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Heat Transfer Enhancement and Flow Physics Behavior of Fluid in Circular Tube with Insert

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Abstract: ***The paper presents computational fluid dynamics study of non-conventional insert vortex generator using Commercial software, to analyze the effect of vortex generator insert on heat transfer augmentation and fluid flow behavior. The study was done for Reynolds number 10000, 15000, 25000, 35000 and 45000 with working fluid as air flowing through a tube with a constant heat flux of 1000 w/m2. Current study validates the experimental results from the literature study. The heat transfer of these inserts with various geometrical arrangements viz. pitch to projected length ratio, angle of attack and height to inner diameter ratio are investigated here with the help of computational fluid dynamics software. The physical mechanism of formation and development of vortex flow from the leading edge to trailing edge of the insert is studied and it is observed that Nusselt number increases as an increment in Reynolds number. The ratio of augmented Nusselt number to smooth tube Nusselt number is found to be decreasing with increase in Reynolds number.***

Index Terms: Ansys Fluent, Computational Fluid Dynamics, Heat Transfer Enhancement, Vortex Generator Insert.

I. INTRODUCTION

The heat transfer characteristics of any heat exchanger can be enhanced by certain techniques that are active techniques and passive techniques. In active technique, help of some external power supplying unit is taken and the passive technique involves heat transfer enhancement without external power supplying unit. The passive technique uses various types of inserts which are reported in the literature survey. Deshmukh et al. [1] studied the use of delta wing vortex generator as an insert in a tube. In this study effect of vortex generator on heat transfer performance is analyzed. They have studied thermohydraulic characteristics of vortex generator for various geometrical parameters viz. height to inner tube diameter ratio, pitch to projected length ratio (p/pl) and angle of attack. The working fluid is used as air. The ratio of Nusselt number (Nua/Nus) with insert and without insert is found to be ranging from 1.3 to 5.0. Promvonge et al. [2] studied conical-shaped ring turbulator insert and their effects on heat transfer and friction factor are analyzed. The result of experiment shows that there is a large effect of the ring to tube diameter ratio and ring arrays on thermal performance. Salam et al. [3] did an experimental investigation on rectangular cut twisted tape of stainless steel. They observed increment in the heat transfer efficiency in the range 1.9 to 2.3, with increment in Reynolds number. Eiamsa-ard et al. [4] used twisted tape inserts with peripherally cuts on it and conducted an experiment with uniform flux condition with Reynolds number ranging in between one thousand to twenty thousand. They found that the tube with his insert shows significantly higher heat transfer rate and friction factor mainly due to vorticity generated due to the cuts on the insert. Wongcharee et al. [5] investigated the effect of twisted tape insert placed inside a tube with alternate axes that is clockwise and counterclockwise with Reynolds number range of 830 to 1990 for different twist ratios with uniform heat flux and water as a working fluid. The results of the research show that the smallest twist ratio as very efficient in the enhancement of heat transfer.

To study the effect of various types of inserts on heat transfer enhancement with this experimental work certain numerical study is carried out. Salman et al. [6] did numerical investigation on parabolic cut twisted tape and classical twisted tape with working fluid as water-copper oxide Nanofluid and it was observed that parabolic cut twisted tape shows better performance. Bhuyan et al. [7] studied heat transfer enhancement using full length twisted tape insert in a tabular shaped u loop pipes at a uniform flux. Results show that full length twisted tape shows better heat transfer enhancement in comparison with short length tapes. Eiamsa-ard et al. [8] did the study on loose fit twisted tape and tight fit twisted tape. It is found that at smallest clearance ratios there is a better performance in comparison with other all clearance ratio in terms of swirl flow generation and heat transfer rate.

Sharifi et al. [9] had done a CFD study on wire coiled insert in laminar flow using hexahedral mesh. The result shows maximum Nusselt number and lowest performance drop for coiled wire for a pitch of 69mm. Guo et al. [10] had done investigation on heat transfer enhancement of laminar flow with center cleared twisted tape insert. In this study they compared the results from conventional, short width and center cleared twisted tape,

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concluding that twisted tape with center cleared tape shows augmentation in thermal performance factor showing best performance among all twisted tape stated. Park et al. [11] studied CFD analysis of
the flow when the helical wire is inserted in a tube. From the study, the swirl flow generation due to a helical wire is observed and results show that increasing wire diameter increases swirl flow generation but more than wire diameter pitch length is found to be more dominant factor than the wire diameter. For design of swirl flow generation, the pitch length is found more dominant parameter than the wire diameter. There is an increase in swirl flow generation on increasing pipe length.

