Experimental Investigation of Trapezoidal Duct using Delta Wing Vortex Generators

Gokul N Wakchaure, Prof. Shivanand S Talwar

***Abstract*— This paper deals with experimental study of heat transfer and flow characteristics of air flowing through trapezoidal duct. The duct is roughened with delta wing vortex generators. Three cases viz. delta wing VGs making angle 30^0, 45^0, 60^0 with base surface of duct are considered for the present project work. Experiments are performed for each case to estimate Nusselt number, Stanton number, and pressure drop & friction factor as a measure of heat transfer and flow characteristics. Also above parameters are evaluated for smooth duct and comparison of different cases with & without VGs is done. For the validation purpose, The Nusselt number and friction factor which are obtained from the smooth trapezoidal duct are compared with the correlations of Dittus-Boelter; Blasius and Petukhov for turbulent flow in ducts. Percentage increase in friction factor as compared to smooth duct was 14 to 21% for $\beta = 30^0$, 19 to 36% for $\beta = 45^0$, 31 to 49 % for $\beta = 60^0$ over the range of Reynolds number considered. Heat transfer rate was enhanced by around 29 to 67% for β=30^0, 23 to 43% for β=45^0, 14 to 27% for β=60^0 when compared with smooth duct over the range of Reynolds number.**

***Index Terms*— Convective heat transfer, Delta wing VG, Friction Factor, Nusselt Number, Pressure drop**

I. INTRODUCTION

Various applications in engineering domain needs heat addition or extraction. These application uses no. of devices to exchange the heat. Performance of these devices is judged by improvement in heat transfer coefficient and reduction in pressure drop. Some heat transfer improvement technique increases the rate of transfer of heat, along with pressure drop. This subsequently raises the pumping cost. Thus any device which helps to improve augmentation should be optimized in between the merits of the increased heat transfer coefficient and the higher cost involved because of the increased friction. [1]

HT Enhancement techniques are of two types i.e. passive and active methods. Active techniques need external supply of power to maintain the enhancement mechanism. Passive techniques does not need any such power input. Using surface modifications or geometrical alterations to flow channel, they alter the existing flow behaviour and promote higher values heat transfer coefficients. [2]

A. Vortex Generators:

A vortex or turbulence generator is an aerodynamic device, it consists of small vanes that is attached to an aerofoil, and are positioned obliquely so that they have an angle of attack with respect to the local airflow. The basic principle of (VG) is to create secondary flow, which disturbs or cuts the thermal boundary layer developed along the surface of wall and by doing so it removes the heat energy from the wall and gives it to the core of the flow by creation of turbulence. Different types like rectangular and triangular wings VG and winglets VG have been studied by several researchers, which are shown in Fig. 1. Most researches have focused their attention on wings and winglets which could be punched easily or can be mounted easily on the channel walls.

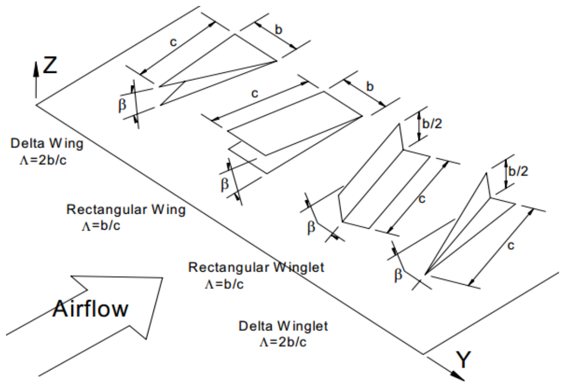

Fig.1: Basic forms of vortex generators

Turbulence promoting devices like delta wing or delta winglet VGs are used to interrupt the flow field and they can greatly improve the thermal performance of system. [3], [4]

B. Literature review

Sujoy Kumar Saha (2010) in the research work focused on experimentation to study HT and the pressure drop or flow characteristics in square ducts. Duct was having internal axial corrugations combined with twisted-tape inserts. Working Fluid was air with turbulent flow. Heat duty improvement upto 55% and pumping power reduction upto 47% was observed by using combined geometry.[5] The effect of delta wing VG on the wall of square duct and pressure drop, combined effects of geometrical parameters of VG on friction factor are observed for the Reynolds number which is based on duct hydraulic diameter. Through this experimental study decrease in friction factor (FF) ratio with increase in pitch to height ratio, increase in FF ratio with increase in ratio of VG height to hydraulic diameter of duct, with increase in aspect ratio and increase in Reynolds number was observed.[1] Pongjet Promvonge et al. (2012) carried out experimental research on turbulent flow. Characteristics of heat transfer in a square duct were studied. Duct was fitted with diagonally placed finned tape with fins making angle of 300. Friction factor and HT improvement with smaller fin pitch spacing was observed during the study.[6]

