surface they are attached to. As air flows over the surface, the fins generate small vortices that help to prevent the boundary layer from separating from the surface, which can cause turbulence and reduce lift. This helps to improve the overall aerodynamic performance of the aircraft or other object.

Vortex generators are often used in combination with other aerodynamic features, such as winglets, to improve efficiency and reduce drag. They are particularly useful in situations where an object is operating at low speeds or in turbulent conditions, such as during takeoff and landing or in gusty winds.

1.3 Selection Criteria for Vortex Generators (VGs):

The dimension selection criteria for vortex generators (VGs) depend on a variety of factors, including the intended application, the size of the aircraft, and the aerodynamic performance goals. Here are some of the key considerations for selecting the dimensions of VGs

Height: The height of the VGs is one of the most important dimensions to consider. The height should be large enough to create a strong vortex that can improve aerodynamic performance, but not so large that it causes excessive drag or interferes with other aircraft components.

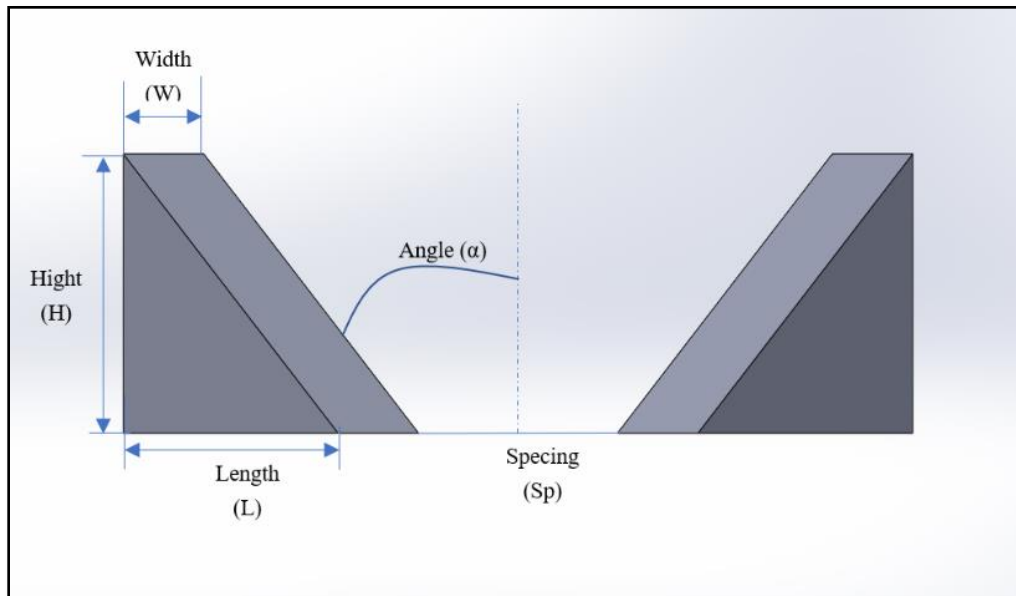
Width: The width of the VGs is also an important consideration. The width should be large enough to create a strong vortex, but not so wide that it interferes with the airflow over the surface of the aircraft.

Length: The length of the VGs depends on their location on the aircraft and their intended function. VGs placed on the leading edge of the wing or on the tail may need to be longer than VGs placed elsewhere on the aircraft.

Shape: The shape of the VGs can also affect their performance. For example, sawtooth VGs are effective at creating strong vortices, while curved VGs are better at preventing separation in the boundary layer. The shape of the VGs should be chosen based on the specific aerodynamic performance goals.

Spacing: The spacing between VGs is also an important consideration. The spacing should be close enough to create a continuous line of vortices, but not so close that the VGs interfere with each other.

In general, the selection of VG dimensions depends on a variety of factors, and it is important to consider the intended application and the specific aerodynamic performance goals when selecting VG dimensions. A combination of empirical testing and computational simulations can be used to optimize VG dimensions for specific applications.



CHAPTER 2:

LITERATURE SURVEY

1. “Flow Structure and Heat Transfer in a Channel with Multiple Longitudinal Vortex Generators,” 1992. [1]

Authors- S. Tiggelbeck, et al

They have combined staggered and in-line HX layouts with the Delta half-wing longitudinal varieties of VGs. For measurements of local heat transfer, unsteady liquid-crystal thermography and flow visualization are utilized.

The second row's flow structure is qualitatively comparable to the previous row's flow pattern. The spacing between the two rows has a significant impact on second row's the highest value of the span-averaged Nusselt number at the wake.

2. “Numerical study of flow and heat transfer enhancement by using delta winglets in a triangular wavy fin-and-tube heat exchanger,” *Journal of Heat Transfer*, vol. 131, no. 9, pp. 1–8, Sep. 2009, doi: 10.1115/1.3139106. [2]

Author- L. Tian, Y. He, P. Chu, and W. Tao

They have employed Delta VGs with Triangular Wavy Fin-and-Tube HXs. It uses a computational approach. HXs were configured in a staggered fashion. Mathematical modeling is used for numerical analysis. Both a corner vortex and a downstream main vortex are produced by each delta winglet. The heat transmission behind the tube in the wake zone is significantly improved by vortices.

3. **“A review of airside heat transfer augmentation with vortex generators on heat transfer surface,”** *Energies*, vol. 11, no. 10. MDPI AG, Oct. 01, 2018.
doi: 10.3390/en11102737. [3]

Author- L. Chai and S. A. Tassou

“They have used finned oval-tube and finned flat-tube HXs with Staggered and In-line configurations. Both Longitudinal and Transverse type of VGs are used. of HXs were used. Compared to the finned circular tube heat exchangers, the finned oval-tube and finned flat-tube HXs with VGS usually show better thermohydraulic performance.

4. **“Heat transfer enhancement using different types of vortex generators (VGs): A review on experimental and numerical activities,”** *Thermal Science and Engineering Progress*, vol. 5. Elsevier Ltd, pp. 524–545, Mar. 01, 2018.
doi: 10.1016/j.tsep.2018.02.007. [4]

Author- M. Awais and A. A. Bhuiyan

They have combined circular, oval, and elliptical type VGs with fin and tube type HXs. HXs were arranged in both staggered and in-line arrangements. employed computational and experimental techniques. By creating longitudinal vortices, vortex generators while increasing turbulence strength and flow mixing can reduce the wake region behind tubes. The Reynold number, however, is the sole factor that determines the strength and severity of these vortices.

5. “Experimental investigations of heat transfer enhancement by plane and curved winglet type vortex generators with punched holes,” *International Journal of Thermal Sciences*, vol. 78, pp. 26–35, Apr. 2014, doi: 10.1016/j.ijthermalsci.2013.11.010. [5]

Author- G. Zhou and Z. Feng

They have combined Delta and Rectangular VGs with Finned tube HXs. Both laminar and turbulent flow areas were experimented with. There is an experimental approach. HXs were arranged in both Staggered and In-line configuration. In both turbulent and laminar flow zones, when compared to plane winglet VGs in terms of flow resistance and enhancement in heat transfer the curved winglet type VGs perform better than corresponding matching.

6. “Vortices, generators and heat transfer,” *Chemical Engineering Research and Design*, vol. 76, no. 2, pp. 108–123, 1998, doi: 10.1205/026387698524686. [6]

Author - M. Fiebig, et al

A computational method was utilized to analyze the use of extended surface HXs in both in-line and staggered configurations with triangular, rectangular, and delta vortex generators (VGs). Results showed that in laminar flow conditions, as there is increment in Reynolds number there found to be increment in the overall heat enhancement. Additionally, it was observed that for a constant winglet the heat transfer was found to be increased for aspect ratio with the maximum AOA.

7. **“Heat transfer characteristics of a circular tube bank fin heat exchanger with fins punched curve rectangular vortex generators in the wake regions of the tubes,”** *Applied Thermal Engineering*, vol. 75, pp. 224–238, Jan. 2015
doi: 10.1016/j.applthermaleng.2014.09.043. [7]

Author - B. Gong, L. B. Wang, and Z. M. Lin

They have combined rectangular VGs with circular tube bank fin HXs in both staggered and inline arrangements. There is an experimental approach. Better heat transfer performance can be attained since the length of base arc of Vortex Generators is approximately 3.8 times that of their ideal height. When the ratio of spacing between the fins and the outer diameter of the tube is 0.239 for operating conditions with varying Reynolds numbers, improved heat transfer performance is attained.

8. **“Flow Structure and Heat Transfer in a Channel with Multiple Longitudinal Vortex Generators.”**

Author - Stefan Tiggelbeck, Nimai Mitra and Martin Fiebig

In a compact heat exchanger, the Parallel Plate with VGs punched and bend out of plates. Using Liquid Crystal thermography with symmetrical pair of winglets the experiment was carried out. They found that only low Reynold Number can be used. The conversion of elliptical shape vortex generator to approx. circle strongly depends on streamwise position. In analysis of qualitative flow, the number of developing Vortices generated are found to be almost independent of the oncoming flow. The transfer of heat at Leading Edge is higher than at Trailing Edge. They have concluded that Future Research is necessary with Staggered row arrangement.