Wenbin Tu et al. [12] numerically investigated the effect of the pipe as an insert in a tube for turbulent flow with Reynolds number ranging from 2892 to 28915. Working fluid is used as water. From results, it is found that there is a decrease in heat transfer rate with an increase in spacer length, with spacer length of S/D=10 the high flow resistance with the highest heat transfer is observed. It is also seen that the installation angle is also an important factor while designing heat exchanger as it directly affects heat transfer performance. In comparison with three pipes, the four pipes insert have better heat transfer characteristics at high Reynolds number, mainly due to their high turbulence intensity.

CFD study on a new type of insert for fluid flow through the tube is done. In the numerical study of insert for heat transfer enhancement that has been reported were mainly focused on heat transfer enhancement, in this paper with the study of heat transfer enhancement with flow physics behavior of the fluid along the length of the tube is studied. The variation in the flow due to curved delta wing vortex generator is observed and it is compared with the fluid flow through a smooth tube.

II. SCHEMATIC MODEL OF A TUBE WITH VORTEX GENERATOR

The model of a circular tube with vortex generator is designed as shown in Fig. 1.

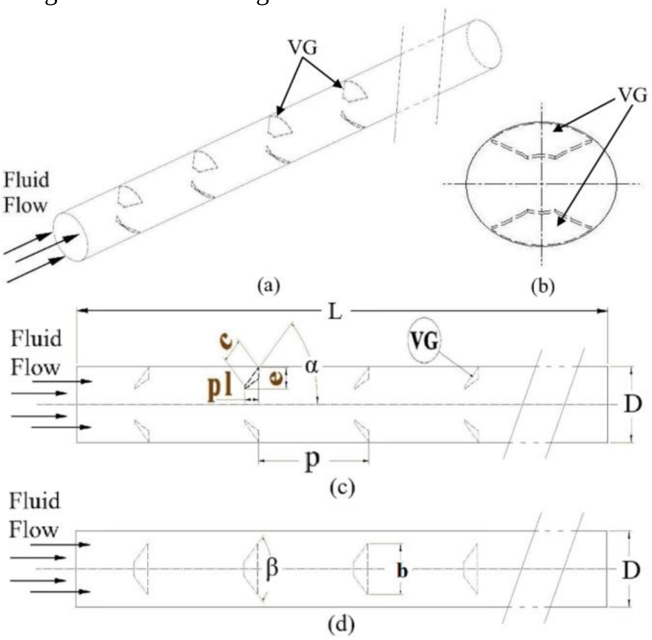


Fig. 1. Schematic Model of a tube with vortex generator (a) isometric view, (b) front view, (c) side view and (d) top view

Fig. 1 (a) shows isometric view for the schematic model of a tube with vortex generator for α=45o, p/pl=1.6 and e/d=0.25 showing the direction of fluid flow. The outside tube is made of stainless steel of length 1000 mm and diameter 25mm. The vortex generator designed is made of an aluminum sheet of thickness 0.5mm.

Fig. 1 (c) shows a side view of tube which indicates certain geometrical parameters of vortex generator, these geometrical parameters are varied and various models of the tube with vortex generator are obtained for different cases as stated in Table- I.

Table- I: Dimensions of insert for each case

Case No.	α	p/pl	e/d
1	15	1.4	0.09
2	15	2.9	0.09
3	15	5.8	0.09
4	30	1.6	0.17
5	30	2.1	0.17
6	30	3.2	0.17
7	30	6.4	0.17
8	45	1.6	0.25
9	45	2.0	0.25
10	45	3.9	0.25
11	45	7.9	0.25

These are the eleven cases mentioned above, in each case, there are certain changes in geometrical parameters. Effect of change in a geometric parameter of vortex generator on heat transfer behavior and fluid flow behavior is analyzed.

III. MESHING

The above model is designed in CATIA V5 and then it is imported to ANSYS for CFD study. Fig. 2 shows a meshed model of vortex generator. The hexahedral meshing of the model is done in ICEM software.

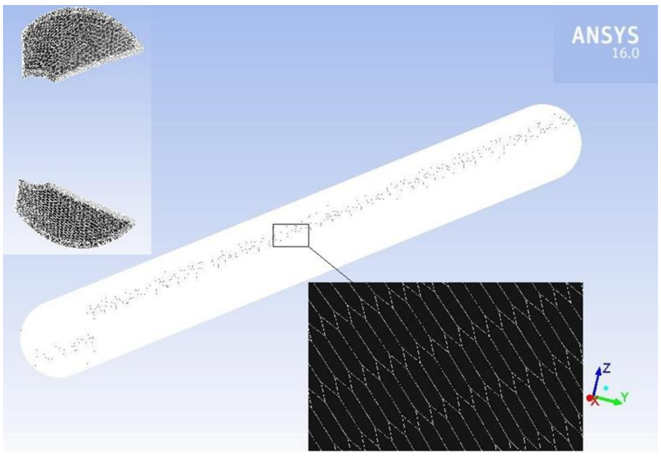


Fig. 2. Meshing Model of the tube with vortex generator

Consider a case with α=45' and p/pl=7.9. The mesh properties of this model can be stated as, there are 6571249 nodes, total 7949625 faces with 1258586 cells. Which denotes a good quality of mesh.