The experiments were also conducted to study above parameters in a narrow rectangular channel placed horizontal

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with longitudinal vortex generators. The working medium or fluid was water. The result shows that LVG greatly improves the rate of heat transfer by 10 – 45%, when they are mounted on the two sides of duct than mounted on one side.[7] Numerical investigation was conducted to study the effects of common flow up pair produced by VG in the rectangular channel flow. Fluid flow characteristics and heat transfer properties were studied. The values of thermal boundary layers, skin friction and heat transfer properties were observed much closer to the experimental values of other researchers.[8]

Modified LVG which were mounted in rectangular channel was used for experimental study of Flow and heat transfer characteristics. A modified LVG which is obtained by cutting off the four corners of edges of rectangular wing. The study indicates that modified wing pair shows better results than pair of rectangular wing VG.[9] The influences of various parameters of LVG in a rectangular duct were studied. Average Nusselt no. value and the flow loss increases with the increase in area of LVG. With fixed area, when we increase the length winglet pair, it results in more heat transfer. With the same LVG area, delta winglet VG pair is more effective [10]

The influence of VG on a friction for fully developed flow of in a triangular duct is studied. Results are indicating the rise in friction factor by 43.5% when attack angle was changed from 30^0 to 50^0 for triple pair case.[11] Numerical study of forced convection HT in a triangular channel ribbed with longitudinal winglet VG was carried out. Turbulent air flow with constant rate of heat flux was considered. Significant effect of rib and the VGs on the smooth wall channel along with higher values of Nusselt no. and friction factor is observed.[12] Experimental study of structure of flow with two rows of half delta-wing VG was carried out. Duct with Equilateral triangular shape was considered for the study.[13] Atole Santosh (2014) in his research work experimentally studied the HT enhancement in a triangular shaped duct with rectangular wing.[14]

Numerical results for natural convection HT were reported in the partially divided cavities of trapezoidal shape. The effects of Prandtl no., baffle height, Rayleigh number, and location of baffle on heat transfer are studied. The study reveals a reduction in heat transfer rate due to the presence of baffles and with its rate was generally increasing with the rise in baffle height.[15] An enlarged model of trapezoidal duct was built up in the nearby region the leading-edge in the blade. The effects of the impinging jets, swirl, cross and effusion flow are investigated experimentally. A result reveals that small jets effectively impinges target wall while the large jets contributes to induce and impel a strong anticlockwise vortex.[16]

The above literature review shows Numbers of experiments has been conducted in order to study the influence of various enhancement techniques on HT and flow characteristics of fluid flowing through ducts. Many of this study concentrate on mixed convection, internal flow in non-circular channels and ducts such as square, polygonal, rectangular, triangular and trapezoidal.

A very less quantity of experimental work has also been conducted using trapezoidal channel using baffles and impingement jets. In much of the studies carried out, LVG's & Delta wing VGs have given better performance in terms of HT enhancement. Review also shows that very less or no work has been done to analyze the flow in trapezoidal duct using any kind of vortex generators.

II. Experimental Set-Up

A. Description of Experimental Set-Up

The schematic diagram of arrangement made for experimental work is given in Figure 2. It consists trapezoidal duct assembly fabricated from a 1 mm thick galvanized iron sheet. The Duct assembly consists of two consecutive trapezoidal sections: a 1000 mm long entrance duct for the better development of flow, 800mm long test duct for convection and fluid friction measurement, 200 mm long exit duct. The total length of entrance duct and test duct was over 20 times of hydraulic diameter, which ensured a fully developed turbulent flow in a significant portion of test duct.

To provide uniform heating, Nichrome wire electrical heater was wound uniformly around the external surfaces of duct. The electric power supplied was controlled & maintained at 150 W by using a variable-voltage transformer throughout every experiment. The whole duct assembly was thermally insulated from environment by 20 mm thick glass wool blanket and 5 mm thick foam sheet.

