Heat Transfer Augmentation in Solar Air Heater using Trapezoidal Winglets

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Abstract. In this paper we will investigate about the thermal effectiveness of a solar air heater which consists of trapezoidal type vortex generators by experimentation and validating with numerical simulation. The trapezoidal type vortex generator is placed inside the duct having a test section of 400*300*30mm. Trapezoidal vortex generators are placed in 3 different arrangements inside the duct, and having an array of 5 winglets in each row. The vortex generator is categorized as a winglet and the height of the winglet is half the height of the air duct. The analysis of trapezoidal winglet is done for wide range of Reynolds Number ranging from 3500 to 25000. Thermal performance factor is calculated by Webb’s correlation factor equation for roughness of surface, which considers Nusselt Number and friction Factor as a parameter for thermal effectiveness. Numerical simulation was carried out using Ansys Fluent Software. Comparison of experimental and numerical results was done. Experimental and Numerical results showed that an increase in heat transfer rate of upto 65% was obtained when compared to smooth channel duct.

1. INTRODUCTION

The rate of heat transfer between the absorber plate and air is poor because of low thermal conductivity of air. The heat transfer rate can be improved by creating disturbance to the flow of air inside the duct. This disturbance creates turbulence in the air flow and hence heat transfer rate can be improved. The method for turbulence generation is categorized into two types- active and passive. In passive method, Turbulence can be generated by using insert device such as fins, winglets, baffles, wings and ribs. These insert device when placed in the flow path they disturb the flow and produces secondary flow as longitudinal vortices which will disrupt the thermal boundary layer formed along the wall. In this way the rate of heat transfer is increased by creating vortices. Introducing vortex generators would eventually increase the power required to maintain the flow because of drop in the pressure across the duct channel. This would also result in increased friction factor. Hence, vortex generators has to be placed in optimal position in order to obtain maximum effectiveness.

2. LITERATURE REVIEW

Comparing different vortex generator winglets and wings, winglets has been proved to have the highest thermal performance and thus it is widely used in channel ducts and heat exchangers. Different
geometry of winglets and wings has been adopted. Some of them are rectangular, delta, elliptical, curved and complex geometry shapes.

Tiggerbeck et al [1] compared different wings and winglets and found that winglets performed better than wings. His experiment was conducted in low Reynolds Number up to 9000.

Biswas et al [2] has studied the performance of delta winglet and wing in a duct having rectangular channel. His study concluded that the delta winglet performed better than delta wing, when overall performance was taken into consideration. Feibig et al [3] did experiments on different types of vortex generators. Both experimental and numerical simulations where studied in different flow regions such as laminar to transitional to turbulent. He compared longitudinal and transverse vortices and found that longitudinal vortices has higher heat transfer rate than transverse vortices and the maximum heat transfer rate was found in low Reynolds Number i.e., near laminar transitional region.

Hitesh et al [4] did analysis on heat transfer enhancement in solar air heater with punched hole delta winglets and found that the heat transfer rate increased by adopting delta winglets and this increased with increase in the number of rows. There was a slight decrease in the pressure drop by punching a hole on the winglet.

Gulshan et al [5] performed experiments on various types of vortex generator and found that it would increase the rate of heat transfer in solar air heater. Ferrouillat et al [6] designed a multifunctional heat exchanger which intensifies the rate of heat transfer and potential advantages such as better reaction control, improved selectivity etc. Skullong et al [7] did experiment on solar air heater having delta winglet type vortex generator with varying angle of attacks in the Reynolds number region ranging from 5000 to 24000 with constant heat flux. Yadav et al [8] performed Computational Fluid Dynamics analysis in Ansys Fluent and found that K-epsilon equation yields the best equation for a two dimensional fluid flow inside a solar air heater. Zhou et al [9] performed experiments on curved trapezoidal winglet instead of conventional shape of winglet and found that the winglet performed best in laminar and transitional region of flow. Kamboj et al [10] performed Computational Fluid Dynamics analysis on plain and curved type vortex generators having holes punched on it.