The faces are with a minimum face area of 2.8667*10-09 m^2 and maximum face area of 2.0607*10-06.

IV. BOUNDARY CONDITION

At inlet, velocity inlet condition was applied where air with 298.15 K temperature with the respective velocity enters from inlet. Pressure outlet condition is given at outlet for all simulations. Simulations are carried out at constant heat flux of 1000 w/m2 at the wall of the pipe. Table- II shows input values applied as a boundary condition for a case, similarly for all eleven cases the boundary conditions are applied which varies with input Reynolds number.

Table- II: Inlet air conditions

Sr. No.	Reynolds Number	Velocity (m/s)	Mass flow rate (Kg/sec)
1	10,000	5.96	0.00343
2	15,000	8.95	0.00516
3	25,000	14.92	0.00860
4	35,000	20.89	0.01204
5	45,000	26.85	0.01971

V. SOLUTION METHOD

Steady-state, gravity-dependent analysis is done. Simple semi-implicit pressure linked equations for pressure-velocity coupling method were used for this simulation. For continuity momentum and energy, unwinding was used to check the variables inside every cell. Simulations are performed until equations of flow and energy are converged.

VI. ANALYSIS OF SMOOTH PIPE

Initially study on the smooth pipe is done to analyze heat transfer behavior and fluid flow behavior of a pipe without an insert. In this study, the same boundary conditions are applied as that of augmented case. The variation in temperature of a smooth pipe is found as shown in Fig. 3.

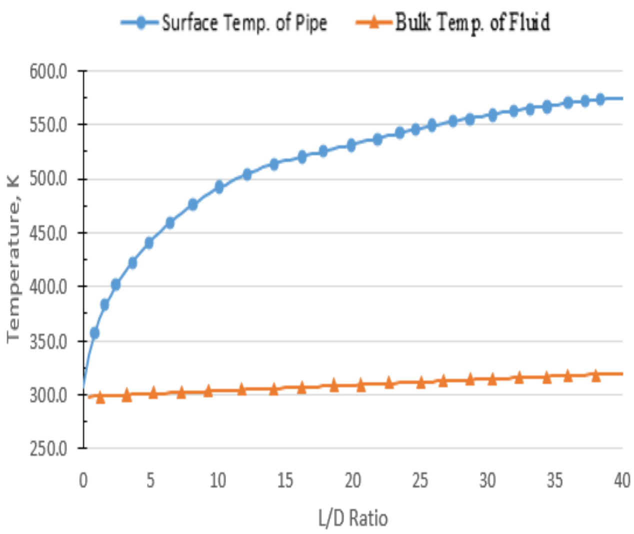


Fig. 3. Graph of surface temperature and bulk temperature for smooth pipe

Fig. 3 shows graph of the temperature versus pipe length in which two curves are observed. Orange colored curve shows the bulk temperature or centerline temperature of the fluid flowing through the pipe. Another blue colored curve shows the wall temperature of the pipe along the length of the pipe. From the graph it is clear that there is no significant change in the temperature of the fluid at the center, it remains the same but as far as wall temperature is concerned there is a gradual increment in the temperature along the length of the pipe.

