Heat Transfer Enhancement in Solar Air Heater Duct Fitted With Punched Hole Delta Winglets

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Abstract. This paper investigates the thermal performance of solar air heater fitted with delta winglet type vortex generators with holes punched on it by experimental and numerical analysis. Delta winglet type vortex generators having holes punched onto it are fitted in a duct of size 400*300*30mm. It is placed in duct in 3 different configurations, as an array having 5 pair in one row. Delta winglet pair has an attack angle of 30degree, with height of winglet equal to half of duct height. The study is done for Reynolds’s no in the range of 9000 to 25000. Thermal performance is evaluated by analyzing both friction factor and Nusselt’s number using Webb’s correlation for surface roughness. Numerical simulation is done using Ansys fluent. Experimental and numerical results are then compared. Results shows that heat transfer enhancement of about 20-150% can be achieved by using punched hole delta winglet.

1. Introduction
Thermal efficiency of conventional solar air heater depends up on its ability to convect heat between surface of absorber plate and air. This is considered to be very low due to its high thermal resistance or low heat transfer capability between absorber plate and flowing air. Hence increasing heat transfer coefficient can increase the thermal performance of air heater. Convective heat transfer between surface and air can be improved by promoting turbulence in the flow, or by creating artificial roughness in the surface. There are several methods to increase convective heat transfer rate from surfaces. Bergles et al [1] identified about 14 enhancement techniques used for the heat exchangers. These enhancement techniques can be classified into active and passive techniques. These methods are divided into two types. Active and passive methods. Former method uses external supply of energy to bring disturbance in flow, while latter one uses any insert devices to disturb flow. Insert devices are solid devices with certain shapes and geometry which can be inserted or mounted into the flow channel. Ribs, fins, baffles winglets are example of insert devices, which are generally used in channel heat exchangers. Insert device disturb flow by generating vortices hence these devices are called as vortex generator. If these vortex generators are inserted into the flow, it produces secondary flow in the form of longitudinal vortices[2,3], which will interrupt or disconnect the thermal boundary layer which is developed along the wall. Also this will transfer the heat from the wall to the core of the flow by means of large-scale turbulence. Use of vortex generators in channel heat exchangers increase heat transfer along with increase in pressure drop which in turn increase pumping power. Pressure drop can be reduced by punching holes in vortex generators at appropriate positions[8].
Among various types of vortex generators wings and winglets have been widely investigated to improve thermal performance in various heat exchangers and channel ducts. Biswas et al [2] did a numerical study of heat transfer and flow characteristics in a rectangular channel duct fitted with delta wing and winglet. They compared performance of wings and winglets and their study concluded that performance with delta wing was better than winglets in terms of heat transfer. Overall performance was better for delta winglet compared to delta wing, when pressure drop is taken into account. Tiggelbeck et al [4] did performance comparison of various types of wings and winglets for enhancement in heat transfer in heat exchanger channels. Experiments were conducted for Reynolds number in the range of 2000-9000, and angle of attack \( \theta \) ranging from 30° to 90°. From the results it was concluded that winglets performs better than wings.

These investigations show advantage of using delta winglets in improving heat transfer. Heat transfer enhancement using vortex generator is brought by 3 mechanisms, developing boundary layers, flow destabilization and by swirl or vortices. Performance of vortex generators varies with change in turbulence conditions and type of vortices it creates. Feibig et al [5] studied the effect on heat transfer enhancement using various types of vortex generators. Numerical and experimental study was carried out to learn the heat transfer in laminar, transition and turbulent boundary layers, for both longitudinal and transverse vortices. It was found that heat transfer is more by longitudinal vortices compared to transverse vortices and heat transfer enhancement is higher in laminar region than turbulent. These studies also show that the pressure drop increases with the heat transfer enhancement. Chen et al [6] found out that, the reason for the pressure drop is due to dominance of form drag of longitudinal Vortex generator.

This paper attempts to study fluid friction and heat transfer characteristics in solar air heater duct fitted with Delta winglet having punched holes, by CFD simulations and experimentation. Delta winglet pairs having holes punched, at attack angle of 30° and height equal to half duct height, thickness 3 mm, are placed in duct of dimension 400×300×30mm. The different arrangements used are as follows.

