CFD Simulation of Heat Transfer Enhancement by Rectangular, Trapezoidal, Delta Winglet Type Vortex Generators

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Abstract— Numerical CFD simulation was carried out to investigate the performance of winglet vortex generators of various dimensions and shapes. Mainly three types: rectangular, trapezoidal and delta type are taken for study. Performance of the VGs in terms of dimensionless numbers (Colburn number, Friction factor, Nusselt number) is compared with changing shape of vortex generators, Reynolds number and attack angle. The processes in solving the simulation consist of modeling and meshing the basic geometry of rectangular channel with VGs using the package ANSYS ICEM CFD 15.0. Result are examined and graphs are made for getting comparative results of performance variation of VGs. This work presents a numerically study on the mean Nusselt number, Colburn factor, friction factor and heat enhancement characteristics in a rectangular channel having a pair of winglet type VGs under uniform heat flux of 416.67 W/m². The result showed that curved winglets have better heat transfer enhancement and low flow resistance than the plane winglets. Effect of angle of attack is studied; results showed that lower attack angle gives better performance. Reynolds number (9000, 15000, 21000) are taken for study, higher Reynolds number gives better performance with lower friction resistance to flow having lesser pressure drop.

Keywords: better, result, performance, factor, channel, transfer

I. INTRODUCTION

In analyzing and studying problems including heat transfer and fluid flow Computational Fluid Dynamics (CFD) is a best available tool in present scenario. The subject of heat transfer enhancement is of significant interest in developing compact heat exchanger to meet the desire of high efficiency and low cost with the volume as small as possible and the weight as light as possible. A large amount of investigations have been carried out in this area since 1960s. Artificially generated vorticity is efficient in fluid mixing and heat transfer since it enhances the exchange of fluid particles between the different flow regions with relatively small increases in pressure loss. Several methods exist for generating vorticity, in present study our main interest is on vortex generators. The vortex generator (VG) can be regarded as a special kind of extended surface, which can be stamped on or punched out from the fin. Although the heat transfer surface area may not be changed before and after the set up of VG, the fluid flow can be strongly disturbed because of the generation of vortex when fluid flows over it. In the conventional point of view, vortex generators not only disturbs the flow field, disrupt the growth of the boundary layer, but also makes fluid swirling and causes a heavy exchange of core and wall fluid, leading to the enhancement of heat transfer. The vortex may be divided into transverse vortex (TV) and longitudinal vortex (LV) according to its rotating axis direction. The axes of TVs lie perpendicular to the main flow direction, while LVs have their axes parallel to the main flow direction, thus they are also called stream wise vortices. In general, the LVs have been reported to be more efficient than TVs for heat transfer enhancement. In this paper we focus on a technology (vortex generator) potentially able to produce both heat transfer and mixing: a pair of delta winglets and a pair of rectangular winglets and a pair of trapezoidal winglets. These types of turbulence promoters integrated in a heat exchanger have flexible design and high heat-transfer performance.

II. NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>RE</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>Pr</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>Nu</td>
<td>Nusselt number</td>
</tr>
<tr>
<td>f0</td>
<td>Darcy friction factor of smooth channel (i.e. without VG)</td>
</tr>
<tr>
<td>f</td>
<td>Darcy friction factor</td>
</tr>
<tr>
<td>D</td>
<td>Hydraulic diameter of the air channel (m)</td>
</tr>
<tr>
<td>j</td>
<td>Colburn factor</td>
</tr>
<tr>
<td>j0</td>
<td>Colburn factor of smooth channel (i.e. without VG)</td>
</tr>
<tr>
<td>x</td>
<td>Length of vortex generator (mm)</td>
</tr>
<tr>
<td>y</td>
<td>Height of vortex generator</td>
</tr>
<tr>
<td>L</td>
<td>Length of tested channel along air flow direction (m)</td>
</tr>
<tr>
<td>LVG</td>
<td>Longitudinal vortex generator</td>
</tr>
<tr>
<td>P</td>
<td>Pressure (Pa)</td>
</tr>
<tr>
<td>Pr</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>S1</td>
<td>front edge pitch of a pair of vortex generators (mm)</td>
</tr>
<tr>
<td>S2</td>
<td>Distance of vortex generator pair downstream (mm)</td>
</tr>
<tr>
<td>T</td>
<td>Temperature Kelvin</td>
</tr>
<tr>
<td>V</td>
<td>Velocity (m/s)</td>
</tr>
<tr>
<td>VG</td>
<td>Vortex generator</td>
</tr>
<tr>
<td>k</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>R</td>
<td>Performance Ratio</td>
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</table>
III. LITERATURE REVIEW