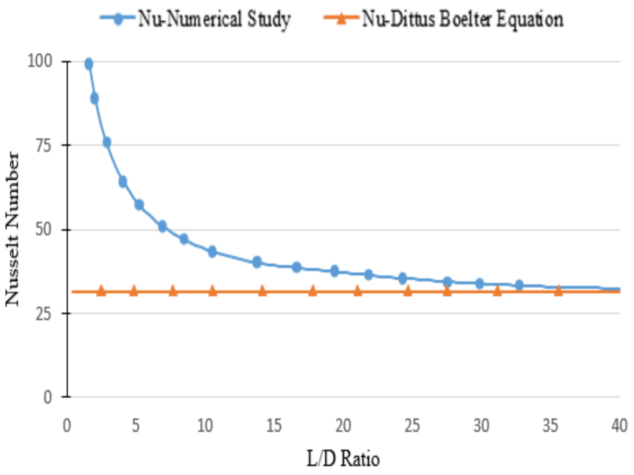
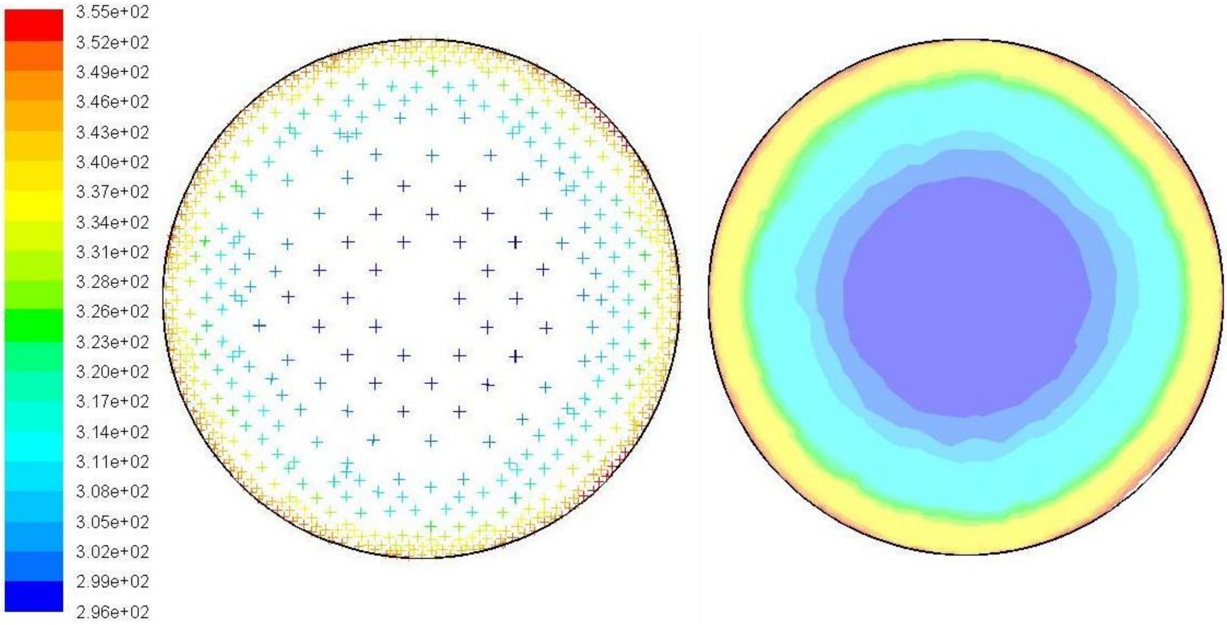


Fig. 4. Graph of Analytical Nusselt number and Practical Nusselt number

The graph of Nusselt Number Versus Pipe length, as shown in Fig. 4, shows variation between the numerical Nusselt number and theoretical Nusselt number. From this graph, it is observed that for Nusselt number initially there is very high value and it can be seen that along the length of the pipe there is a decrement in the Nusselt number. This is because initially at the entrance of the pipe there is a very large scope for heat transfer so heat transfer occurs at the high rate. Gradually it decreases and at a point of time, it matches with the theoretical Nusselt number.



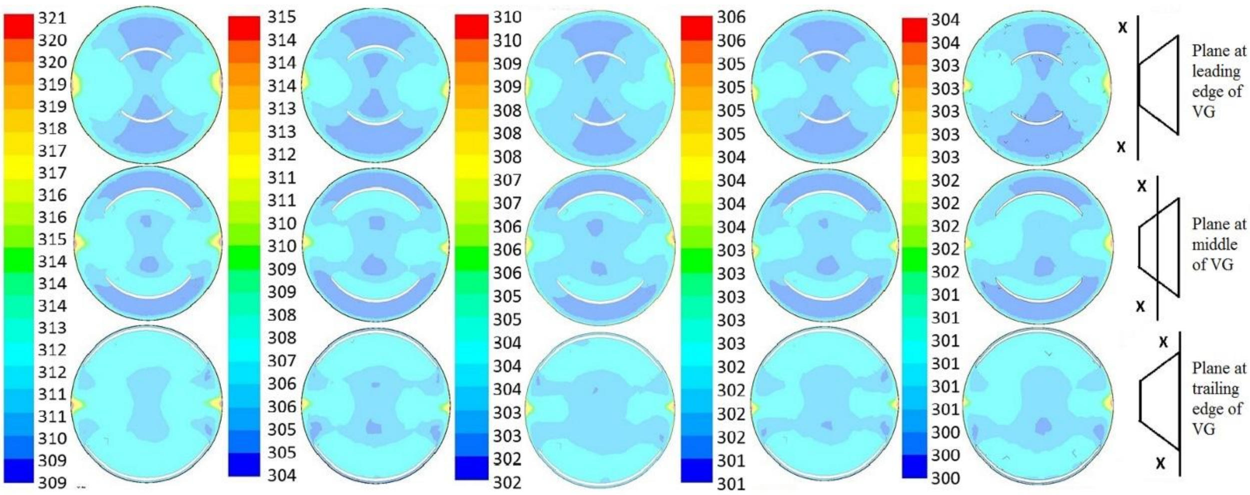
(a) Velocity vector colored by temperature **(b) Temperature distribution Contour**