3. EXPERIMENTAL SETUP

The complete experimental setup is shown in the figure 3.1, the apparatus consists of a rectangular duct which is made of aluminium having thickness 1.2 mm. The length, breadth and thickness are 600*300*30mm respectively. A blower was used to maintain the flow across the duct and the speed was varied accordingly to attain required Reynolds Number. The entry section of the duct had a diverging section in order to maintain a uniform flow. Flat plate heater having a power rating of 250 Watts was fixed at the top of the duct which produces uniform heat flux. The flat plate heater along with glass wool insulation was securely placed on top of the duct using a stainless steel plate. Trapezoidal winglets were made using GI Sheet having a height of 15mm on the larger side 7.5mm on the smaller side. Trapezoidal winglets were soldered to a test plate and was placed inside the duct. Air is passed through the duct using variable speed blower. The temperatures at the top surface and at the outlet are measured using K-Type thermocouples. Pressure is measured at the entry and exit using pressure sensor and pressure drop is calculated. The performance parameters considered are Friction Factor and Nussult Number.
Different relations between the parameters are shown below:

Heat Transfer Coefficient

\[ h = \frac{Q}{T_s - T_b} \]  

(1)

Where, \( Q \) is the Heat flux applied in W/m\(^2\)
\( T_s \) is the Average surface Temperature = \( \sum T_i \)

Where, ‘i’ is the temperature at different locations on the absorber plate
\( T_b \) is the bulk mean temperature

\[ T_b = \frac{T_i + T_o}{2} \]  

(2)

Where, \( T_i \) is the temperature at inlet and \( T_o \) is the temperature at exit

Nusselt Number is obtained using equation,

\[ Nu = \frac{hd}{k} \]  

(3)

Where ‘h’ is convective heat transfer coefficient, ‘d’ is hydraulic diameter of the Rectangular duct, ‘k’ is thermal conductivity of the Air

Thermal performance factor is calculated using the equation below

\[ \eta = \left( \frac{Nu}{Nu_0} \right) * \left( \frac{f}{f_0} \right)^{-\frac{1}{3}} \]  

(4)

Nusselt Number and Reynolds Number were obtained by measuring the average temperature of the absorber plate surface and at the outlet.

4. NUMERICAL SIMULATION

Simulation was done using Ansys Fluent v17.1. Three dimensional continuity, momentum and energy equations were used. The flow was assumed to be steady and incompressible, keeping the properties of air constant. Automatic meshing using tetrahedral mesh was done. Automatic meshing method was adopted because it is easier and would yield good results for simple geometry. K-epsilon model was used as it yields the best result for a two dimensional fluid flow inside a solar air heater. The boundary conditions are: velocity inlet, pressure outlet & three adiabatic walls and top wall having a heat flux of 1000 Watt/m\(^2\). The convergence criteria of 10\(^{-4}\) was adopted in order to obtain convergence.

The figure 4.1 shows the mesh generation for the rectangular duct having three rows trapezoidal winglet. The pressure and top surface temperature contours is shown in the figure 4.2 and figure 4.3.
4. RESULTS

The experiment was done with different number of rows of winglets and is compared with smooth channel flow. The experimental results which are obtained is compared with numerical results and validated. The graphs 5.1, 5.2, 5.3 & 5.4 show the variation of Nusselt Number with Reynolds Number for a smooth channel, one row, two row and three row trapezoidal winglets. The graph represents both simulation and experimental results. For a three row trapezoidal winglet there is 10% to 13% of deviation in experimental value with numerical value followed by 8% to 14% of deviation.
for two row trapezoidal winglet and 10% to 16% for single row trapezoidal winglet. As the Reynolds Number increases there is increase in Nussult Number for all the cases. Hence, we can say that as the number of rows of winglets increases the rate of heat transfer increases.

Figure 5.1 Three row trapezoidal winglets

Figure 5.2 Two row trapezoidal winglet

Figure 5.3 One Row Trapezoidal Winglet
Figure 5.4 Smooth Channel Duct

Figure 5.5 Comparison of Different Number of Rows of Winglets with Smooth Channel

Figure 5.6 Friction Factor for Various Arrangements

Figure 5.5 represents the Nussult Number for various rows of winglets, the rate of heat transfer is maximum for the 3 row trapezoidal winglet and minimum for one row trapezoidal winglet.