9. **“Vortices, Generators and Heat Transfer”**

Author - M. Fiebig

Laminar and turbulent boundary layers are arranged in co-rotating and counter-rotating fashion to study the winglet type VGs and heat transfer associated with it. They looked at the channel flow and discovered Booster Effect because of the second row, and smaller Vortex Generator heights are preferable for high Reynolds numbers. They discovered that heat transmission is accelerated by both transverse vortices and longitudinal and that laminar flow is highly conducive to heat transfer than turbulent flow. The point at which laminar boundary values terminate is roughly where the highest heat transfer occurs. Additionally, by minimizing the space between the VGs in a single row arrangement which depends on the angle of attack and the length to height ratio heat Transfer can be improved.

10. “Heat Transfer Enhancement of Laminar Nanofluids Flow in A Triangular Duct Using Vortex Generator”

Author - H.E. Ahmed et al.

Use of Nanofluids resulted in the increase of Nusselt Number. SiO₂-EG gives best heat transfer efficiency than the other fluids. For SiO₂ at 6% volume and $Re = 800$, Average Nusselt Number is found to be 50% higher than that of $Re = 1004$. Friction coefficient between 0-1% & volume fraction slightly increased. Nusselt number is found to be increasing with increment in the Reynolds number.

11. “Enhancing Heat Transfer in A Plate-Fin Heat Sink Using Delta Winglet Vortex Generators”

Author -Hung-Yi Li et al.

At lower Reynolds No. It was found that there was increment in the heat transfer from that heat sink and reduction in the pressure difference value. At higher Re No. heat transfer was slightly improved by heat sink and the pressure difference increased too. A high amount of pressure difference formed when VGs are fixed at end of heat sink. Thermal resistance increases with AOA of vortex generators also significant increment in the pressure difference. With lower power equipment the VGs at AOA=30° yields better thermal performance. Lower thermal resistance and the higher-pressure difference is produced by the taller VGs.

CHAPTER 3

OBJECTIVES

1. To perform literature review to understand the physics behind the working of vortex generators
2. Understanding the simulation process through Ansys courses
3. To prepare initial CAD model of Heat exchangers and Vortex generators.
4. Run the initial simulation to understand the process.
5. To perform software validation
6. To perform numerical analysis using Ansys Fluent
7. Perform a parametric study.
8. Discussion of result

CHAPTER 4

METHEDOLOGY

4.1 Parametric study:

The Parameters on which the given investigation was carried out are Coefficient of drag, Skin friction Coefficient, Surface Heat Transfer coefficient, Surface Nusselt number and surface Stanton number.

1. Drag Coefficient:

The general formula for drag force is:

$$c_d = \frac{2F_d}{\rho u^2 A}$$

Where,

F_d - Drag force, ρ - Fluid density, v - Velocity, C_d - Coefficient of drag, and A : reference area of the object.

The drag coefficient (C_d) varies with factors like the size of the object, shape of the object, the Reynolds number (a dimensionless quantity that characterizes the fluid flow), the roughness of the object's surface, and the angle of attack of the surface.

2. **Skin Friction Coefficient:** The coefficient of skin friction is a dimensionless quantity that characterizes the amount of frictional drag experienced by the object caused by the viscous effects of the fluid.

The general formula for the coefficient of skin friction is:

$$C_f = \frac{\tau_w}{0.5 * \rho * V^2}$$

Where,

Cf- Coefficient of skin friction, τ_w - Wall shear stress, ρ - Fluid density,
V- velocity

The wall shear stress is given by formula:

$$\tau_w = \mu * \frac{du}{dy}$$

Where,

M- Dynamic viscosity of the fluid, u- Velocity of the fluid at a point close to the surface of the object, $\frac{du}{dy}$: rate of change of velocity with respect to the distance from the surface.

The skin friction coefficient varies with the shape and surface roughness of the object, as well as the properties like viscosity and density of the fluid. It can be used to calculate the skin friction drag on an object, which is a component of the total drag experienced by the object in the fluid.

3. **Surface Heat Transfer Coefficient:** The coefficient of heat transfer formula gives the rate of heat transfer per unit area between a solid surface and a fluid due to convection. The coefficient of heat transfer is a measure of the ability of the fluid to transfer heat to or from the surface.

The general formula of the surface coefficient of the heat transfer due to convection is:

$$h = \frac{q}{T_s - T_\infty}$$

Where,

h- Heat transfer coefficient, q- Rate of heat transfer per unit area, T_s - Surface temperature of the solid object, and T_∞ - Ambient temperature

The coefficient of heat transfer is determined experimentally and depends on various properties of the fluid (like density, viscosity, and thermal conductivity), the velocity and temperature of the fluid, the shape and surface of the solid object, and the orientation of the object.

4. **Surface Nusselt Number:** The surface Nusselt number formula relates the convective heat transfer rate to the difference of temperature between a solid surface and a fluid.

The general formula for Nusselt number is:

$$Nu = \frac{hL}{k}$$

Where,

Nu- Nusselt number, h- Convective heat transfer coefficient, L- Hydraulic length or characteristic length and k- Thermal conductivity of the fluid.

Nusselt number is used to characterize the heat transfer in different flow regimes such as laminar, transition, and turbulent. The value of Nusselt number depends on the properties of the fluid, such as its density, viscosity, and thermal conductivity and too the geometry and orientation of the object.

5. **Surface Stanton Number:** The surface Stanton number formula relates the rate of convective heat transfer to the temperature difference and the flow properties of a fluid.

The general formula for the Stanton number is:

$$\mathbf{St} = \frac{h}{\rho * C_p * v}$$

Where,

St- Stanton number, h- Coefficient of convective heat transfer, ρ - Fluid density C_p - Specific heat capacity of the fluid, and v- Velocity.

The Stanton number is used to describe the convective heat transfer in a fluid and is often used in conjunction with the Nusselt number (Nu) to characterize the heat transfer. The relationship between the St and the Nu is given by:

$$\mathbf{St} = \frac{Nu}{(Re * Pr)}$$

Where,

Re- Reynolds number,

Pr- Prandtl number.

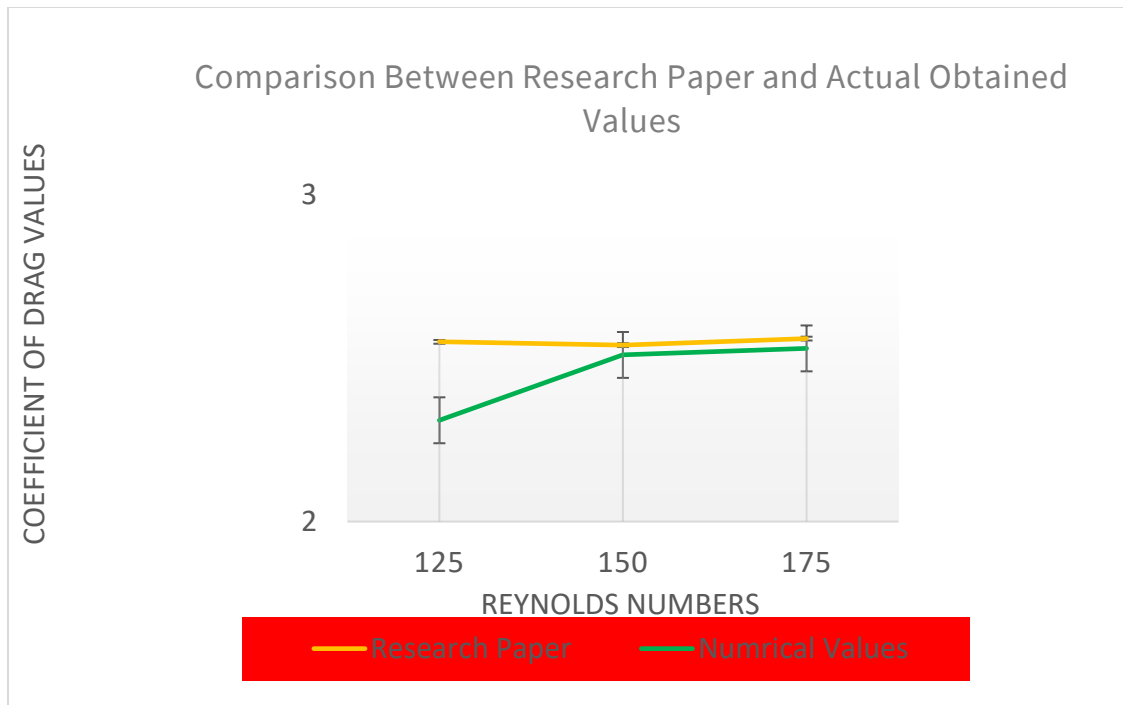
4.2 Software Validation:

For the software validation purpose the research paper used was **“Far-wake characteristics of two-dimensional flow past a normal flat plate by Arun K. Saha”** [20]

A 2D flat plate was tested at steady laminar flow at Reynolds no of 125,150 and 175. The Coefficient of drag was calculated through simulation and results were compared.