1. Single row of 5 pairs of delta winglet placed at entry of duct (figure 1.1 a)
2. Two row of 5 pairs of delta winglet placed starting at entry of duct with a pitch equal to twice duct height (figure 1.1 b)
3. Three rows of 5 pairs of delta winglet placed starting at entry of duct with a pitch equal to twice the duct height (figure 1.1 c).

Experimental analysis is done for Reynolds’s No range of 9000-21000. This is done to compare performance of winglet with and without punched holes. Thermal performance is found by finding out Nussult’s number and friction factor. Webb et al [12] correlation for surface roughness is used to determine thermal performance.

![Figure 1.1. Arrangement of winglet with and without punched holes inside duct for second case](image)

2. Numerical Simulation

2.1. Physical Model

The Computational Fluid Dynamics Analysis were done using FLUENT 14.5 Software that uses the finite-volume method to solve the governing equations. Geometry creation and meshing was done using Gambit. Meshing considered was tetrahedral mesh. Unstructured mesh was used so that meshes near VG’s are highly concentrated. Simulation was done for Reynolds’s number ranging from 5000-
Figure 2.1 shows grid generated for duct having 2 rows of winglets. Table 2.1 shows mesh details.

![Image](image_url)

**Figure 2.1.** Mesh generated for duct with 2 rows of winglets

| Arrangement | No of elements |
|-------------|----------------|
| 1 Row       | 548139         |
| 2 Rows      | 452951         |
| 3 Rows      | 761509         |

**Table 2.1.** Mesh details

### 2.2. Numerical Method

Three dimensional continuity, momentum and energy equations in the fluid region is followed here. Flow is assumed to be steady, incompressible for constant properties of air. Velocity and pressure linkage was solved by simple algorithm. Grid independent test has been performed for the physical model for validating the accuracy of numerical solutions. Unstructured mesh is used so that areas near wall and VGs are highly concentrated.

K-Epsilon turbulence model was used, with convergence criteria for energy as $10^{-6}$ for momentum, and mass conservation as $10^{-3}$ is used for calculated parameters. Boundary conditions were selected as velocity inlet for inlet, and pressure outlet for out flow, wall for 3 walls of duct and top wall of the duct, where uniform heat flux of 1000 watts/m² is given. Material for wall is selected as aluminum with thickness of 1.2 mm. The air inlet temperature was given as 300 K and three assumptions made here are 1) the uniform heat flux was along the length of rectangular channel 2) Wall of the channel will be perfectly insulated 3) Steady and incompressible flow.

### 3. Experimental analysis

Experimental set up is designed as shown in figure (3.1). Rectangular duct of size 600*300*30 is made using aluminum sheet of 1.2 mm thickness of which 200 mm is entry length, 400 mm test section and remaining 50 mm exit section. Variable speed blower is used to blow air at varying speed. It is connected to duct using pipe and divergent section.

![Image](image_url)

**Figure 3.1.** Sketch of experimental Setup
Flat plate heater of test section size is made using heating coils, which is fixed inside mica sheet. Which is fixed in stainless steel sheet which act as holder. Heater is fixed on to top surface of the duct using screws.

Winglets are made using GI sheets of .3mm thickness, with a span length of 60mm and height of 15mm. Holes are punched in the winglet at position h/h’=1/2, and h/h’ = 1/3, along length wise and height wise respectively (figure 3.2). Winglets are fixed into a movable plate by means of slots on plate which was soldered. Whole set up is insulated by glass wool.

\[
\text{Figure 3.2. Position of hole in winglet}
\]

Different parameters considered here are -friction factor, Nusselt number to determine heat transfer rate, friction factor is found out by determining pressure drop.