The ambient air flow was driven through the duct assembly by a 0.56 Hp centrifugal blower, which was installed in such a way that delivery side is connected to the inlet of entrance duct through a circular pipe. The blower delivery was connected to a circular pipe of 60 mm diameter. Other end of pipe was connected to inlet of entrance duct. As the experiments were performed at different flow rates, electric power supplied to drive the blower was adjusted by using another variable-voltage transformer, which enabled the experimentation to be carried out at a wide range of Reynolds numbers from 10000 to 16000. All connecting parts were joined with gaskets and seals to prevent air leakage, and soap bubble and smoke was used to detect any air leakage at each joint. The temperatures and pressures obtained from the experimental investigation were used to calculate the forced convection and fluid friction.

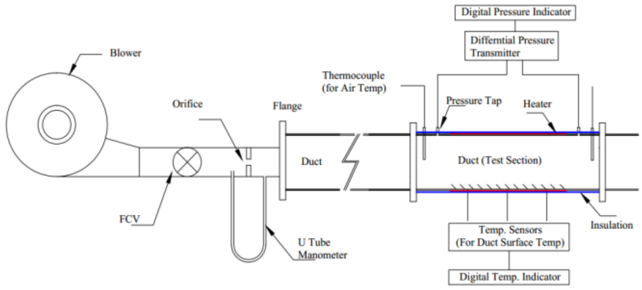

Fig 2: Schematic diagram of experimental Setup

Dimensions of trapezoidal duct are,

- Cross sectional dimensions of duct
  - Top Side, a = 55 mm
  - Bottom Side, b = 135 mm.
  - Height, h = 69 mm
  - Angle, $\theta = 60^{\circ}$
- Perimeter of duct
  - P = 350 mm
- Heat transfer surface are of duct
  - As= 0.28 m2

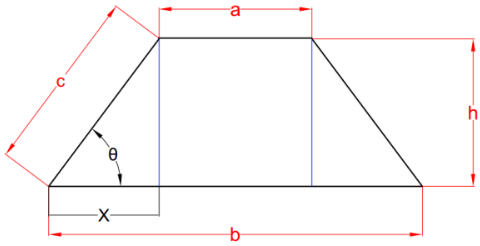

Fig 3: Cross section of trapezoidal duct

The delta wing VGs were mounted on bottom surface of duct. The geometrical parameters of delta wing vortex generators used in the present study are as follows. These vortex generators are mounted in a single row on the bottom surface of the trapezoidal duct.

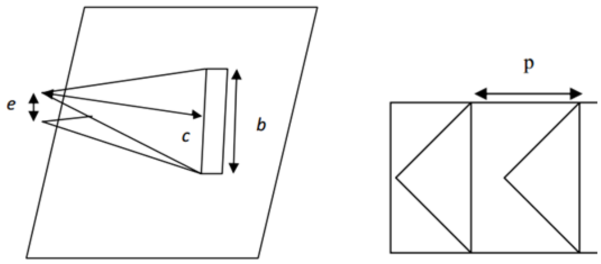

Fig 4: Geometry of delta wing VG

Table 1: Geometrical parameters of delta wing VG

Parameter	**Symbol**	**Value**
Axial pitch	p	50 mm
Base	b	30 mm
Chord length	*l*	37.5 mm
Angle of Attack	β	30^0, 45^0, 60^0
No of VG	n	16

B. Measurement of Experimental Parameters

Wall Temperatures: A digital thermometer connected with K-type thermocouples which were installed at three junctions (on each surface) along the axial length of the test duct, was used to record the duct's surface temperatures. Temperature sensors were installed on the duct surface at equal distance from each other (200mm). These data were then averaged to give the mean wall temperatures of the test duct (TS).

Airflow Temperatures: Steady-state temperatures of the airflow at entrance and exit of the test duct were measured by a K-type probe thermocouple connected to the digital thermometer. The diameter of this long probe thermocouple was only 5 mm which led to a negligible effect on the flow pattern during each measurement. Thermocouples were installed 50mm away from entrance and exit of the test duct, respectively.

Pressure Drop: To determine the axial pressure drop (ΔP) along the test section of the horizontal duct, two static pressure taps of diameter 6 mm were installed at 100mm away from entrance and exit of the test duct, respectively. Digital Differential pressure transmitter was connected to these pressure taps which gives the pressure drop directly in mm of water column.

Air flow rate: To measure the airflow rate U tube differential manometer was installed across the orifice meter in a circular pipe section. A difference in height of water column across the orifice (ho) was recorded using this manometer. A volume flow rate or discharge of air through orifice ($Q_{orifice}$) was then calculated.