Reynolds No.	Research Paper Cd Values	Numerically Obtained Cd Values	Percentage Error
125	2.55	2.30	9.8
150	2.54	2.51	1.18
175	2.56	2.53	1.17

Table no. 4.1



Graph no. 4.1

Findings of research:

- The behavior of the fluid flow downstream of the plate at a significant distance from the plate.
- At a large distance from the plate, the fluid flow becomes fully developed and the flow pattern becomes independent of the details of the plate geometry and upstream conditions. The flow in the wake of the plate is characterized by the formation of vortices and their subsequent shedding, which results in a periodic fluctuation in the flow properties such as turbulence, pressure, and velocity.
- The flow in the wake region can be described using various parameters such as Reynolds number, Strouhal number, , and wake length.

- Experimental and numerical studies have shown that the far-wake characteristics depend on the Reynolds number and the plate geometry. At low Reynolds numbers, the flow in the wake region is dominated by viscous forces, and the vortices shed from the plate are small and regular. At high Reynolds numbers, the flow becomes turbulent, and the vortex shedding becomes irregular. The wake length also increases with increasing Reynolds number.

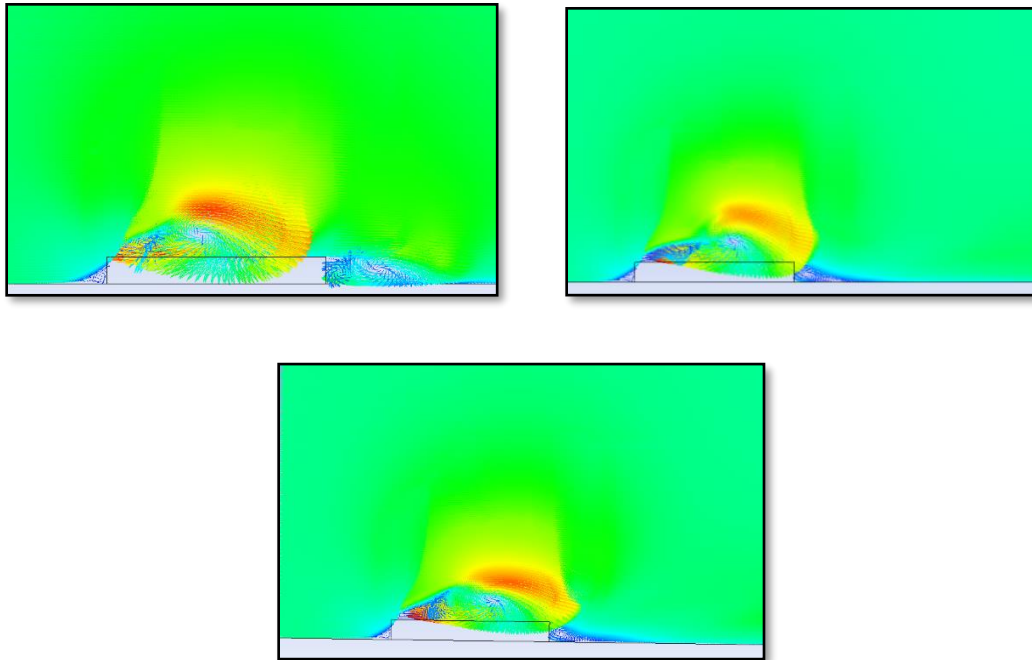


Fig. 4.1 – Vorticity counters of flow over a flat plate at Reynolds no. 125, 150 and 175.

4.3 Modeling and Meshing:

Modelling and meshing are essential steps in computational fluid dynamics (CFD) simulations. While investigating the flow parameters over flat plates, accurate dimensions are crucial for creating realistic models. For a flat plate, the dimensions are 100*50*1 mm. The domain size should be symmetrical to the XY plane and be 50mm.

For specific analysis, different kinds of vortex generators (VGs) are added on the flat plate. For example, triangular VGs with a length and width of 5mm and height of 3mm were used to create aerodynamic effects. The domain size was again symmetrical and 50mm, and the resulting mesh had 2,266,970 cells, 4,761,010 faces, and 421,839 nodes.

For rectangular VGs, dimensions of 7.5mm in length, 1mm in width, and 2mm in height with an angle of 30 degrees were used. The domain size and symmetry remained the same, but the resulting mesh consisted of 2,440,350 cells, 5,174,514 faces, and 456,030 nodes.

Delta VGs was also used, with dimensions of 7.5mm in length, 1mm in width, and 5mm in height and an angle of 30 degrees. The domain size and symmetry remained the same, and the resulting mesh consisted of 2,290,745 cells, 4,824,606 faces, and 427,007 nodes.

Finally, curved delta-type VGs were used, with dimensions of 7.5mm in length, 1mm in width, and 5mm in height and an angle of 30 degrees. The domain size remained 50mm and symmetrical to the XY plane, and the resulting mesh consisted of 2,266,970 cells, 4,761,010 faces, and 421,839 nodes.

In conclusion, the accurate modelling and meshing of flat plates with different types of VGs enable accurate analysis of the aerodynamic effects of these VGs.

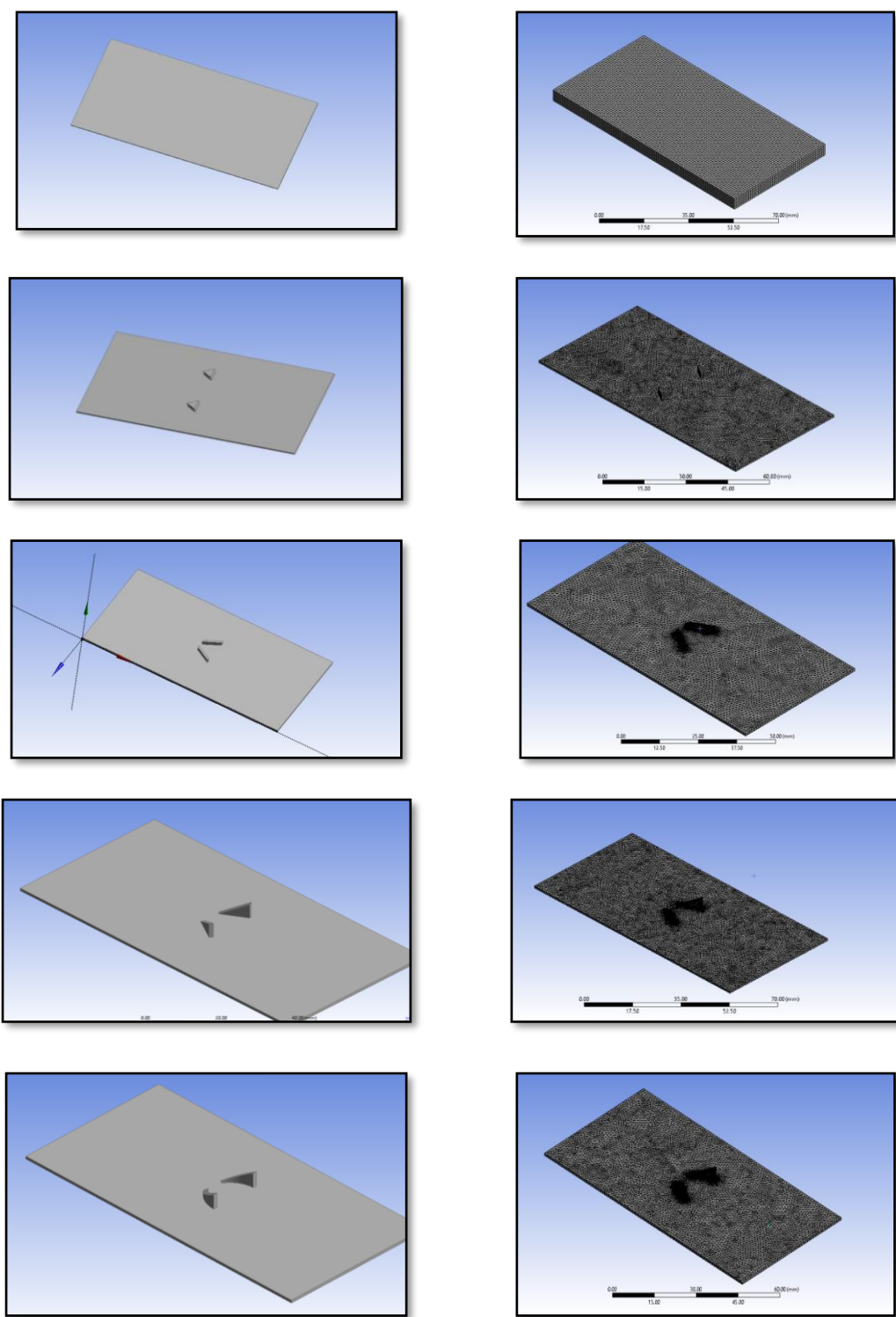


Fig. 4.2 – Model Geometries

4.4 Simulation:

The generation of Mesh and computations has been done in Ansys Software (Fluent). The energy equation is turned on, indicating that the simulation will account for the transfer of thermal energy in addition to fluid dynamics. The flow is laminar, meaning that the fluid is moving in a smooth and orderly manner. The base plate is heated to 400 K, which may represent a real-world scenario where a flat plate is subject to high temperatures. The inlet velocity is varied as 5, 10, and 15 m/s. The method used is Simple, Green-Gauss Cell Based with Wrapped-Face Gradient Correction and High Order Term Relaxation enabled. Hybrid initialization is used, which refers to a technique where a steady-state solution is obtained first and then perturbed to simulate transient behavior. The simulation is run for 500 iterations each, which may be sufficient to reach a steady-state solution. Overall, this simulation is to be investigating the transfer of heat and fluid dynamics of a laminar flow passed over a uniformly heated thin finned cross sectional flat plate heated at bottom face and constant temperature under different flow rates.