Fig. 5. For smooth pipe (a) velocity vector and (b) temperature contour at Reynolds No. 10000

Fig. 5 (a) shows velocity vectors colored by static temperature for the pipe without insert (smooth pipe). It shows fluid flowing in an exact uniform manner without any disturbance similarly it shows that the static temperature for velocity vectors don't have any significant change. Also, in Fig. 5 (b) it is observed that the temperature contour for the smooth pipe which shows the same temperature distribution around the periphery of the tube, at every location there is the same temperature. No any abrupt change in temperature distribution or in the fluid flow is observed.

VII. HEAT TRANSFER ANALYSIS

Initially, heat transfer enhancement for the smooth pipe is observed by applying boundary conditions as mentioned above then by varying certain geometrical parameters eleven models are built and these models are analyzed for Reynolds number 10000, 15000, 25000, 35000 and 45000. Total eleven cases are tested for above five Reynolds number. Here the same amount of heat input is given for all the cases as constant heat flux is maintained to the walls of the pipe for both smooth tube and tube with insert. The temperature contour for the smooth tube is shown in Fig. 5 (b). The gradual distribution of temperature across the pipe is seen. The temperature contour for augmented cases as shown in Fig. 6, clearly shows that the area with the vortex generator with effective heat transfer.



(a) Re = 10000 (b) Re = 15000 (c) Re = 25000 (d) Re = 35000 (e) Re = 45000

Fig. 6. Contours of static temperature at various locations for p/pl ratio=3.9

Fig. 6 shows temperature distribution contour for p/pl=3.9 (case 10) and at various locations as section plane at the leading edge, center, and trailing edge respectively. Fig. 6 (a) shows contours of static temperature at all the three section planes for p/pl=3.9 for Re=10000 within the color temperature band of 309k to 321k. Similarly, to show the variation in temperature distribution various temperature bands are given for various Reynolds number. From this, it is observed that as Reynolds number increases the temperature difference in the color band decreases showing the decrement in the temperature with increase in Reynolds number.

For temperature contour of section plane at the center, there is no turbulence at the center of the tube and therefore heat transfer is low and nearly constant. While there is a generation of vortices around the vortex generator placed at the periphery of the tube resulting in a high heat transfer rate compared to the center. Contours of static temperature for section plane at the leading edge shows the early stage of development for the vortices that are turbulence due to vortex generator. Similarly, section plane at trailing edge shows static temperature contours at trailing edge, in this image exact scenario of temperature distribution can be observed. It shows a difference between temperature in the region where vortex generator is placed and region without vortex generator insert. The region with a vortex generator shows decreased temperature due to turbulence as a result of vortex flow motion of the fluid

VIII. FLUID FLOW BEHAVIOR

Fig. 7 is the indicative representation of the velocity vectors for p/pl=3.9 and α=45° (case 10) among all the eleven cases mentioned in Table- I, For Reynolds number 10000.

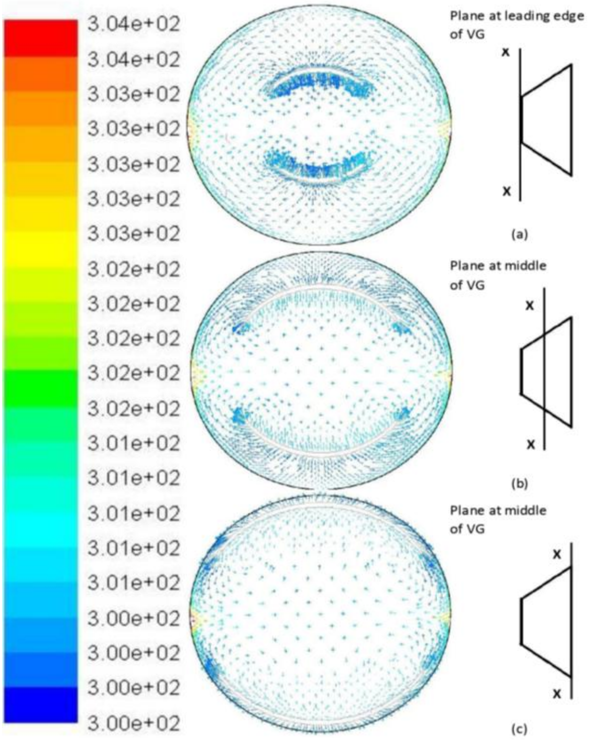


Fig. 7. Velocity vector colored by static temp. (a) at the Leading edge (b) at the center (c) at the trailing edge for p/pl ratio = 3.9 and for Reynolds number 45000

