Numerical Study of Heat Transfer Enhancement in Solar Air Heater Duct Fitted with Delta Winglets

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Abstract

The paper brings Numerical study of thermal performance of solar air heater channel in which delta winglet type vortex generators with and without holes punched on it are attached. Delta winglet type vortex generators having holes punched onto it are fitted in an array having 5 pair in one row, having 3 such rows starting at the entry of test section. With pitch of 60mm. Delta winglet pair have an attack angle of 30 degrees, with height of winglet equal to half of duct height. The study is carried out for Reynolds’s No in the range of 5000 to 25000 by changing airflow rate in the test section with its upper channel wall provided with a uniform heat flux. Results are then compared with that of duct mounted with delta winglet without holes. Thermal performance is evaluated by analyzing both friction factor and Nussult’s number using R L Webb’s correlation for surfaces with roughness. Numerical simulation is done using Ansys fluent software. Analysis findings says that use of winglets brings enhancement in the heat transfer and thus increases the thermal performance. Arrangement of winglets also influences the performance. Improvements in design and performance can be brought by using winglets with different attack angles and span length.

Keywords: Delta Winglet, Longitudinal Vortices, Thermal Enhancement Factor, Vortex Generator

1. Introduction

Performance of conventional solar air heater depends up on its ability to convert heat between surface of absorber plate and air. Hence increasing heat transfer coefficient can increase the thermal performance of air heater. Convective heat transfer b/w surface and air can be augmented by promoting turbulence in the flow, or by creating artificial roughness in the surface. There are various methods to raise convective heat transfer rate from heat transfer surfaces. These methods are divided into 2 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 disturb flow by generating vortices hence these devices are called as vortex generator. These VGs when inserted into flow, induces secondary flow, notably longitudinal vortices (LVs), that may break off the thermal boundary layer formed along the wall and eliminate the heat from the wall to the core of the flow with the aid of large-scale turbulence. VGs in channel heat exchangers inflate heat transfer along with rise in pressure drop which in turn increase pumping power. Pressure drop can be reduced by punching holes in VGs at appropriate positions, as holes form a bypass for airflow.

Among various types of VGs wings and winglets have been widely investigated to improve thermal performance in various heat exchangers and channel ducts. Wings and winglets comes in various shapes, which include rectangular, trapezoidal, delta(triangular). In did numerical and experimental study to determines the Architecture of flow, in high level detail, at trailing side of a winglet type vortex generator attached in a fully developed laminar channel flow. Their study says that flow architecture...
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is complicated. It is composed of a main vortex, a corner vortex and induced vortices.

The aim of investigation was to learn about how a delta winglet type vortex generator perform in enhancing heat transfer. In\(^2\) was did a numerical study on flow attributes and heat transfer in a rectangular channel duct attached with delta wing and winglet. He compared performance of wings and winglets. Their study concluded that delta wing performed better than winglets in terms of heat transfer. Overall performance is better for delta winglet compared to delta wing, when pressure drop is taken into account. In\(^5\) did a comparison performance of various types of wings and winglets for improvement in heat transfer in channel heat exchangers. Experiment is conducted for Reynolds number in the range of 2000-9000, also for various attack angles ranging from 30-90. Results shows that winglets perform better than wings.

These investigations show advantage of using delta winglets in improving heat transfer. Augmentation of heat transfer by vortex generator is brought by 3 mechanisms, developing boundary layers, flow destabilization and by swirl or vortices. Performance of VGs varies with change in turbulence conditions and type of vortices it creates. In\(^6\) did a study of effect of vortices from various vortex generators on heat transfer augmentation. 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 heat transfer is more by longitudinal vortices compared to transverse vortices and heat transfer augmentation is higher in laminar zone than in turbulent.

These studies also show that there will be pressure drop along with the heat transfer enhancement. In\(^2\) study says that form drag of the Longitudinal Vortex generator is dominant for the dip in pressure, and the Longitudinal Vortices the many added dip in pressure of the flow. As to the other portion i.e., the drag which is generated due to the friction between the LVs and wall surface, In\(^2\) founded that the transverse enlargement of LV holds an important part of the reason. After detachment of flow which occurs at VG’s edge, a low-velocity recirculation region exists at the back of the LVG, which deplete the kinetic energy. This is the major point of origin of the form drag which inflate with the increase in angle of attack opposed to the flow. So the measures to reduce the low-velocity recirculation region holds the key to reduce the form drag and then the overall dip in pressure created by the LVG.