CHAPTER 5

RESULT AND CONCLUSION

The values of different parameters, including Skin Friction Coefficient, Drag Coefficient, Surface Nusselt Number, Heat Transfer and Surface Stanton Number, for flow velocities of 5m/s, 10m/s, and 15m/s. As the flow velocity increases, all the parameters tend to increase as well.

5.1 Flat Plate without Vortex Generator

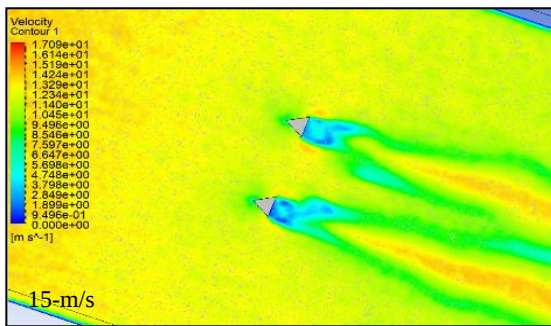
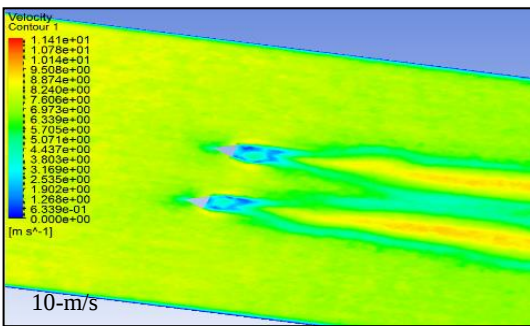
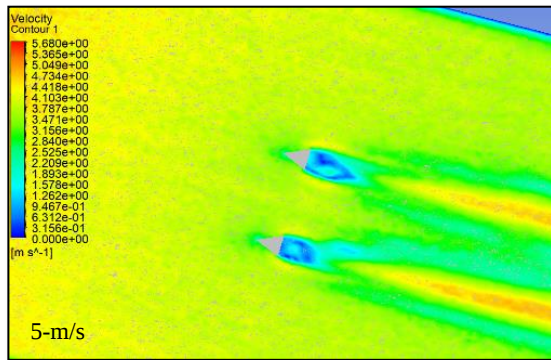
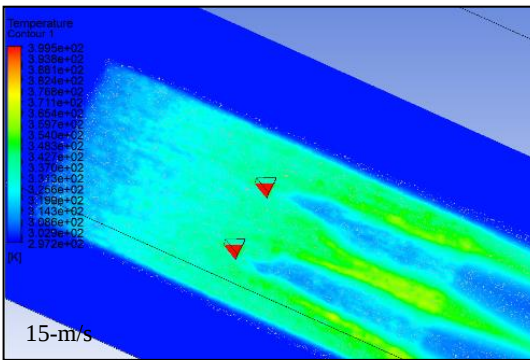
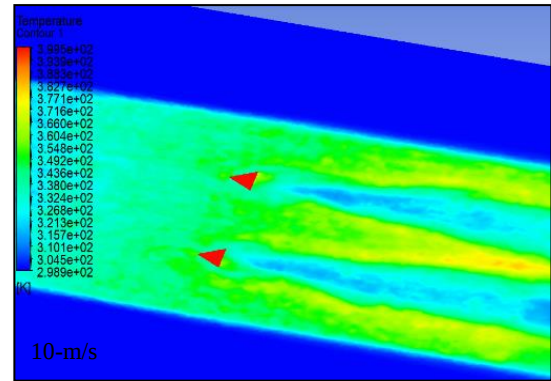
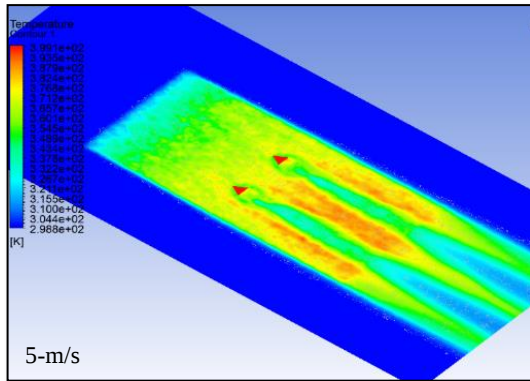
Parameters	5 m/s	10 m/s	15 m/s
Drag Coeff.	0.00926	0.02523	0.04264
Skin Friction Coeff.	0.10857	0.31422	0.4998
Heat Transfer Coeff.	1.44688	2.1155	2.11864
Surface Nusselt No.	60.8459	87.4466	89.8275
Surface Stanton No.	0.001194	0.001716	0.001763

Table no. 5.1

5.2 Flat Plate with Triangular type of Vortex Generator:

Parameters	5 m/s	10 m/s	15 m/s
Drag Coeff.	0.01501	0.04374	0.07810
Skin Friction Coeff.	0.18288	0.52555	0.92357
Heat Transfer Coeff.	2.31262	3.49183	4.11982
Surface Nusselt No.	95.6001	144.354	170.3101
Surface Stanton No.	0.00187	0.00283	0.00334

Table no. 5.2



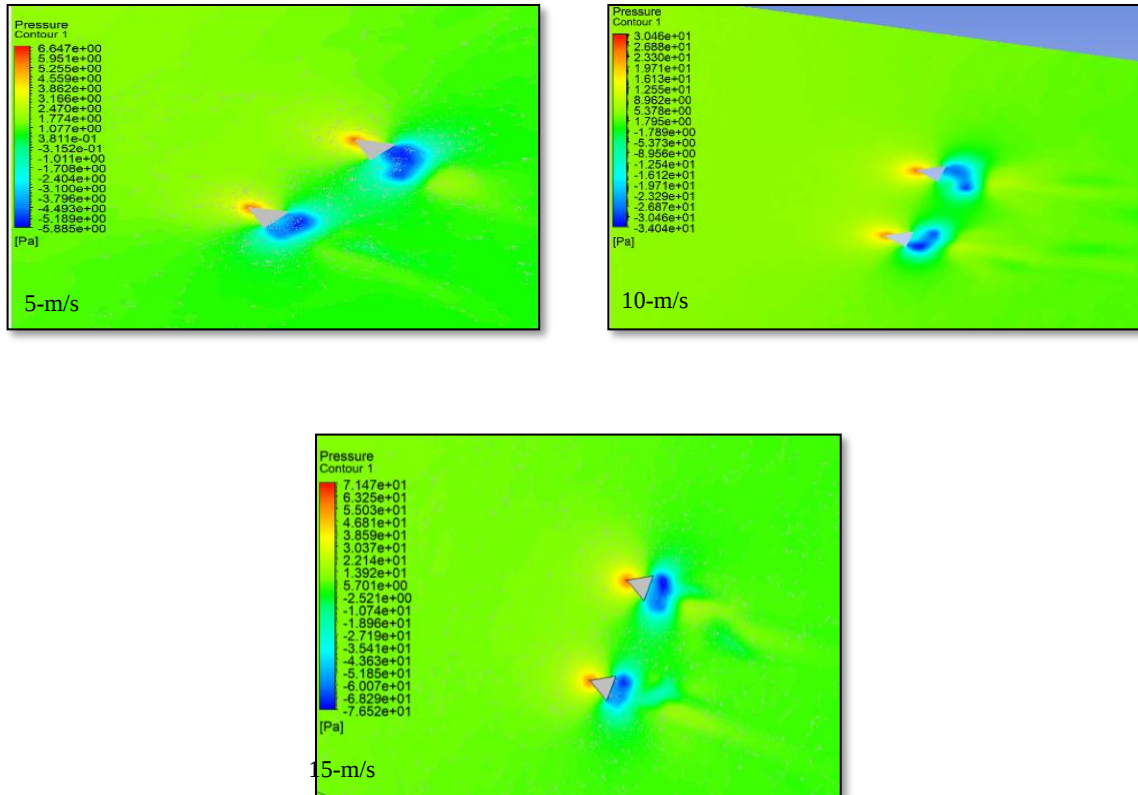
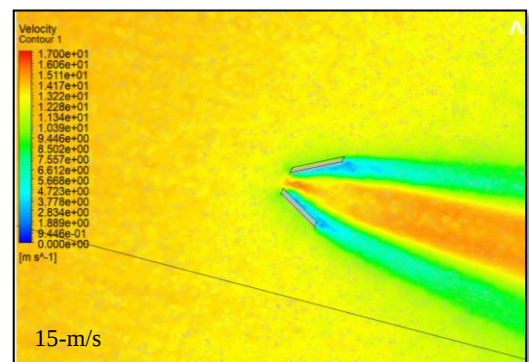
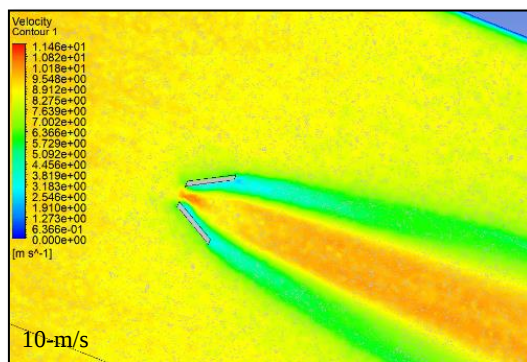
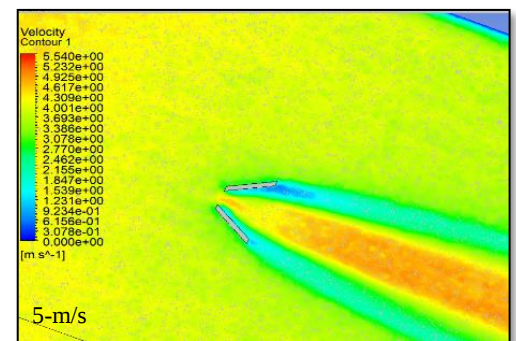
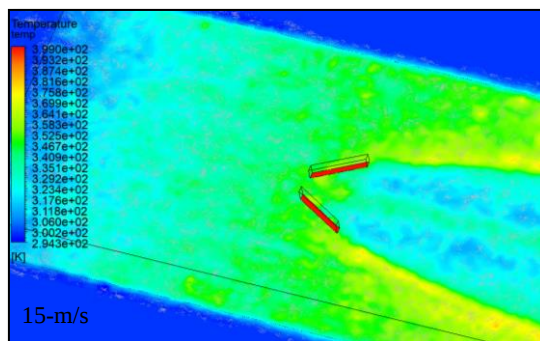
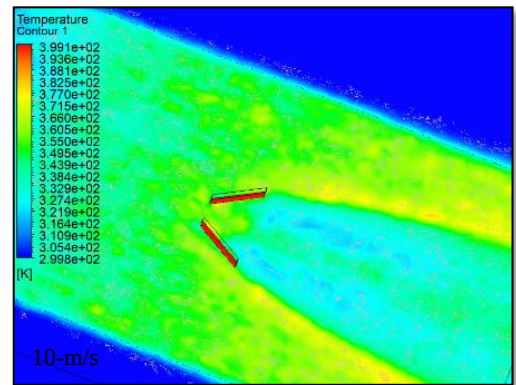
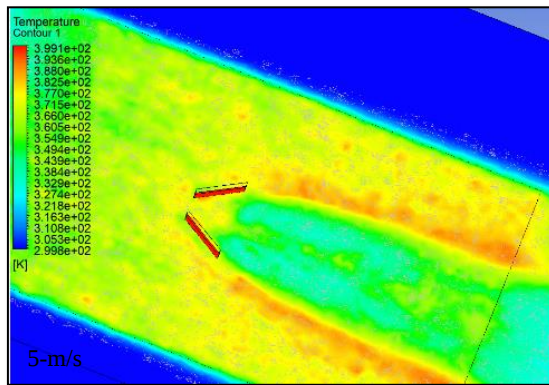