C. Specifications of the set up:

Hydraulic diameter of duct = Dh = 75 mm
Inner diameter of blower pipe = (d1) = 0.06 m.
Length of test section = L =0.8m.
Capacity of blower = 0.56h.p.
Diameter of orifice (do) =0.03m.
Range of Dimmerstat = 0 to 2 amp. 0-270V AC.
U-tube manometer = 0 - 460 mm of WC
Calibrated chromel alumel thermocouple (K-type)
Range: - 270^0C to 1372 ^{0}C.
Nichrome wire resistivity = 1.5 x 10-6Ωm

III. DATA REDUCTION

The main aim of the present work was to investigate the heat transfer and flow friction behaviors in a trapezoidal duct with delta wing VGs.

- As the heat is being added uniformly to air, average coefficient of heat transfer was calculated from the measured data by using the following equations:

$$Q_{air} = Q_{conv} = m\, C_p\, (T_o - T_i) \quad (1)$$

Where, To and Ti are the inlet and outlet temp. of air

- Heat flux is calculated as, $q = \frac{Q_{air}}{Surface\ Area}$ (2)

- A sample observation table is shown below to understand the parameters observed.

Table 2: Sample observation table

Sr No.	Temperatures °C					Manometer Diff.	
	T_1	T_2	…	T_{13}	T_{14}	h_o	H_d

Where,
T_2 to T_{13} are the surface temperatures and T_1 and T_{14} are the ambient temperatures of air at inlet and outlet.

h_o and H_d is U-tube manometer difference in mm across the orifice and duct.

- Avg. Surface Temp., $Ts=(T_2+T_3+\ldots\ldots+T_{13})/12$ (3)

- Avg. Temp of air, $Tb=(T_1+T_{14})/2$ (4)

- From table of properties for air the parameters like density, Kinematic viscosity, thermal conductivity (k), specific heat, Prandtl number (Pr) was taken.

Air Flow rate through Orifice-meter

$$Q_{orifice} = Cd \frac{A_0 A_1}{\sqrt{A_0^2 - A_1^2}} \sqrt{2g\left[\frac{\rho_w}{\rho_{air}} - 1\right] h_o} \quad (5)$$

Where, $Q_{orifice}$ = Volume flow rate of air,
A1 = Area of pipe,
A_o = Area of orifice
C_d = Co-efficient of discharge

- Mass flow rate, $\dot{m} = Q_{orifice} \times \rho_a$ (6)
- Velocity of air, $V = Q_{orifice}/A$

Where, A= c/s area

- Heat carried out, $Q = \dot{m}*Cp*(T_{14}-T_1)$ (7)

$$h = \frac{Q}{A\,(T_s - T_b)} \quad (8)$$

Where, h = heat transfer coefficient.

- The Reynolds number which is based on hydraulic diameter of duct is,

$$Re = \frac{VDh}{\upsilon} \quad (9)$$

Where, V= velocity of the fluid
D_h= Hyd. Dia. of Duct
ν = Kinematic viscosity of the fluid.

- The pressure drop across the test duct is given by,

$$\Delta P = \rho \times g \times H_d \quad (10)$$

- The friction factor is calculated from the formula given below:

$$f = \frac{\Delta P}{\frac{L}{D} \times \frac{\rho_a V^2}{2}} \quad (11)$$

Where, L= length of test section and
Δ P= pressure difference across test section.

- The experimental Nusselt number is:

$$Nu = hD_h/k \quad (12)$$

Where, h = heat transfer coefficient
k = thermal conductivity of fluid
D_h = Hydraulic diameter of test section

- Stanton number (St) which is calculated by following equation,

$$St = \frac{h}{\rho \times v \times C_p} \quad (13)$$

- The thermal performance enhancement factor, TEF, defined as the ratio of the heat transfer coefficient of a duct with VG to that of a smooth duct, at an equal pumping power is given by following relation.

$$TEF = \eta = \frac{(Nu/Nu_o)}{(f/f_o)^{1/3}} \quad (14)$$

As per the methodology discussed above the experimental calculations were carried out for the duct with and without VG. [5], [17]

IV. Results & Discussion

A. *Validation of the smooth duct*

The experimental results of heat transfer and friction characteristics of flow in the smooth wall trapezoidal duct were validated in terms of Nusselt no. and friction factor. The Nusselt no. and friction factor which are obtained from the present smooth trapezoidal duct were compared with various correlations i.e. Dittus-Boelter; Blasius and Petukhov equation for turbulent flow in ducts.