Fig. 7 shows velocity vector colored by static temperature; it shows the generation of vortex flow due to vortex generator insert. To visualize the development of vortex flow three section planes are taken on the vortex generator as on the trailing edge, on the leading edge and one on the center of vortex generator. In Fig. 7 (a) section plane at the leading edge, it is observed this as the first stage of development of vortex flow, and in Fig. 7 (b) the partially developed vortices, the deviation in the fluid flow due to the insert can be clearly seen. Similarly, Fig. 7 (c) shows section plane at trailing edge in which the formation of the vortices at four different locations in the tube can be seen clearly and turbulence is created due to this vortex. As these velocity vectors are colored by static temperatures the effect of the insert can be seen in terms of generation of turbulence and eventually in a decrement of temperature in the region where the inserts are located.

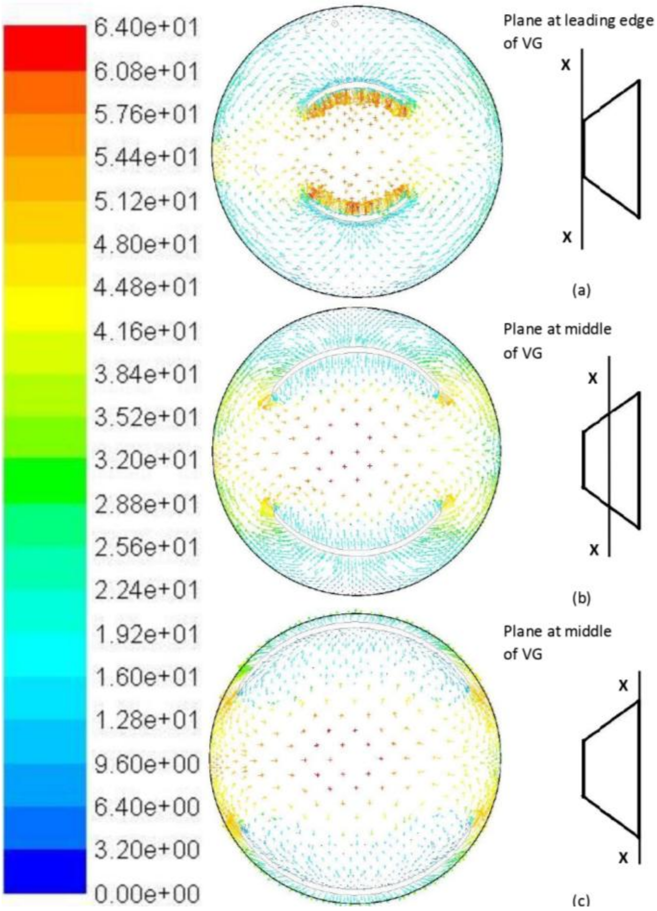


Fig. 8. Velocity vector colored by velocity magnitude (m/s) (a) at the Leading edge (b) at the center (c) at the trailing edge for p/pl ratio = 3.9 and for Reynolds number 45000

To visualize the development of vortex flow three section planes are taken on the vortex generator as on the trailing edge, on the leading edge and one on the center of vortex generator. In Fig. 7 (a) section plane at the leading edge, it is observed this as the first stage of development of vortex flow, and in Fig. 7 (b) the partially developed vortices, the deviation in the fluid flow due to the insert can be clearly seen.

Fig. 8 shows the velocity vectors for p/pl ratio = 3.9 and for Reynolds number 45000 which are colored by velocity magnitude which shows the flow of the fluid inside the pipe and their colors shows velocity at a respective location with color band given at left-hand side. Higher velocities are observed at the center of the pipe and at the region without an insert, here fluid strikes to the vortex generator which causes a change in the path of fluid with a generation of turbulence. Due to the geometry of this insert vortices are generated around the insert.

IX. RESULTS AND DISCUSSION

Simulations are done on above vortex generator for Reynolds number ranging from 10000 to 45000, every Reynolds number is tested for all the seven cases.