Fig. 5.2 Velocity, Temperature & Pressure Counters for Triangular VGs.

5.3 Flat Plate with Rectangular type Vortex Generator

Parameters	5 m/s	10 m/s	15 m/s
Drag Coeff.	0.0145	0.03748	0.071714
Skin Friction Coeff.	0.17798	0.45613	0.85594
Heat Transfer Coeff.	2.27986	2.88635	3.71052
Surface Nusselt no.	94.2324	119.31	153.386
Surface Stanton no.	0.001859	0.00234	0.00301

Table no. 5.3



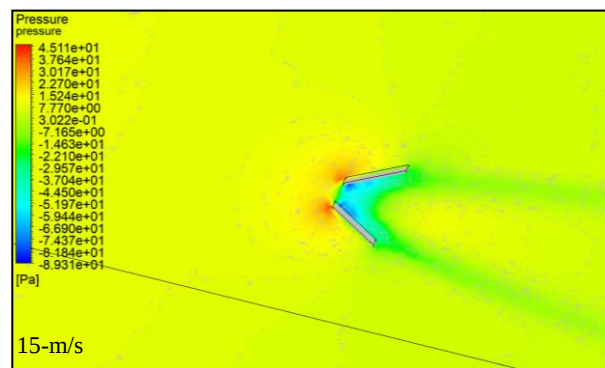
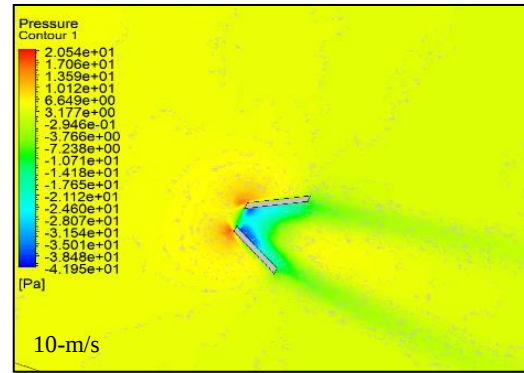
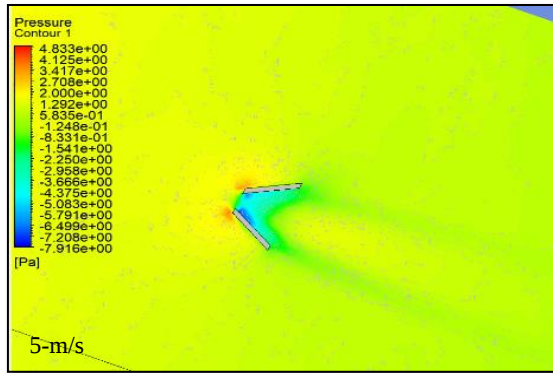
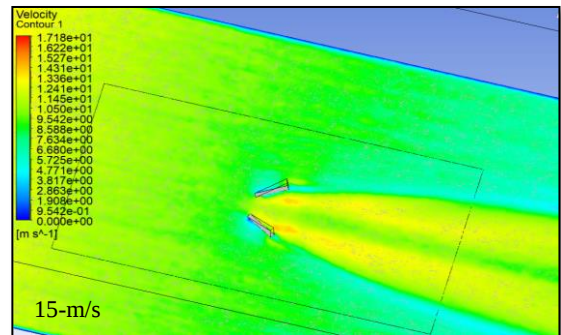
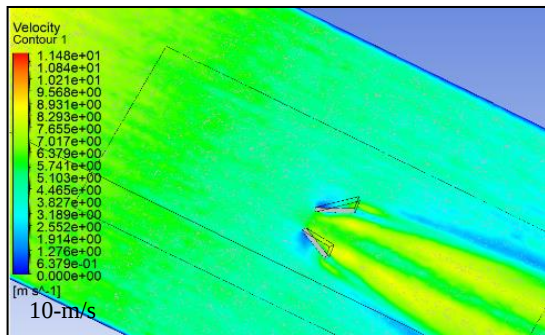
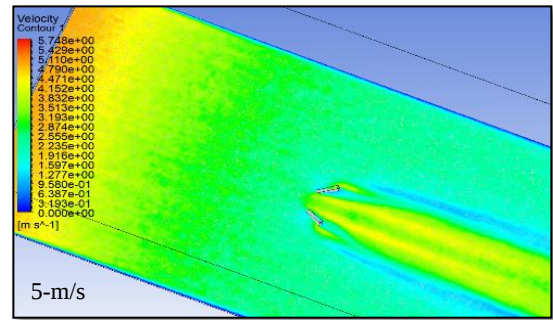
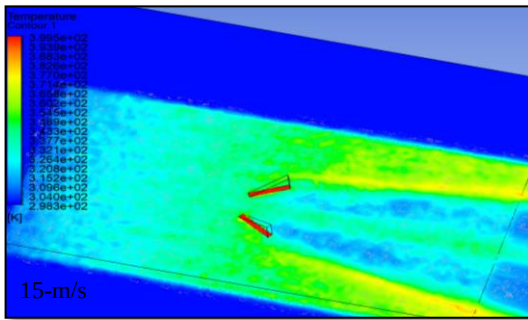
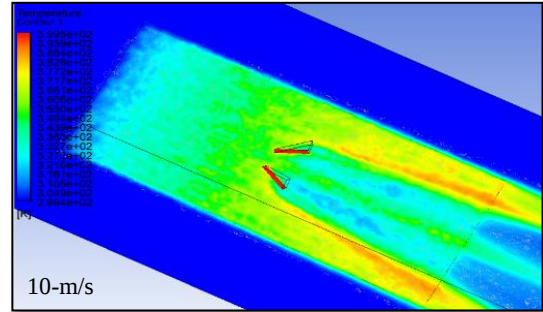
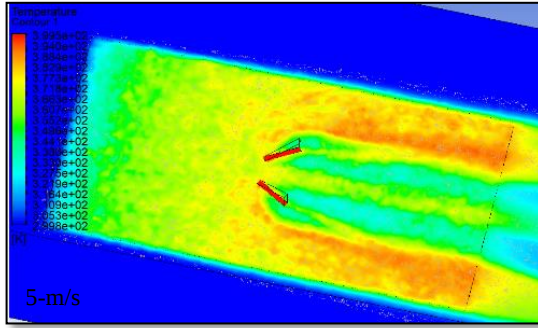


Fig. 5.3 Velocity, Temperature & Pressure Counters for Rectangular VGs.