- Theoretical Nusselt number was calculated by Dittus-Boelter equation.

$$Nu_o = 0.023 \times (Re)0.8 \times (Pr)0.4 \quad (15)$$

- The friction factor was calculated by Petukhov and Blasius correlation.

$$f_o = (0.79 \ln Re - 1.64)\text{-}2 \quad (16)$$
$$f_o = 0.316Re^{-0.25} \quad (17)$$

A comparison of friction factors obtained from the present work with those from correlations of Blasius and petukhov was done. In the fig. 5, the present smooth duct results are in excellent agreement within 15 % error with the correlation data, especially for *Re* more than 11657 for the friction factor correlation of Petukhov.

A comparison of Nusselt number obtained from the present work with those from correlation of Dittus bolter was done. In the figure 6, the present smooth duct results are in excellent agreement within 08 % error with the correlation data.

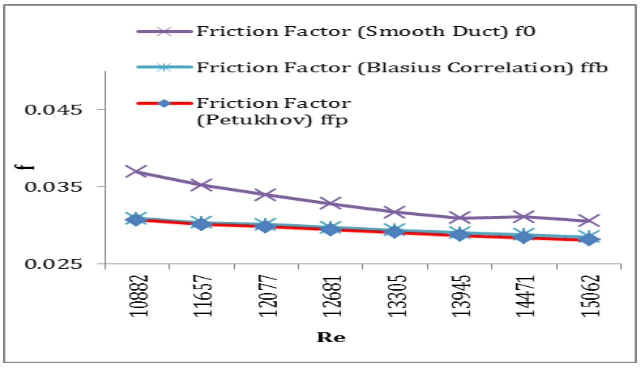

Fig 5: Variation of Experimental and theoretical friction factor for smooth duct

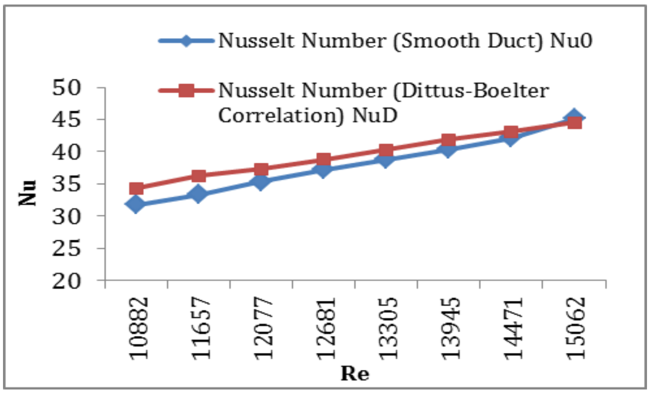

Fig 6: Variation of experimental and theoretical nusselt number for smooth duct

B. *Flow Characteristics*

1) *Effect of Reynold Number on Friction Factor:*

The experimental results were obtained over a range of Re varying from 11657 to 15062 under steady-state conditions. The experimental data were rearranged in a relationship between Nu and Re, as presented graphically in Fig. 7. Experimental results for a similar smooth trapezoidal duct are also plotted on this graph.

It can be seen from above graph that friction factor increases due to addition of vortex generators, however it reduces with the increasing Reynolds number. Highest friction factor of 0.0523 was obtained for the duct with 60^0 VG at Reynolds number 11657 while it was lowest i.e. 0.0349 for 30^0 VG at Reynold number 15062.

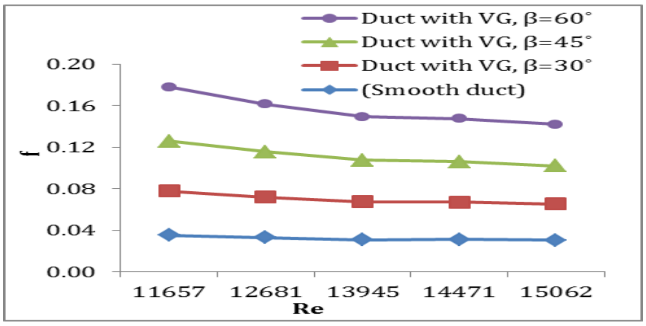

Fig 7: Effect of Reynold number on friction factor

Due to the addition of vortex generators, Percentage increase in friction factor as compared to smooth duct was 14 to 21% for $\beta = 30^0$, 19 to 36% for $\beta = 45^0$, 31 to 49 % for $\beta = 60^0$ over the range of reynolds number considered.

2) *Variation in Friction Factor Ratio with Re:*

A figure below indicates the variation of friction factor ratio with Reynolds number.