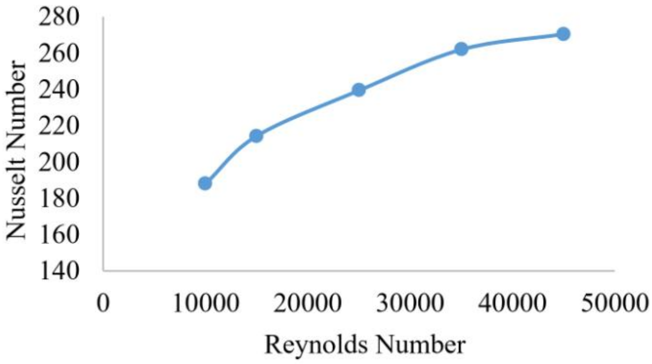


Fig. 9. Nu v/s Reynolds number for First Case (p/pl=1.4)

Fig. 9 is an indicative representation of changes in heat transfer rate with the Reynolds number for the first case with p/pl=1.4, α=15° and e/d=0.09 to analyze the heat transfer behavior for various Reynolds number.

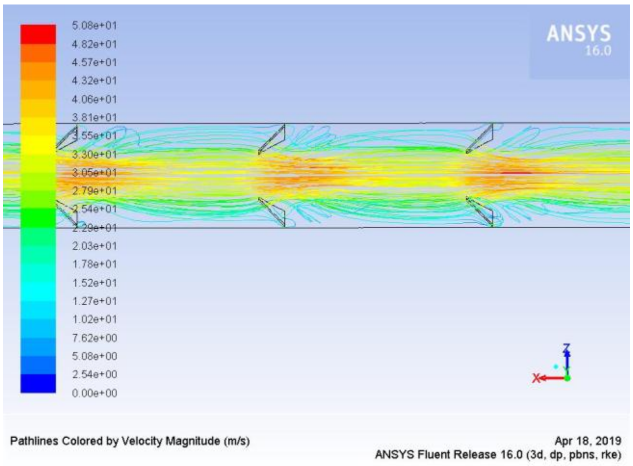


Fig.10. Path lines colored by velocity Magnitudes.

The changes in Nusselt number with Reynolds number are observed in the Fig. 9, it shows that as Reynolds number increases the Nusselt number also increases. Fig. 10 shows path lines of the fluid flow colored by velocity magnitudes. Vortex swirl movement of the fluid can be clearly seen in the Fig. 10 at the vortex generator which are symmetric to the axis of the pipe. Similarly, Fig. 11 shows a graph of $Nu(z)/Nu_s$ versus Reynolds number.

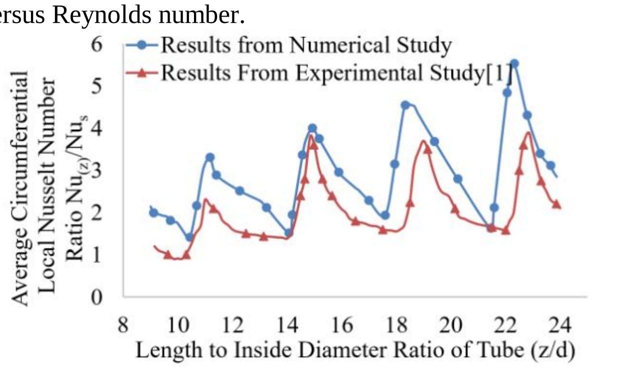


Fig. 11. Nu (z)/Nus variation for Re = 25,000 (p/pl = 12.8, α = 30°, e/d = 0.17).