Computational Fluid Dynamics (CFD) is tool which solves problems involving flow of fluid and heat transfer to the fluid. In\(^8\) studied how CFD can be applied in designing of solar air heater. Investigation was done to choose most suitable turbulence model for designing of solar air heater by using ANSYS FLUENT v12.1 2-D Flow was simulated for 5 different turbulence models (STD \(k-\epsilon\), RNG \(k-\epsilon\), realizalbe \(k-\epsilon\), std \(k-W\), SST \(K-W\)). RNG-\(k-\epsilon\) yielded best results. In\(^10\) carried out 3-D CFD simulations out to learn about how plane and curved rectangular winglet type Vortex Generators (VGs) performs. Effects of shape of the VGs on heat transfer improvement were analysed with the help of dimensionless numbers - \(j/j_0\), \(f/f_0\) and \(h = (j/j_0)/(f/f_0)\). Curved winglet type VGs was found to have comparatively higher heat transfer enhancement than that of plain winglet type in both zones of flow laminar and turbulent. In\(^11\) did experimental study of the same and found out that curved winglet type VGs provides higher heat transfer enhancement and lesser resistance to flow compared to corresponding plane winglet VGs in both zones of flow.

In\(^12\) did an experiment to study about Turbulent Convection in Solar air heater channel which is attached with Delta Winglet vortex Generator. Delta winglets are mounted in absorber plates in 2 different arrangements for various attack angles (30, 45, 60) and pitches and relative heights (b/H). One at entry and in other type on absorber plate. Test was done for various Reynolds number (5000-24000). At the entry DW at 30-degree attack angle with pitch= 1 provides better performance. Second case, 30 degree DW at b/H=0.4 performs better. In\(^13\) did a numerical study on thermo hydraulic performance of rectangular winglets having punched holes on wall of the channel and learned that the case with punched holes have bit more average Nu number (about1.1%) and bit lesser average friction factor (about 1.2%) compared with the case without punched holes. Location of punched holes was in front of the baseline of winglet VG.

This paper attempts to study heat transfer and fluid friction characteristics in solar air heater duct attached with Delta winglet with and without punched holes, by CFD simulations. Effects of various arrangement of placing pair of delta winglets in a duct are studied. Duct of size 400*300*30 is considered, with thickness of winglet 3mm and height equal to half duct height. Simulation for both delta winglets with and without punched holes are done for following arrangement of winglets in the duct (Figure 1).
1. Single row of 5 pairs of delta winglet placed at entry of duct (Figure 1a)
2. Single row of 5 pairs of delta winglet with punched holes placed at the entry of duct (Figure 1b)
3. Two row of 5 pairs of delta winglet placed starting at entry of duct with a pitch equal to twice duct height (Figure 1c)
4. Two row of 5 pairs of delta winglet with punched holes placed starting at entry of duct with a pitch equal to twice duct height (Figure 1d)
5. Three rows of 5 pairs of delta winglet placed starting at entry of duct with a pitch equal to twice duct height (Figure 1e)
6. Three rows of 5 pairs of delta winglet with punched holes placed starting at entry of duct with a pitch equal to twice duct height (Figure 1f)

**Figure 1.** Arrangement of winglet with and without punched holes inside duct for second case.

Simulation is carried out for Reynold’s number in the range of 5000-25000 to study thermal performance. Analysis is done to compare performance of winglet with and without punched holes. Thermal performance is found by finding out Nusselt’s number and friction factor. Webb’s correlation for surface roughness is used to determine thermal performance

### 2. Numerical Analysis

#### 2.1 Physical Model

The CFD analysis were done using FLUENT 14.5. Tool that uses the finite-volume method which provides solution to the governing equations. Geometry creation and meshing was done using Gambit. Meshing considered was tetrahedral mesh. Unstructured mesh was used so that mesh at VG’s is highly concentrated. Simulation was done for Reynold’s number ranging from 5000-25000.

#### 2.2 Numerical Method

Three dimensional equations of continuity, momentum and energy 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 was done for the physical model for validating the accuracy of numerical solutions. Unstructured mesh is used so that areas near wall and VGs is highly concentrated.

K-Epsilon turbulence model was used, with convergence criteria for energy as 10-6 and for momentum, and mass conservation as 10-3 is used for calculated parameters. Boundary conditions was selected as velocity inlet for inlet, and pressure outlet for outflow, wall for 3 walls of duct and top wall of the duct, where uniform heat flux of 1000watts/m2 is given. Material for wall is selected as aluminium with thickness of 1.2mm. The Temperature at the air inlet was taken as 300 K and three assumptions were made in model: (1) Steady and incompressible flow (1) the uniform heat flux was along the length of the channel. (2) channel wall is considered to be perfectly insulated.