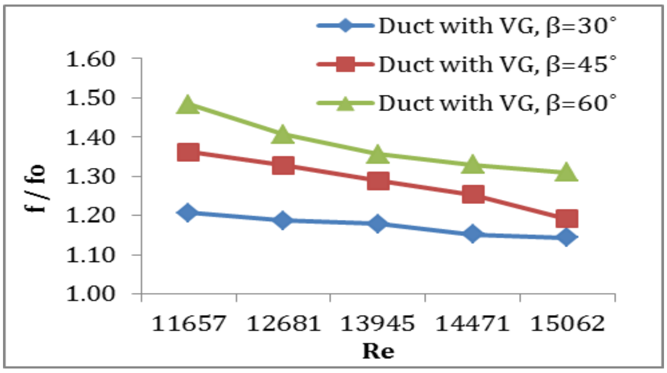

Fig 8: Variation in (f/fo) with Re

It can be seen from the above graph that friction factor ratio decreases with increasing Reynolds number. Thus it was observed that unlike nusselt number, smaller friction factors are obtained for the higher values of reynold number. This is because, from the definition of friction factor, for a certain pipe or duct, a higher Reynolds number usually means a higher flow velocity, square of which is in inverse ratio with friction factor.

3) *Variation of friction factor ratio with (e/Dh):*

A figure below indicates the variation in friction factor ratio with the ratio of height of VG from duct surface to the hydraulic diameter.

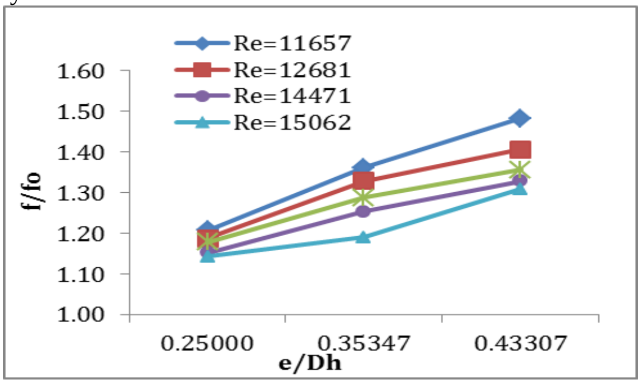

Fig 9: Variation of (f/fo) with (e/Dh)

In the present study hydraulic diameter of duct was kept constant. It can be seen from the graph that, friction factor ratio increases with the increasing value of e/Dh. The angle of attack of the vortex generators in the flow is directly proportional to the vortex generator height. The increased angle of attack at higher e/Dh increases the strength and core size of the vortex. And also the friction factor ratio increases with increase in e/Dh value, which is due to increased projection area of the delta wings normal to the incoming flow increases so that the blockage or obstruction to the flow. As the angle of attack increases, the intensities of the longitudinal vortices also increases and their disturbances on flow are also stronger. As a result, the pressure drop increases with increasing angle of attack.

C. *Heat Transfer Characteristics:*

1) *Effect of Reynolds Number on Nusselt Number:*

It can be observed from the below graph that for all the cases, nusselt number increase with the increase in Reynolds number. For the smooth duct, this is due to more mass flow rate of air available to carry the generated heat.

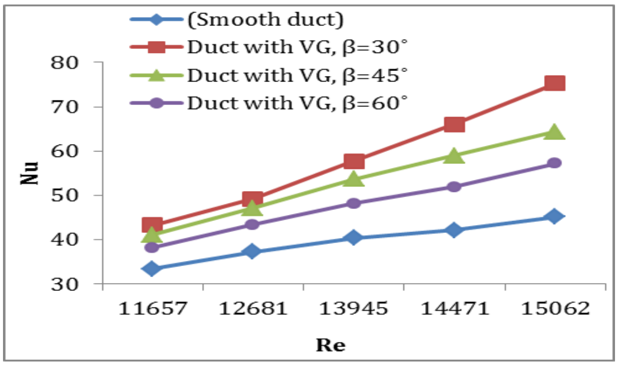

Fig 10: Variation of Re Vs Nu

When the results of nusselt number for smooth duct & duct with VG were compared for the fixed value of Reynolds number, heat transfer rate was observed to be increasing for the duct with VG. This is a clear indication of influence of vortices produced by delta wing on the heat transfer rate. Maximum enhancement in heat transfer was obtained for $\beta=30^0$ for which nusselt number was 75 while the attack angle $\beta=60^0$ are showing the minimum enhancement when compared with all the cases i.e. with and without duct. Heat transfer rate was enhanced by around 29 to 67% for $\beta=30^0$, 23 to 43% for $\beta=45^0$, 14 to 27% for $\beta=60^0$ when compared with smooth duct over the range of Reynolds number.