5.4 Flat Plate with Delta type Vortex Generator

Parameters	5 m/s	10 m/s	15 m/s
Drag Coeff.	0.1282	0.0396	0.0746
Skin Friction Coeff.	0.1541	0.4683	0.8691
Heat Transfer Coeff.	1.8928	2.9890	3.7414
Surface Nusselt no.	78.2518	123.567	154.673
Surface Stanton no.	0.0015	0.0024	0.0030

Table no. 5.4



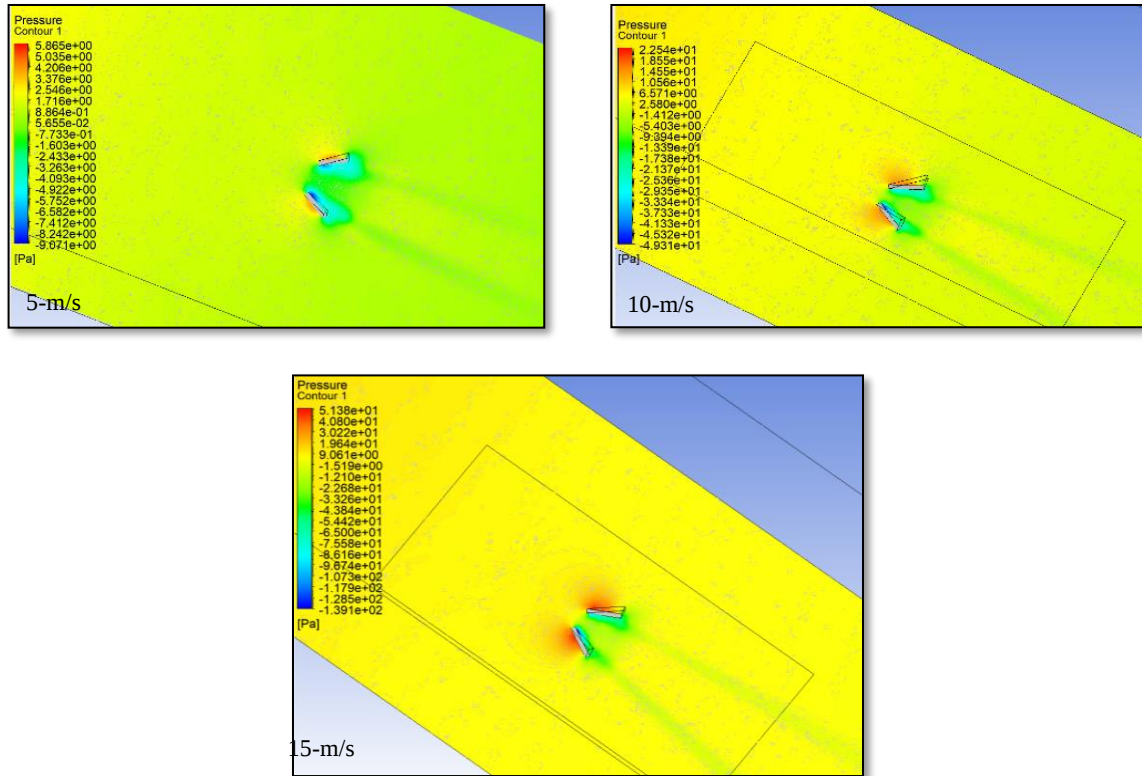
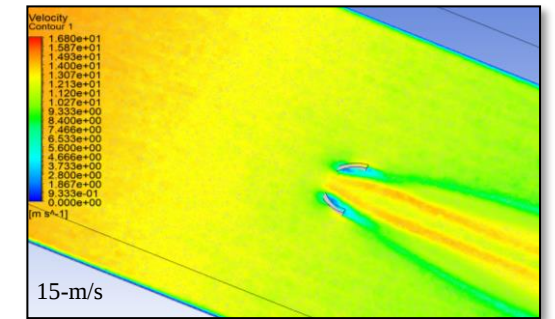
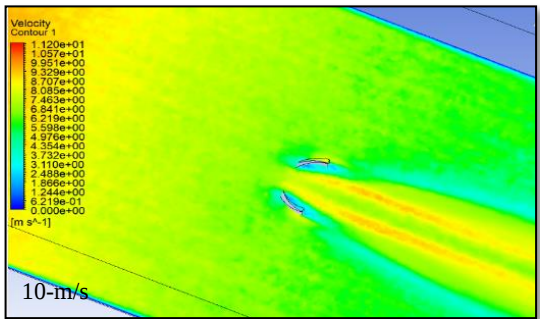
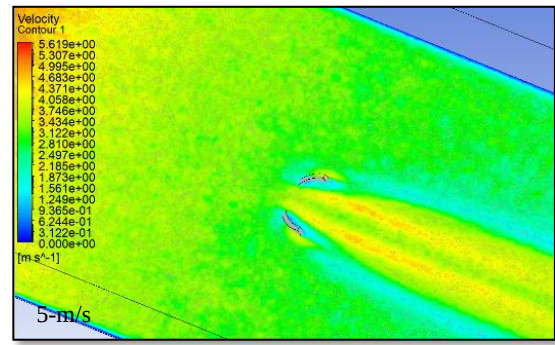
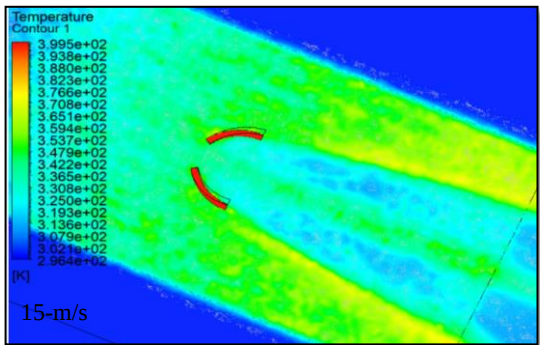
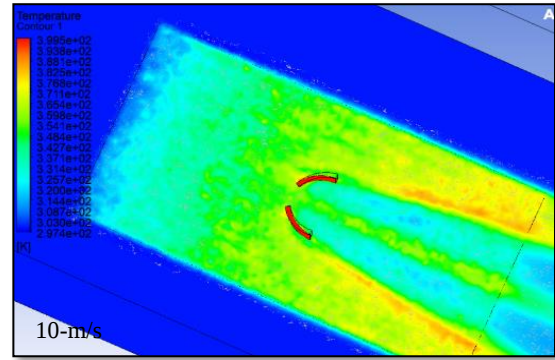
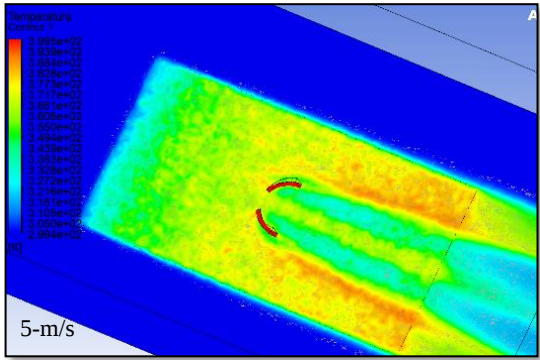


Fig. 5.4 Velocity, Temperature & Pressure Counters for Delta VGs.

5.5 Flat Plate with Curved Delta type Vortex Generator

Parameters	5 m/s	10 m/s	15 m/s
Drag Coeff.	0.0119	0.0388	0.0729
Skin Friction Coeff.	0.1448	0.4655	0.8938
Heat Transfer Coeff.	2.0203	2.9428	3.6935
Surface Nusselt no.	83.516	121.66	152.69
Surface Stanton no.	0.0016	0.0023	0.0029