Different relations used are

Heat Transfer Coefficient, \( h = \frac{Q}{T_s - T_b} \) \hspace{1cm} \text{3.1}

Where, \( Q \) = Heat flux in W/m²

\( T_s \) = Average surface Temperature

\( = \sum T_i \)

Where, \( i \) stands for temperature at different positions

\( T_b = \frac{T_i + T_o}{2} \) \hspace{1cm} \text{3.2}

Where, \( T_i \) = Inlet Temperature and \( T_o \) = Exit Temperature

Nusselt’s number is obtained using equation

\( \text{Nu} = \frac{hd}{k} \) \hspace{1cm} \text{3.3}

Where \( h \) is convective heat transfer coefficient

\( d \) is hydraulic diameter,

\( k \) is thermal conductivity.

The Nusselt number and the Reynolds number were based on the average temperature of absorber plate surface and outlet temperature. The air flow velocity and drop in pressure across the test section, were measured for heat transfer of the heated wall with different arrangements of winglets. The average Nusselt’s numbers and friction factors were obtained. All properties of fluid is taken at bulk mean temperature

Thermal performance factor is given by

\[
\eta = \left( \frac{\text{Nu}}{\text{Nu}_0} \right) \times \left( \frac{f}{f_0} \right)^{-\frac{1}{3}}
\]

Where \( \text{Nu}_0, f_0 \) denotes Nusselt’s number and friction factor for flow without using winglet.

4. Results and Discussion

For five pairs of delta winglet placed at entry, results were compared with experimental data. It showed variation of 3-5% for Nusselt’s Number and 5-7% for friction factor (figure 4.1 a and 4.1b)
Comparison of various arrangements are done by plotting Reynolds number vs. Nussult’s number. Increasing Reynolds’s number increases heat transfer. Heat transfer rate is increased by 42-110% in low Reynolds’s number region, 10-45% in high Reynolds’s no region by placing winglets in above mentioned arrangement. This shows greater enhancement is achieved in low Reynolds’s no region. Heat transfer rate is more for 3 rows of winglets placed. It increases with increase in number of rows. (Figure 4.2)

Figure 4.3 shows variation of Nussult’s Number with Reynolds’s number, for experimental analysis. Nussult’s Number increases with increasing Reynolds’s number. It also increases with increasing Number of rows. Higher heat transfer rate is obtained for duct with 3 rows of winglets, then for 2 rows, 1 row respectively, implying, heat transfer rate increases as no of rows increases.

Figure 4.2. Variation of Nussult’s number with Reynolds’s number for numerical value.
Figure 4.3: Variation of Nusselt’s number with Reynolds’s number for experimental values

Figure 4.4 shows comparison of experimental result with simulation results. There is a variation of 10-15%. This variation is due to losses like heat loss and leakage losses.

Reynold’s number vs. friction factor is plotted in figure 4.5. Friction factor increase with increase in number of rows of winglets, as more the obstruction to flow more will be friction, hence arrangement with 3 rows of winglet have higher friction factor.

Figure 4.4 Graph Comparing Numerical and experimental Results

Figure 4.5. Graph showing variation of friction factor with Reynolds’s number
Friction factor increases by 130-380% in low Reynolds’s number and by 172-500% in high Reynolds’s number region. Increase in friction factor is more in high Reynolds’s number region.

Duct fitted with 3 rows of winglets has higher thermal performance. Performance increases as number of rows of winglets placed increase. High performance in all cases is obtained at low Reynolds’s Number region. Thermal enhancement factor of about up to 1.4 can be achieved by using delta winglets with punched holes.

**Figure 4.6.** Thermal enhancement factor v/s Reynold’s number for numerical values.

**Figure 4.7.** Pressure distribution across winglets in duct fitted with a) single row of delta winglet at 25000 Reynolds’s number. b) two rows of delta winglet at 25000 Reynolds’s number c) three rows of delta winglet at 25000 Reynolds’s number.
5. Conclusions

Following conclusion are drawn from the results.

1. Use of delta winglets in duct, increases heat transfer rate with increase in pressure drop. There is increase of 20-150% in heat transfer and 40-400% in friction factor.
2. Nusselt’s number increases with increase in Reynolds’s number.
3. Heat transfer enhancement is more in low Reynolds’s number region.
4. Increase in number of rows of winglets increases heat transfer rate with increases in pressure drop.
5. Thermal enhancement factor of about upto 1.4 can be achieved by using delta winglets with punched holes.

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