Free stream flow validation is done initially for duct without winglet under same condition. Then simulation for Reynolds’s number ranging from 5000-25000 for delta winglets with and without punched holes for all the arrangements of the winglets mentioned.

#### 2.3 Data Reduction

Parameters that is to be considered here are - Nusselt number to determine heat transfer rate, friction factor, friction factor found out by determining pressure drop to get friction loss and thermal performance, to get the effectiveness of augmented heat transfer in the channel.

**Nusselt’s number can be obtained directly or by finding heat transfer coefficient by using equation**

\[
Nu = \frac{h_d}{k},
\]

where, \( h \) is convective heat transfer coefficient
\( d \) is hydraulic diameter,
\( k \) is thermal conductivity.

Friction factor is determined from pressure drop by using equation
\[ f = \frac{2\Delta P}{\frac{l}{d} \cdot \rho \cdot u^2} \]  

(2)

where, \( \Delta P \) is drop in pressure
\( \rho \) is density
\( u \) is free stream velocity

Average of the channel wall temperature was taken into consideration for the Nusselt's number and the Reynolds number. Temperature at the inlet, drop in the pressure across the test section, and the flow velocity of air were measured for the heated wall with various kinds of VGs. The average Nusselt's numbers and friction factors were noted, with properties of fluid were determined at the overall bulk mean temperature.

**Thermal performance factor is given by**

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

(3)

where, \( Nu_0, f_0 \) denotes Nusselt's number and friction factor for flow without using winglet.

### 3. Results and Discussion

#### 3.1 Validation of Setup

Grid independence study was done to make results independent of mesh size. Mesh of 1.5 times element size was considered for all models, for case of 5 pairs of delta winglet placed at entry, results were compared with experimental data. It showed variation of 3-5\% for Nusselt's Number (Figure 2), and 5 -7\% for friction factor (Figure 3) and 1-5\% deviation for thermal enhancement factor (Figure 4).

#### 3.2 Heat Transfer

Heat transfer rate is more for 3 rows of winglets placed. Heat transfer rate increases with increase in number of rows (Figure 5).

For winglets with punched holes, also heat transfer is more for 3 rows of winglets placed, and also it increases with increase in number of rows. Heat transfer rate is slightly less for delta winglet with punched holes than without punched hole.
Heat transfer rate is increased by 40-150% in laminar region, 52-120% in transition region, 50-112% in turbulent region. Here also enhancement is more in laminar region.

In general, Nusselt’s number increases with increasing Reynolds’s number.

### 3.3 Friction Factor

Friction factor is slightly less for winglet with punched holes compared to that without holes, this may be because hole may have acted as bypass for airflow (Figure 6).

**Figure 6.** Graph showing variation of friction factor with Reynolds's number for second case.

Friction factor increases by 130-380% in laminar region, 135-430% in transition region, 172-500% in turbulent region. Increase in friction factor is more in turbulent region.

In general friction factor decreases with increase in Reynolds’s number.

### 3.4 Thermal Performance Factor

Duct fitted with 3 rows of winglets with punched holes gives higher thermal performance. Winglets with punched holes performs better than that without punched holes. This is due to fact that by punching holes even though there is slight decrease in Nussult number, slight decrease in friction factor is enough to bring the enhancement (Figure 7).

In general, for all above cases, thermal performance is high in laminar region and the decreases slightly with increase in Reynold’s number and becomes almost constant in higher Reynold’s number region.

This result shows advantage of using delta winglet with punched holes in enhancing thermal performance of solar air heater duct.

**Figure 7.** Graph showing variation of thermal enhancement factor.

Figures 8–11 shows Pressure and Temperature distribution across the winglets fitted in the duct as obtained from CFD analysis.

**Figure 8.** Pressure distribution across winglets in duct fitted with single row of delta winglet at 25000 Reynold’s number.

**Figure 9.** Temperature distribution across winglets in duct fitted with single row of delta winglet at 25000 Reynold’s number.

**Figure 10.** Pressure distribution across winglets in duct fitted with one row of delta winglet at 25000 Reynold’s number.
4. Conclusion

Using 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. Nusselt’s number rises with rise in Reynolds’s number. Heat transfer enhancement is more in low Reynolds’s no region. Increasing number of rows of winglets placed increase heat transfer rate and also with increases in pressure drop. Thermal enhancement factor of about up to 1.4 can be achieved by using delta winglets with punched holes.

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