The figure 5.6 shows the friction factor for different rows of winglets with increase in Reynolds Number. The friction factor is maximum for 3 row trapezoidal winglet and it is maximum for all the arrangements at lower Reynolds Number.
Figure 5.7 shows the thermal performance factor of different arrangements of trapezoidal winglet. The maximum value thermal performance factor is 1.24 and this maximum exists in the region of low Reynolds Number. The maximum thermal performance factor is found in one row trapezoidal winglet. Despite of having least Nusselt Number the thermal performance of one row trapezoidal winglet is highest because of the reduction in friction factor. The maximum thermal performance factor for three row trapezoidal winglet is 1.15.

4. CONCLUSIONS

The following conclusions are drawn:
1. Use of trapezoidal shaped winglets increases rate of heat transfer by 100 % and pressure drop is increased by 550%.
2. Nusselt number increases with the increasing Reynolds Number in all the regions of flow
3. Increasing the number of rows of the trapezoidal winglets increases the rate of heat transfer along with the increase in the pressure drop.
4. Rows of winglet pairs arranged in staggered manner produce higher friction factor making its performance poor.
5. Thermal performance factor of about 1.24 can be achieved by using trapezoidal winglets.
6. Thermal performance factor is highest in lower Reynolds number region for all the arrangements.

5. REFERENCES

[1] Tiggelbeck S, Mitra N K and Fiebig M, 1994, “Comparison of Wing type Vortex Generators for Heat Transfer Enhancement in Channel Flows,” Transactions of the ASME, Vol. 116, pp. 880-885

[2] Biswas G, Deb P. and Biswas S, 1994, “Generation of Longitudinal Streamwise Vortices: A Device for Improving Heat Exchanger Design,” Journal of Heat Transfer, Vol. 116, pp. 588- 597.

[3] Fiebig, M., 1998, “Vortices, Generators, and Heat Transfer,” Transactions of Institute of Chemical Engineers, Part-A, Vol. 76, pp. 108-123.

[4] Hitesh U. Warrier and Vinod Kotebavi “Numerical Study of Heat Transfer Enhancement in Solar Air Heater Duct Fitted with Delta Winglets” Indian Journal of Science and Technology, Vol 9(48), DOI: 10.17485/ijst/2016/v9i48/108430, December 2016
[5] Gulshan S, Kasana KS. Thesis on computation of heat transfer augmentation in a plate-fin heat exchanger using rectangular / delta wing.

[6] Ferrouillat S, Tochon P, Garnier C, Peerhossaini H. “Intensification of heat transfer and mixing in multifunctional heat exchangers by artificially generated stream wise vorticity” Applied Thermal Engineering. 2006; 26(16)

[7] Skullong S, Promvonge P. “Experimental investigation on turbulent convection in solar air heater channel fitted with delta winglet vortex generator”, Fluid Dynamics and Transport Phenomena Chinese Journal of Chemical Engineering. 2014; 22(1):1–10. DOI: 10.1016/S1004-9541(14)60030-6

[8] Yadav AS, Bhagoria JL “Heat transfer and fluid flow analysis of solar air heater: A review of CFD approach”. Renewable & Sustainable Energy Reviews. 2013; 23:60–79

[9] Zhou GB, Ye QL. “Experimental investigations of thermal and flow characteristics of curved trapezoidal-winglet type vortex generators”. Applied Thermal Engineering. 2012; 37:241–8

[10] Kamboj R, Dhingra S “CFD simulation of heat transfer enhancement by plain and curved winglet type vortex generators with punched holes”. International Journal of Engineering Research and General Science. 2014 Jun–Jul; 2(4)

[11] Hithesh.U.Warrier and Vinod.M.Kotebavi “Heat Transfer Enhancement in Solar Air Heater Duct Fitted With Punched Hole Delta Winglets” IOP Conf. Series: Materials Science and Engineering 149 (2016) 012225.