Martin Fiebig (1) carried out work in the field of embedded vortices in internal flow for heat transfer and pressure loss enhancement. Results from study show that at all Reynolds numbers, longitudinal vortices are more effective than transverse vortices. Gentry and Jacobi (2) experimentally studied the heat transfer enhancement performance of delta wing vortex generators in a flat-plate flow by a naphthalene sublimation technique. The results indicated that the average heat and mass transfer could be enhanced by 50–60% at low Reynolds number over the unenhanced performance. Fiebig M, Valencia A , Mitra N.K (3) determine the local heat transfer in case of plate and tube fin heat exchanger in staggered arrangement. The use of vortex generator can enhance the heat transfer for flat tube by a factor of two or more. Similarly pressure loss also increase by a factor of two or more. The flow losses are 50% smaller in case of flat tube and VGs compared to round ones. Chunhua Min , Chengying Qi, Xiangfei Kong, Jiangfeng Dong (4) carried out experimental study on rectangular channel with modified rectangular longitudinal vortex generators. A modified rectangular longitudinal vortex generator (LVG) obtained by cutting off the four corners of a rectangular wing is used. . Results show that the modified rectangular wing pairs (MRWPs) have better flow and heat transfer characteristics than those of rectangular wing pair (RWP). Guobing Zhou, Qiuling Ye (5) carried out experimental investigations on thermal and flow characteristics of curved trapezoidal winglet type vortex generators. . The performance of a pair of new vortex generators - curved trapezoidal winglet (CTW) has been experimentally investigated and compared with traditional vortex generators - rectangular winglet, trapezoidal winglet and delta winglet using dimensionless factors - j/j0, f/f0 and R = (j/j0)/(f/f0).J.M. Wu, W.Q. Tao(6) performed a numerical study on laminar convection heat transfer in a rectangular channel with longitudinal vortex generator. This study presents numerical computation results on laminar convection heat transfer in a rectangular channel with a pair of rectangular winglets longitudinal vortex generator punched out from the lower wall of the channel. G. Biswas, K. Torii, d. Fuji and k. Nishino (7) performed numerical and experimental determination of flow structure and heat transfer effects of longitudinal vortices in a channel flow. Their study determines the flow structure, in detail, behind a winglet type vortex generator placed in a fully developed laminar channel flow. K. Torii, K.M. Kwak, K. Nishino (8) carried out work for heat transfer enhancement accompanying pressure-loss reduction with winglet-type vortex generators for fin-tube heat exchangers. Their paper proposes a novel technique that can augment heat transfer but nevertheless can reduce pressure-loss in a fin-tube heat exchanger with circular tubes in a relatively low Reynolds number flow, by deploying delta winglet-type vortex generators. Pankaj Saha and Gautam Biswas (9) performed numerical simulation of turbulent flow in a rectangular channel with periodically mounted longitudinal vortex generators. The simulation shows that the secondary flow is stronger in the regions where the longitudinal vortices are more active. The wake like structures of stream wise velocity occurs due to strong distortion of the boundary layer by vortices. The span wise distributions of turbulent kinetic energy and Reynolds stress show the evidence of strong secondary flow. Guobing Zhou, Zhizheng Feng (10) performed Experimental investigations of heat transfer enhancement by plane and curved winglet type vortex generators with punched holes. Rectangular, Delta and trapezoidal type (both plain and curved) winglet type were used for study. 60 degree attack angle was used for study. Winglets with holes at centre are also studied. Results from their work show that curved winglets gives better results. Also punching holes reduces friction factor and there by increases overall performance of winglets.

IV. NUMERICAL SIMULATION

A. Physical model

An air channel of length 1000 mm having rectangular cross section with width and height (240mm and 40mm) is considered for study. Material of bottom is taken as copper and that of side walls is taken as steel. Winglets are placed at a distance 320mm from the inlet end having a pitch of 20mm.Reynolds number for test is varied by varying inlet velocity to the channel. Inlet temperature of air to the channel is taken as atmospheric (293 Kelvin). Outlet pressure is also taken as atmospheric (1.013 bar) or zero gauge pressure during set up for the problem. Heat flux of 416.67 J/m² is applied at bottom wall with 5% losses taken during transmission as in experimental data of Guobing Zhou, Zhizheng Feng(15).Figure 1 shows the physical model with detail dimensions. Properties of air taken is given in table no. 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value Taken</th>
</tr>
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<tbody>
<tr>
<td>Specific heat capacity, Cₚ</td>
<td>1006 J/kg K</td>
</tr>
<tr>
<td>Thermal conductivity, k</td>
<td>0.0242 W/m K</td>
</tr>
<tr>
<td>Density, kg/m³</td>
<td>1.225 kg/m³</td>
</tr>
<tr>
<td>Dynamic Viscosity,µ, kg/(m·s)</td>
<td>1.81×10⁻⁵ kg/(m·s)</td>
</tr>
</tbody>
</table>

Following are the variations taken for the numerical simulation.