2) Effect of Reynolds Number on Nusselt Number ratio:

The figure below shows the variation of the ratio of experimental nusselt number for duct with VG to that of smooth duct with Reynolds number. For Re = 11657, experimental Nusselt number observed was 1.296, 1.23, 1.142 times more than that of smooth duct for $\beta = 30^0, 45^0, 60^0$ respectively. For Re = 15062, the same values observed were 1.668, 1.426, 1.268 respectively.

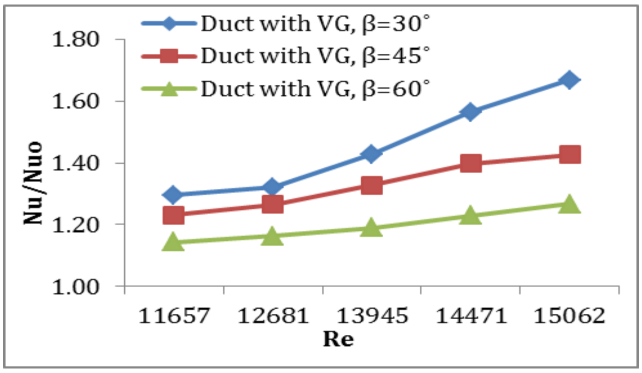

Fig 11: Effect of Re on Nusselt Number ratio

Thus it is clear from above graph that for the specific value reynold number i.e. for same mass flow rate; heat transfer is enhanced when compared with the result of the smooth duct. This clearly indicates the influence of presence of VG on the heat transfer enhancement.

3) Variation in Ratio of Experimental & Theoretical Nusselt Number:

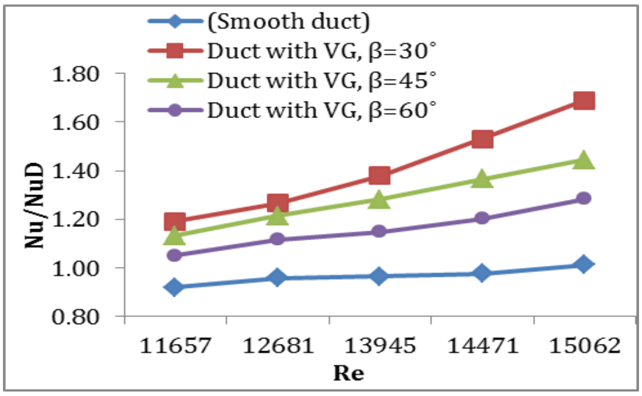

Fig 12: Variaion in Ratio of Experimental & Theoretical Nusselt Number

Above graph shows the Variation in Ratio of Experimental to theoretical Nusselt Number with the Reynolds number. It is clear from above graph that the experimental values of nusselt number obtained for smooth duct were less than expected theoretical results. But the addition of VG improves the experimental nusselt number values for the same mass flow rate or Reynolds number. Due to influence of VG heat transfer rates were significantly observed to be more than the expected theoretical result. Values of experimental nusselt numbers obtained for Re = 15062 were 1.284, 1.445, 1.69 times more than theoretical Value of Nu obtained from Dittus Bolter Equation.

4) Variation in Stanton number with Reynolds number:

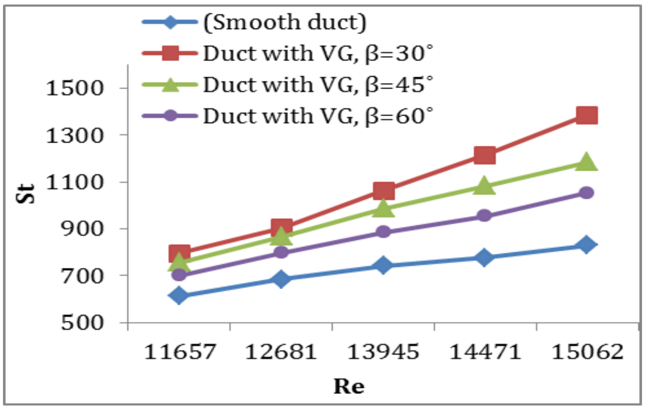

Fig 13: Variation in Stanton number with Re

Above graph shows the variation in Stanton number with Reynolds number. It was observed from above graph that the Stanton number increases with the Reynolds number value. It is obvious for smooth duct that due to increasing mass flow rate, more heat is carried away by the air which leads to higher values of the Stanton number. But for the same values of mass flow rates, Stanton numbers observed for duct with VG are more than that of smooth duct. This clearly shows the influence of presence of delta wings on the heat transfer rate.