Table No. 5.5



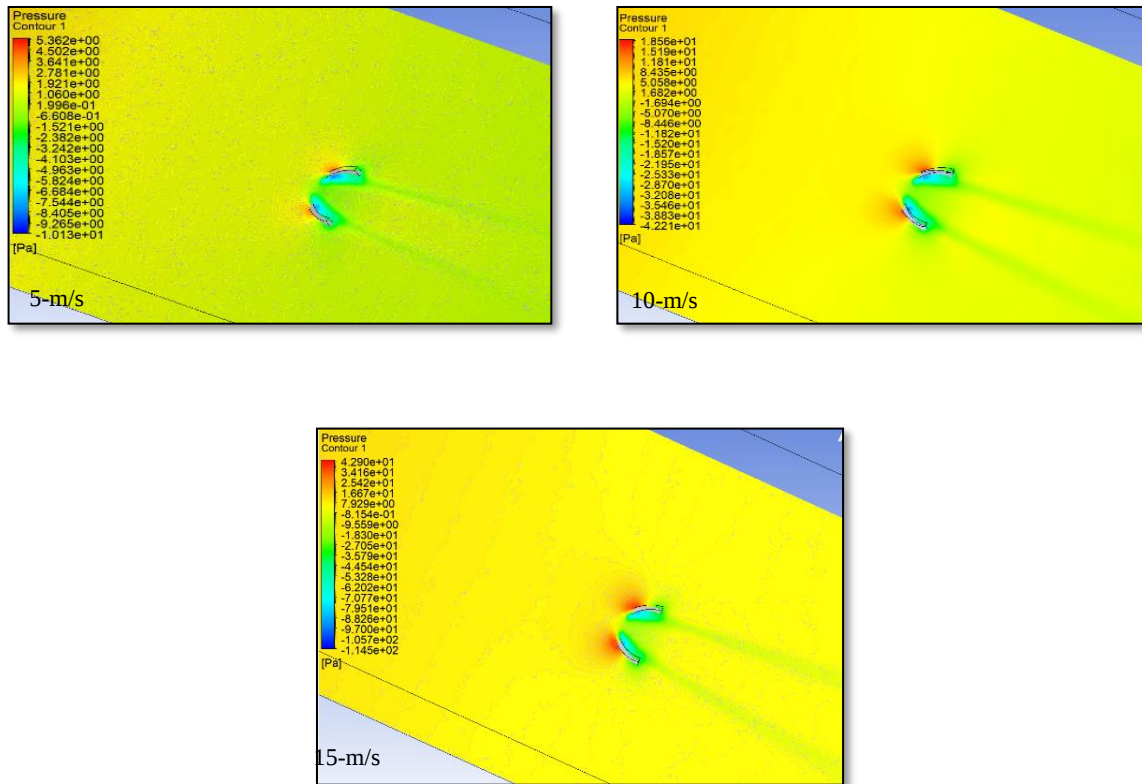
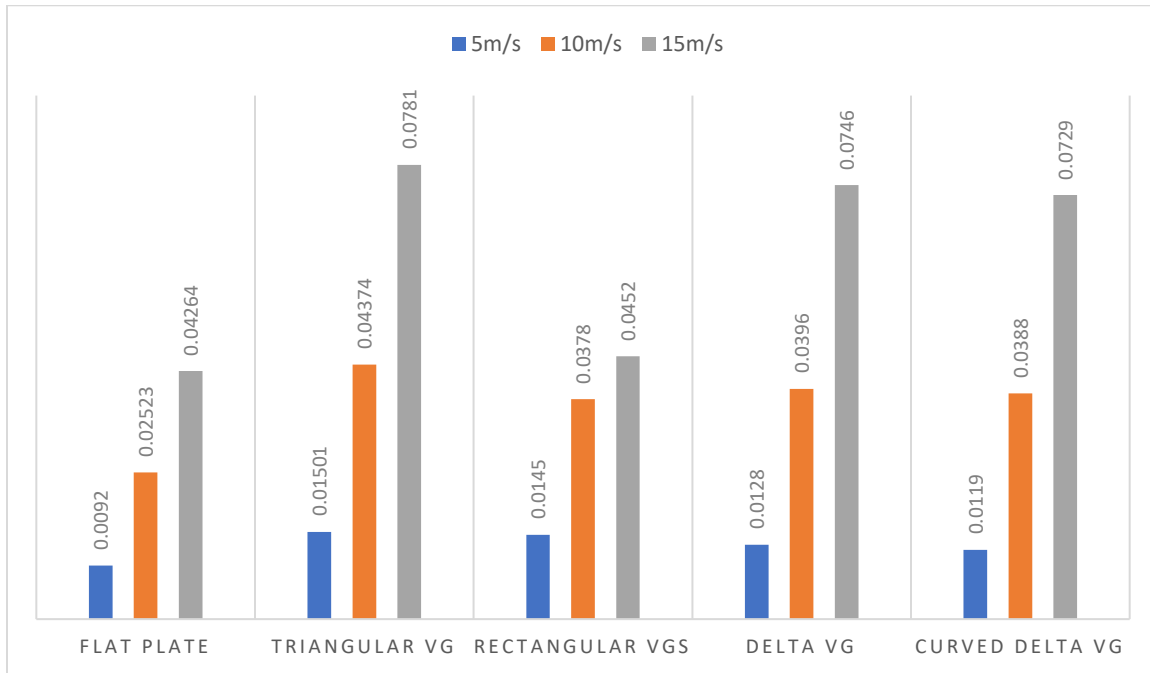


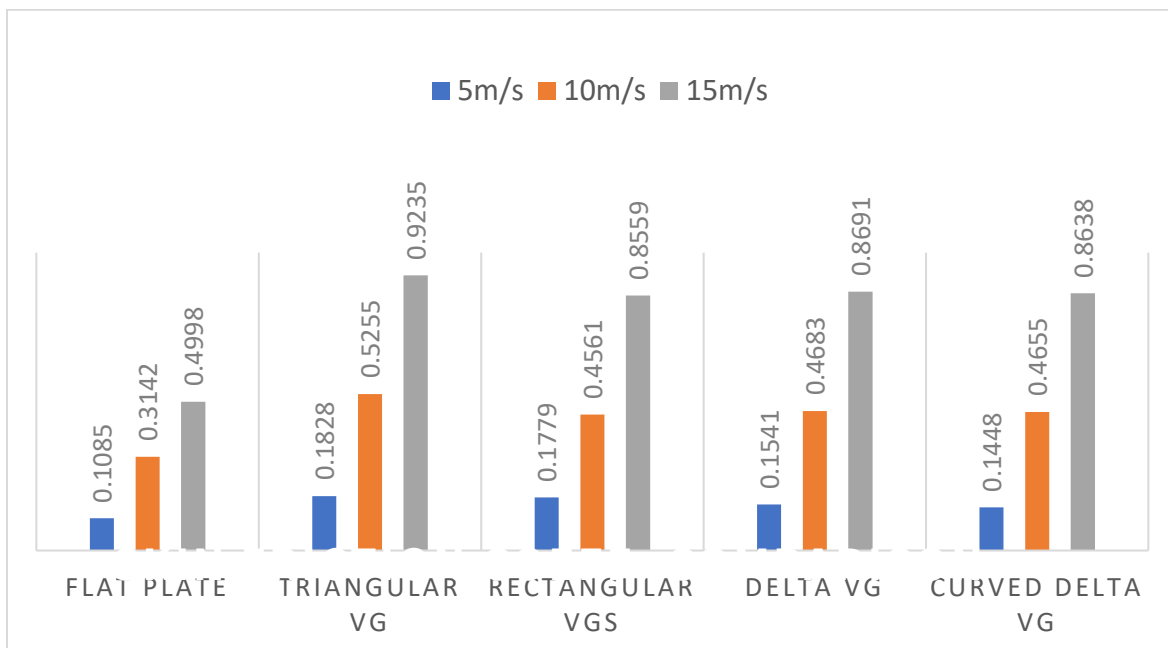
Fig. 5.5 Velocity, Temperature & Pressure Counters for Curved Delta VGs.

5.6 Comparison Plot:

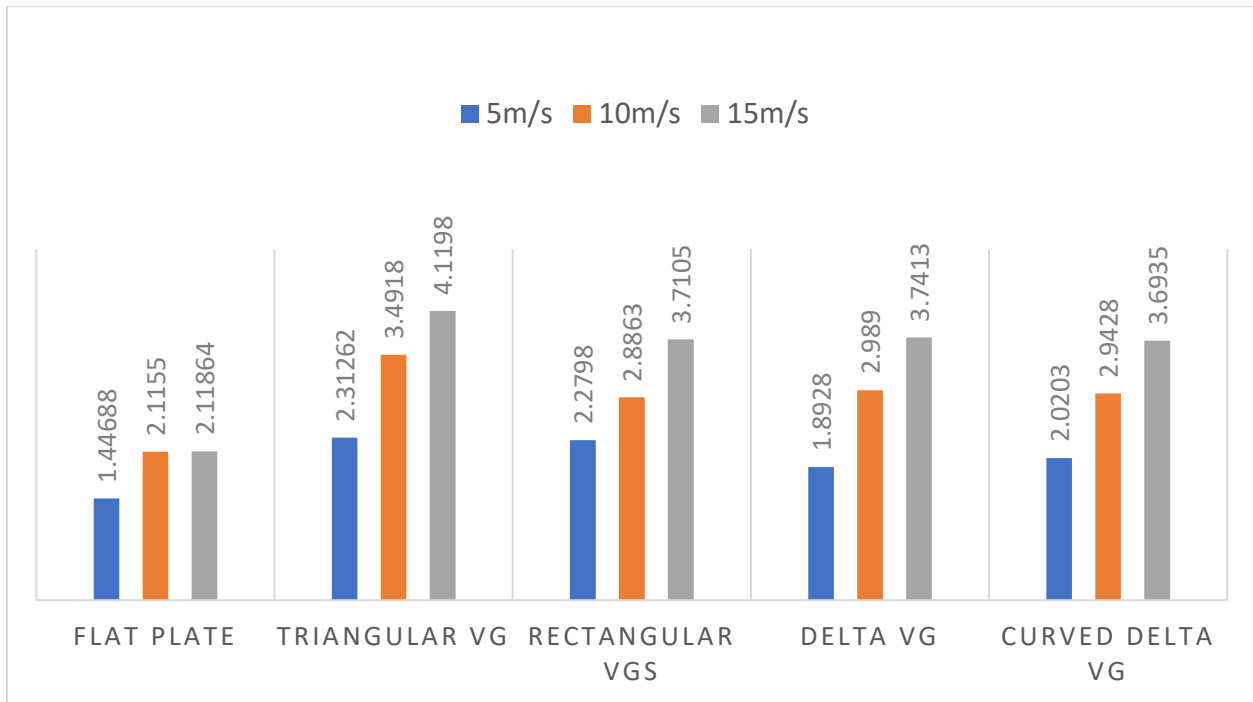
5.6.1 Coefficient of Drag Comparison:



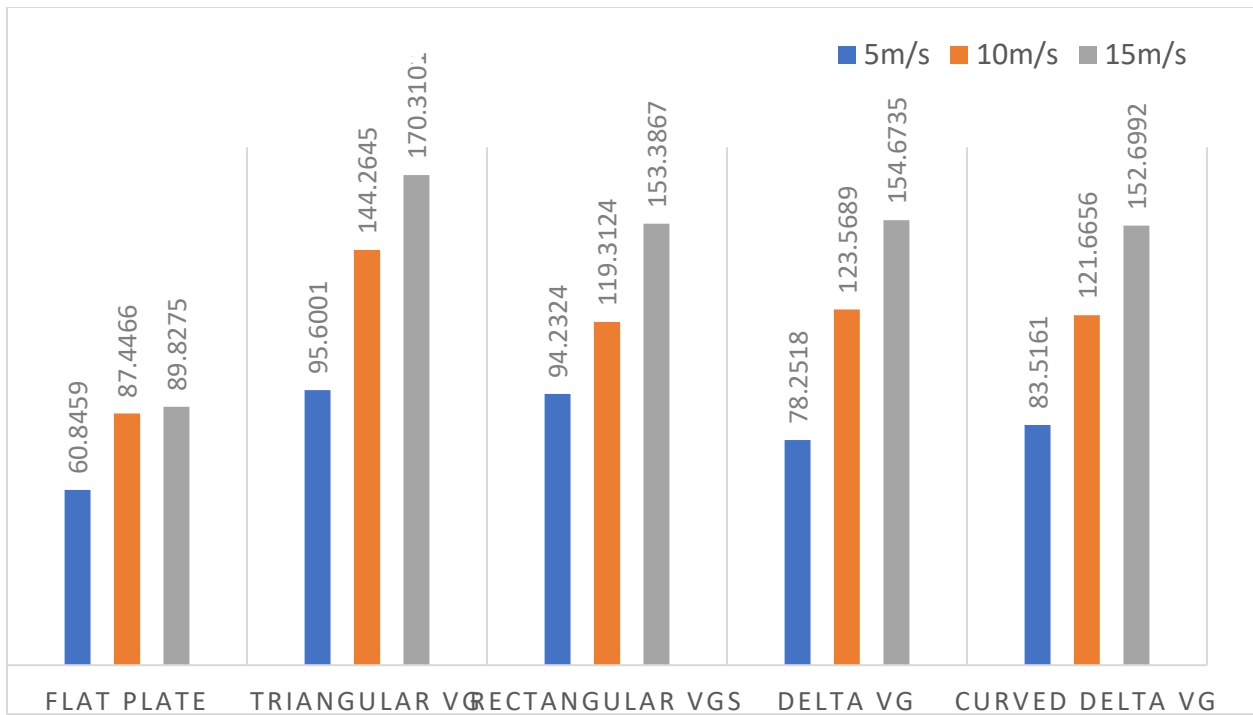
5.6.2 Skin Friction Coefficient Comparison:



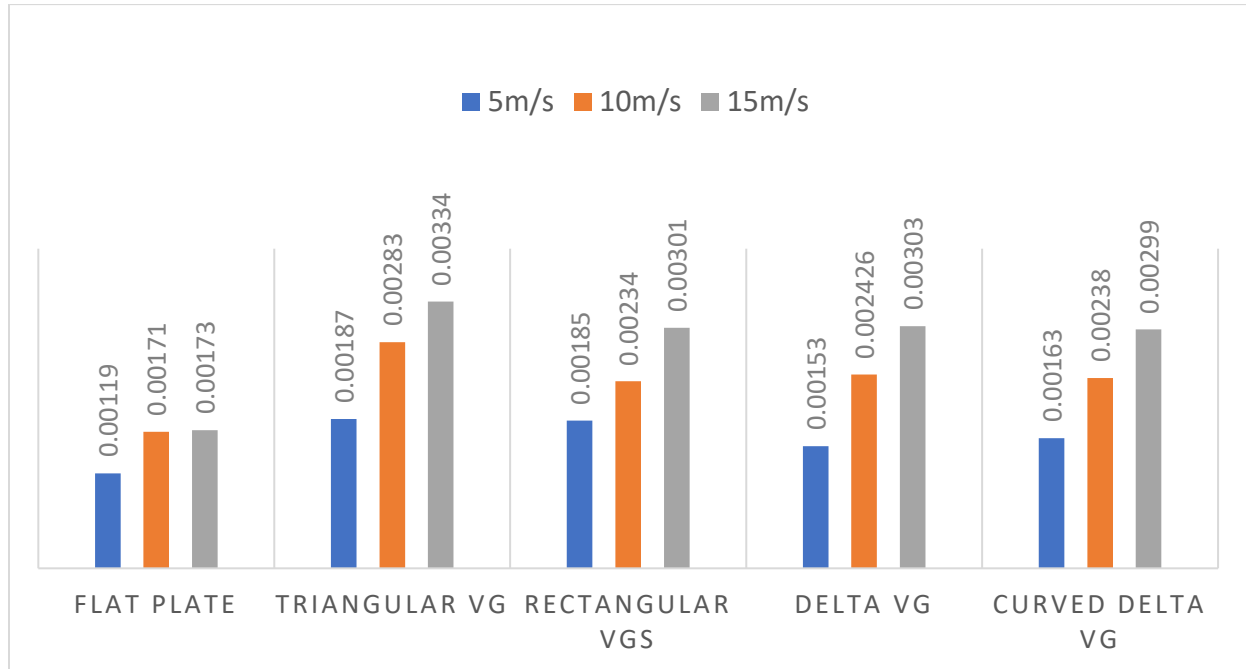
5.6.3 Heat Transfer Coefficient Comparison



5.6.4 Surface Nusselt No. Coefficient Comparison



5.6.5 Surface Stanton No. Coefficient Comparison



5.7 Conclusion:

The conclusion of the simulation indicates that as the velocity of the fluid flow increases, parameters such as surface skin friction coefficient, Drag coefficient, surface Nusselt number, surface heat transfer coefficient, And surface Stanton number all increase. Since transfer of heat through surface is directly proportional to these parameters, A significant increment in heat transfer from the surface was observed with an increase in value of these parameters. This suggests that higher fluid velocity better the heat transfer in the system. By comparing the results obtained by simulation of Triangular VGs, Rectangular VGs, Plane Delta VGs and Curved Delta VGs. It was found that the triangular type of VGs provided the best enhancement in heat transfer among all the types used. This is attributed to the production of a greater swirl effect and high back pressure, as there found higher solid- fluid interaction and better heat transfer. The curved delta type vortex generator also produced almost equal performance as the triangular type vortex generator. The simulation results showed that more surface area in the fluid interaction zone produced more drag and friction, which caused better heat transfer. The delta type VGs produced the same effect as that of the Triangular type but was found to be less effective and efficient than the triangular VGs. However, the rectangular type of vortex generator was seen to be less effective than all the other types used. This was due to the lesser flow deviation and significantly less fluid interaction caused by this type of generator. Overall, the simulation results suggest that the use of vortex generators can improve the heat transfer rate in a laminar flow system. Triangular and curved delta type vortex generators are found to be the most effective, While the rectangular type is the least effective. The conclusion also highlights the importance of considering different parameters in heat transfer simulations to better understand the behavior of fluid systems.

Back Pressure effect on Triangular VGs:

Back pressure can have a significant effect on a triangular vortex generator's (VG) ability to improve heat transfer rate. Vortex generators work by inducing vortices in the flow, which can enhance mixing and increase the transfer of heat from a surface to a fluid. However, the presence of back pressure can alter the flow patterns and affect the performance of the VG.

In general, increasing the back pressure can improve the performance of a triangular VG by increasing the flow velocity and enhancing mixing. This is because the increased pressure can force more fluid through the gaps created by the VG, which enhances the mixing of the boundary layer and increases the transfer of heat from the surface to the fluid. Additionally, the increased velocity can help to reduce the thickness of the boundary layer, which can further improve heat transfer.

However, the relationship between back pressure and VG performance is not always straightforward and depends on several factors, including the size and shape of the VG, the characteristics of the flow, and the properties of the surface. For example, if the back pressure is too high, it can cause the flow to separate from the surface, which can reduce the effectiveness of the VG and decrease heat transfer.

Furthermore, the effect of back pressure on VG performance can vary depending on the type of flow. In laminar flow, the effect of back pressure is generally more pronounced than in turbulent flow, as turbulent flow is already characterized by high levels of mixing and fluid velocity.

In summary, the effect of back pressure on a triangular VG's ability to improve heat transfer rate is complex and depends on several factors. While increasing back pressure can generally enhance mixing and increase heat transfer, the relationship is not always linear and requires careful consideration of the specific flow conditions and system properties.

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