B. Vortex generators

Mainly four different configurations are studied. These are as

i. Rectangular winglet (REC)

ii. Delta winglet

iii. Trapezoidal winglet with chamfer (front edge height chamfer of 5mm) (TRAP A)
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Fig. 1: Physical model (front view, top view, side view and 3d model view)

i. Trapezoidal winglet with chamfer (front edge height chamfer 10mm) (TRAP B)
ii. Trapezoidal winglet with chamfer (front edge height chamfer 15mm) (TRAP C)

Geometries are shown in figures 2, 3, 4, 5 and 6 with dimensions.

C. Attack angle (β)

Attack angle of placing the winglets with respect to inlet fluid is varied taking three different angles mainly 30°, 45° and 60°.

D. Reynolds number (Re)

Reynolds numbers taken for study are 9000, 15000 and 21000.

E. Meshing

Meshing of model is done taking very fine meshing near walls and winglets. Inflation is given to boundaries (walls) for better results and capturing boundary layer effects. In solver enhanced wall treatment is used for better boundary capture. A cut section at 330mm from inlet in figure no. 7 shows winglets inside channel. Very fine meshing is done near boundary walls of channel and winglets.

F. Boundary conditions

Air at inlet of channel has temperature of 293 K, the inlet velocity is varied for getting various Reynolds number. Pressure at inlet also varies by changing losses and velocity condition in the channel as outlet pressure is taken as atmospheric (zero gauge). Heat flux at bottom wall is 416.67 W/m². Other side wall are insulated with zero heat flux.

V. DATA REDUCTION

Various parameters studied are Nusselt number (Nu), Colburn factor (j), friction factor (f), Reynolds number(Re). Reynolds number, \( Re = \frac{\rho x V x D}{\mu} \)  

(1)
Nusselt Number, \( \text{Nu} = \frac{h \times D}{\kappa} \)  
(2)

Colburn factor, \( j = \frac{\text{Nu}}{Re \times Pr^{1/3}} \)  
(3)

Friction factor, \( f = \frac{2 \times dp \times D}{\rho \times L \times v^2} \)  
(4)

Characteristic length, \( L = \frac{4 \times A}{P} \)  
(5)

Performance Ratio, \( R = \frac{j/j_0}{f/f_0} \)  
(6)

VI. VALIDATION OF RESULTS

The CFD numerical results of the smooth channel without any VG are validated with the experimental data results of Guobing Zhou, Zhizheng Feng (15) as shown in graph 1 and 2. These results are within ±10% deviation for heat transfer (Nu) and ±10% the friction factor (f) with each other.

Nusselt Number validation results for smooth channel are given in graph 1.

Friction factor validation results for smooth channel are given in graph 2.

Results are also validated with the data available from literature. Various empirical correlation used for validation are:

For fully turbulent flow (10000 to 21000)

Petukhov \( f = (1.82 \times \log_{10} \times Re - 1.64)^{-2} \)  
(7)

Blasius \( f = 0.3164 \times Re^{-0.25} \)  
(8)

For transitional regions (2300-9500)

Ma et al. correlation \( \text{Nu} = 0.089 \times Re^{0.691} \)  
(9)

VII. RESULT AND DISCUSSION

Researches done in past by different researchers show that heat transfer rate increases by placing winglets in fluid channel as compared to channel without it. But due to increased pressure and friction losses their overall performance considering these losses is generally lower than smooth channel. So a balance has to be made between increased heat transfer and increased losses and for that different geometry, shapes and other parameters can be varied to strike out better performance balance.

A. Performance variation with changing shape and geometry

At all attack angles and Reynolds number Delta winglet gives the best overall performance (a higher R value). A better balance between heat transfer and lower friction factor is main reason behind its higher performance. Other than Delta Trap C and Trap B also has higher performance than Rectangular and Trap A type winglet. Colburn factor ratio\((j/j_0)\) of rectangular type decrease with increase in Reynolds number where as in other their Colburn factor ratio\((j/j_0)\) increases with increasing Reynolds number that is the main reason behind better performance of trapezoidal and delta winglets. Rectangular type and Trap A has higher friction losses due larger flow interruption and higher friction losses due higher area of contact with flow.

B. Graph for Specific Attack Angle

Graph 3 shows Trap B, Delta and Trap C gives better Heat transfer at 15000 Reynolds number while REC, Trap A and Trap B types are better at 9000 Re

Graph 4 shows Trap B and Trap C gives better results at higher Reynolds number.
Graph 5 shows a decreasing trend in Colburn factor ratio with increasing Reynolds number. It may be due higher separation of flow from winglet boundary surfaces.