5) Effect of Re on Thermal Performance Enhancement factor:

From the above discussion, it is clear that heat transfer rate increases with the increasing Reynolds number as well as due to addition of vortex generators. This enhancement in heat transfer is always associated with corresponding increase in friction factor due to more blockage and restriction to flow. This in turn increases the pumping power requirement of the system. TEF correlates the improvement in the heat transfer with the increased friction factor presents the value which clearly indicates the thermal performance of the system.

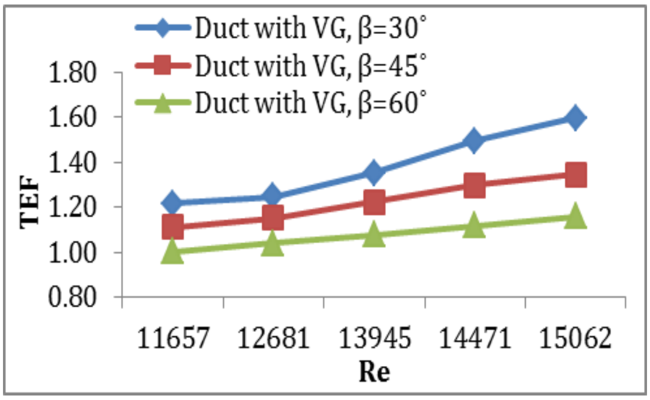

Fig 14: Variation in TEF with Re.

The above graph shows the efficiency of heat transfer i.e. thermal performance enhancement factor to the Reynolds number. It was observed from the graph that, the duct with $\beta = 30^0$ presents the highest TEF of about 1.217 to 1.595 over the range of reynold number studied. For $\beta = 60^0$, TEF is 1.002 to 1.158 while it is 1.11 to 1.345 for $\beta = 45^0$. Thus it is clear that the configuration of vortex generator with $\beta = 30^0$ gives best thermal performance i.e. maximum increment in heat transfer with minimum rise in friction factor.

V. CONCLUSION

In the current work, an experimental study has been performed to obtain pressure loss or friction factor and heat transfer rate for an air flow in trapezoidal duct. The vortices are produced by the insertion of delta wing vortex generators with three different angles of attack. From the experimental results, it can be concluded that

1) For the flow of air in the trapezoidal duct, the friction factor ratio decreases with the increase in Reynolds number. The friction factor ratio is increased with increase in ratio of VG height to duct hydraulic diameter (e/Dh).

2) In the present work, at e/Dh=0.4331, reported are the higher friction factors for all the reynolds number considered, that is 23% higher at Re = 11657 and 15% higher at Re = 15062 compared to e/Dh=0.25.

3) For all the cases, the nusselt number increase with the increase in Reynolds number. The ratio of nusselt for duct with VG to that of smooth duct increases with the increasing Reynolds number. For $\beta=30^0$, higher values of Nu/Nuo were reported i.e. 1.668 and 1.296 over the range of *Re.*

4) When the comparison of experimental and theoretical results was made, the ratio Nu/NuD was observed to be higher for β=30*0*. It was 1.19 and 1.69 over the range of reynold number considered.

5) The Stanton number (St) reported during the experimentation was 1384 and 796 for $\beta = 30^0$ for the range of reynold number considered.

6) Thermal performance enhancement factor (TEF) was reported to be 1.217 and 1.595 for $\beta = 30^0$. Among all configurations, vortex generator with attack angle 30^0 gave best results.

VI. SCOPE FOR THE FUTURE WORK

There is very little work available on the flow and heat transfer characteristics of air flow through trapezoidal duct using vortex generators. Based on the literature survey discussed above, the following scope of work was identified from current work.

1) Using the configuration of the setup used in current work, CFD analysis of trapezoidal duct can be carried out to study flow & heat transfer characteristics using delta wing VGs.
2) The above said CFD analysis and experimentation can also be carried out using other types of vortex generators like rectangular or delta winglet, rectangular wing type or dimples etc.
3) Experimental investigation and CFD analysis of trapezoidal duct to study flow & heat transfer characteristics using VGs with punched holes can be considered.
4) Use of Trapezoidal ducts with vortex generators placed on two opposite walls for improved performance can also be considered.
5) Evaluating the heat transfer and flow characteristics through the different geometries of ducts having different types of vortex generator may be carried out.

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