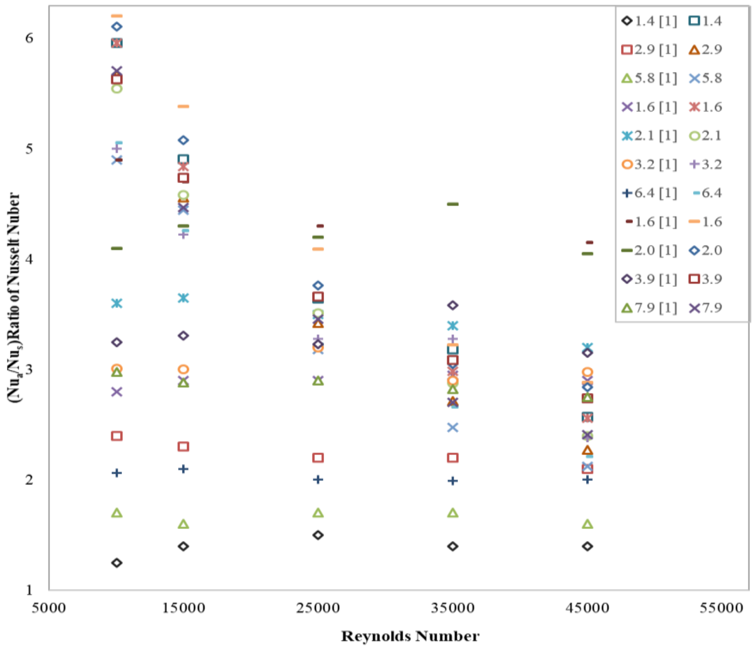


Fig. 12. Graph for the ratio of Nu_a to Nu_s with Reynolds number

Fig. 12 shows experimental results obtained by P. W. Deshmukh [1] at el. on the tube with a vortex generator insert and results obtained using CFD software. The numerical values of the present study are closely matches with the experimental values reported by P. W. Deshmukh [1] et al. In the graph on Y-axis ratio of Nusselt number for an augmented case with the smooth pipe case is taken. It is found that the vortex generator with e/d ratio=0.09, α=15° and for all the three p/pl ratios has the lowest Nusselt number enhancement. This might be due to at low p/pl ratios the centerline flow is not able to penetrate the area in between successive inserts, because of high resistance given by vortex generator which results in a reduction of heat transfer coefficient. The Nusselt number enhancement, Nua/Nus is observed to be maximum for vortex generator arrangement with p/pl ratio 2.0, α=45° and e/d=0.25 and Reynolds number varying from ten thousand to forty-five thousands.

Similarly, Fig. 11 shows validation of experimental results obtained by P. W. Deshmukh [1] at el., it shows a graph of Nu (z)/Nus variation with Nu(z)/Nus ratio on Y-axis and Length to Inside Diameter Ratio of Tube (z/d) on X-axis. Which shows variation in the ratio of Nusselt number along the length of the tube for Re = 25,000, p/pl ratio = 12.8, angle of attack α = 30° and e/d = 0.17 in this graph experimental results are compared with numerical results from CFD analysis. From the graph, it is observed that numerical results are superior to experimental results due to the absence of external losses.

X. CONCLUSION

CFD study of nonconventional vortex generator insert was carried out with the help of ANSYS FLUENT software for turbulent flow. From the results, it is concluded that these vortex generator inserts are found to be a promising technique of passive heat transfer enhancement. The ratio of augmented Nusselt number to the smooth Nusselt number in this numerical study is 40% more compared to experimental study [1]. Pipe with vortex generator for all geometric configurations gives Nusselt number values around 225-650% higher than smooth pipe values. It is observed that inside the tube for particular vortex generator vortex generation starts to develop at leading edge and at trailing edge fully developed vortices are seen.

The flow physics under the influence of vortex generator is studied and it is observed that vortex flow generation is noticed which causes high turbulence resulting in high heat transfer rate. Nusselt number is increased with an increase in the Reynolds number. Pipe wall temperature is reduced in case of insert fitted tube as compared to the wall temperature of the tube without an insert. The vortex generator with α=45o, p/pl=1.6 and e/d=0.25 shows best heat transfer enhancement at various Reynolds number. Generation of vortices and there flow across the tube is studied. The vortex generator produces secondary flows at localized areas hence heat transfer augmentation at particular selective locations can be done easily.

NOMENCLATURE

Symbol	Meaning
A	inside surface area of test section (πdL) (m^2)
c	vortex generator length (refer Fig. 1.c) (m)
d	inside diameter of test section (m)
e	height of vortex generator (e = c sin α) (m)
k	thermal conductivity of the material (W/m K)
L	heated length of test section (m)
l	length of the tube between the pressure taps (m)
m	mass flow rate of fluid (kg/s)
r, θ, z	cylindrical coordinates
p	pitch of vortex generator (refer Fig. 1.c) (m)
pl	projected length of vortex generator (pl = c cos α)
T	temperature (K)
Cp	specific heat at constant pressure (J/kg K)
VG	Vortex Generator

Dimensionless parameters

Re	Reynolds number (ρvd/μ)
Pr	Prandtl number ($\mu c_p/k$)
Nu	local/average Nusselt number
p/pl	ratio of pitch to projected length
e/d	ratio of VG height to inside diameter of tube

Greek symbols

ρ	Density of fluid (kg/m^3)
α	Angle of attack, degrees (refer Fig. 1.c)
β	Included angle degrees, (refer Fig. 1.c)

Subscripts

a	augmented case
b	bulk fluid
i	inlet of test section
o	outlet of test section
s	smooth Tube at constant Re number
w	wall

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Mr. Prafulla R. Hatte has completed his masters in Heat Power Engineering and presently doing research on Engines. His areas of research include Thermal Engineering, I C Engines, and Alternative Fuels. He is International Trainer & Teacher certified by Cambridge University. He has conducted 100+ workshops and training sessions in industries and institutes He has 8 years of industry experience and 17 years of teaching experience. He has also worked as Consultant for many MNCs and has also worked as Chartered Engineer. His professional expertise includes CNC programming, tooling, hydraulics, and pneumatics. Presently he is working as Dean-School of Mechanical & Civil Engineering with MIT Academy of Engineering, Alandi, Pune, India.