Graph 6 shows higher friction factor ratio is given by Rectangular winglet. Trap A has minimum 10% lower friction factor value than Rectangular type winglet which gives second highest friction factor. Delta type winglet gives lowest friction factor. Friction factor ratio reduces with increasing Reynolds number.

Graph 7 shows again a higher friction factor given by rectangular type winglet. 40 to 60% higher than smooth channel where 1 ratio gives smooth channel value.

Graph 8 shows at higher attack angle of 60, all winglets have a decreasing trend in friction factor value with increasing Reynolds number.

Graphs for Specific Reynolds Number
Graph 9 shows Delta gives the lowest value of Colburn factor.

Graph 10 shows Trap B, Trap C and Delta type winglets gives higher Colburn factor and thus heat transfer as compared to all other types. Attack angle 30 and 45 has nearly equal heat transfer rate at Re 15000.
Graph 11 shows Colburn factor value of Trap C increases at 45 attack angle up to 20% from 30 and 60 degree attack angle. In other cases lower attack angle is better.

Graph 12 shows that a higher friction factor value is obtained at higher angle of attack i.e. 60 degree. Rectangular and Trap A gives highest friction factor ratio 50 to 70% higher than smooth channel. Delta gives lowest ratio 20 to 30% higher than smooth channel.

Graph 13 shows a very high friction factor ratio is given by rectangular type winglets 15 to 25% higher than the second higher friction factor ration that is given by Trap A type winglets. Delta gives lowest friction factor value.

Graphs for overall performance ratio ($R = \frac{\text{j/jo}}{\text{f/f0}}$) $R$ variation with Reynolds Number at different attack angle

Graph 14 shows friction factor increase of 5 to 10% in nearly every type of winglets with every 15 degree increase in attack angle.

Graph 15 overall performance ratio increases with increasing Reynolds number. Delta gives nearly equal performance to smooth channel (i.e. 1 value) at 15000 and 21000 Reynolds number. From graph no.11 and 12 a increasing in Colburn factor is 22 to 17% with 15 to 20% increase in friction factor. Trap B gives highest performance ratio of 1.07 (7% higher than smooth channel) at Reynolds number 21000 with 22% increase in Colburn factor with 30% increase in friction factor. Rectangular type gives lowest performance ratio with 15 to 22% Colburn factor increase but hear friction factor is very high,50 to 70% higher than smooth channel.
Graph 15 shows that there is a 2 to 8% higher performance ratio compared to a smooth channel, given by Delta and Trap C winglets at 15000 and 21000 Reynolds number. Also, Trap B gives nearly 100% performance at these Reynolds number.

Graph 16 shows at an attack angle of 30° that a higher performance is obtained compared to 60° and 45° attack angle. Delta, Trap B, Trap C all give a higher performance ratio than smooth channel at 15000 and 21000 Reynolds number. 0 to 17% increase in performance than smooth channel.

Graph 17 shows a R ratio of Delta, Trap B and Trap C increases above 100% and higher R ratio are again obtained at 30° degree attack angle (for Delta 15% higher than smooth channel).

Graph 18, when we compare it with graph 24, we can find that here R ratio of Delta, Trap B and Trap C increases above 100% and higher R ratio are again obtained at 30° degree attack angle (for Delta 15% higher than smooth channel).

Graph 19 shows at Re 21000 Trap B gives higher R ratio than Delta winglet at 30° and 60° degree attack angle. Also Delta and Trap C type winglet gives highest performance ratio at 45° attack angle almost equal to each other.
VIII. CONCLUSION

The simulations for this problem were carried out following as closely as possible to same operating conditions and geometrical configurations of the rectangular channel having different kind of VGs taken from experimental data of Guobing Zhou, Zhizheng Feng (1). The comparative results for the overall heat enhancement for REC, Delta and trapezoidal configuration shows that delta and trapezoidal are best for Reynolds number ranging from 9000 to 21000.

The following results are concluded from the present work.

1. Attack angle 30° gives better performance than 45° and 60°. Colburn is higher 10 to 25% than those of 45 and 60. Also friction factor are 5 to 10% lower than 45° an 60°.
2. Higher Reynolds number is better because of lower friction factor and higher heat transfer, overall performance is higher at higher Reynolds number.
3. Delta and Trapezoidal type gives better performance than Rectangular type winglets.
4. Heat transfer and Colburn factor are higher in Trap A type trapezoidal winglet but due to lower friction factor in Trap C and Trap B type winglets, overall performance (R ratio) is lower in case of Trap A then Trap C and Trap B.

REFERENCES