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Heat Transfer Augmentation in Turbulent Flow through a Circular Tube with Delta Winglet Vortex Generators

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Abstract

An experimental investigation has been carried out to study the convective heat transfer augmentation in turbulent flow through circular tube with delta winglet vortex generators. Eleven different geometric configurations of delta winglet vortex generators (DWVG) made of mild steel were tested for heat transfer enhancement. The pitch ratio, aspect ratio, angle of attack and the chord length of delta winglets were varied in this study. The pitch ratios were varied as 12.86, 8.6 and 4.3. The angles of attack were varied as 25º, 30º, 35º and 40º. The aspect ratios were varied from 0.8 to 1.2. The chord lengths of the delta winglet were varied from 30mm to 40mm. The test section was heated electrically at constant wall heat flux. The Reynolds number in this experiment was varied in the range of 2.0×10^4 to 6.0×10^4. Air velocity, air inlet and outlet temperature, wall temperature and pressure drops along the axial length of the test section were measured to analyse the friction factor, Nusselt number and heat transfer co-efficient. With delta winglet vortex generators Nusselt number was increased remarkably with corresponding increase in friction factor and pumping power. At comparable Reynolds number, the Nusselt number was increased by 140% to 205.7%, friction factor increased by 122.9% to 213.8%, while the pumping power increased up to 248.9% compared to that of smooth tube. A correlation was also developed for the prediction of Nusselt number in turbulent flow for tubes with Delta winglet vortex generators.

Keywords—Heat transfer enhancement, Delta winglet vortex generators, Angle of attack, Aspect ratio.

Introduction

Heat transfer between fluids at different temperature is common in engineering applications such as heat exchangers, refrigeration system, air conditioning and chemical reactors. By enhancing heat transfer, the performance of the heat exchanging device can be improved along with size reduction. The augmentation methods used can generally be divided into two categories: active and passive methods. The active methods require external forces, while the passive methods require special surface geometry or fluid additives. Swirl generators, vortex generators, surface treatment and extended surfaces are popular passive methods. Among the vortex generators, Delta winglet vortex generators is an excellent choice because it increases convective heat transfer by developing a boundary layer, swirl or vortices; as well as through flow destabilization or turbulence intensification. Also, the delta winglet enhances heat transfer more than a rectangular winglet and having the wing pulled backwards it creates very small amount of drag as documented by NASA [7].“Figure 1” shows a sketch of longitudinal vortices behind a DWVG placed in a laminar boundary layer on a flat plate by Torii et al. [12]. The flow separation at the leading edge of the winglet generates a main vortex and the corner vortex is formed by the deformation of near-wall vortex lines at the pressure side of the winglet. Sometimes an induced vortex is also observed rotating opposite

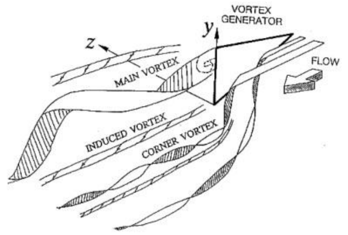

Figure 1.Vortex systems behind a delta winglet [12].

to the main and corner vortex. It should be noted that generation of vortex is preferable as it enhances the heat transfer. Fiebig et al. [4] in 1993 found 55–65% increase in heat transfer, with a pressure drop increase of 20–45% for heat exchanger elements with 3 tube rows in inline tube arrangement and a delta winglet pair downstream of each tube. Tiggelbeck et al. [11], investigated the effect of four types of VGs on local heat transfer and drag of plate fins and compared the results between these types of VGs; in the Reynolds number range 2000-9000 with angle of attack range of 30°-90°. The results show the presence of an optimum angle of attack between 50° and 70° for maximum heat transfer. In 1994 Biswas et al. [3] reported that up to 240% local enhancement of the heat transfer in the recirculation zone can be achieved for a delta winglet pair downstream of tube. Sachdeva et al. [8], conducted experiments with different DWVG at Re 100 and at an angle of attack of 26º yielding an increase in Nusselt number of 74.3% for built in geometry, 130% for stamped one and 75-82% for inline formation. He et al. [5] proposed a new arrangement of vortex generator deployed in a “V” array. The design yields 12-36% augmentation in the total heat transfer as compared to 8-26% obtained by the conventional two-row configuration. Lawson et al. [6] used simplified louvered fin geometry where the maximum winglet augmentation of tube wall heat transfer observed was 8%. Sarkar et al. [9] studied the effect of longitudinal strip inserts for convective heat transfer in circular tube; the heat transfer enhancement was between 1.4 to 3 times with pumping power increased up to 4 times and with wire coil insert [10] heat transfer enhancement was about 2 times. In similar condition Bhuiya et al. [2] using triple helical tape insert found Nusselt number increased by 4.5 times and Ahamed et al. [1]found that, using perforated twisted tape inserts the heat transfer coefficient increased up to 5.5 times for 1.8 times increase in the pumping power.

The objective of this present study is to investigate the effect of delta winglet vortex generators of different geometric configurations in turbulent flow through a circular tube. The pitch ratio (PR), angle of attack (AOA), aspect ratio (AR) and chord length of the delta winglet by the tube diameter (c/D) were varied for these delta winglet configurations. The performance comparison of different delta winglet configurations with respect to smooth tube is made.

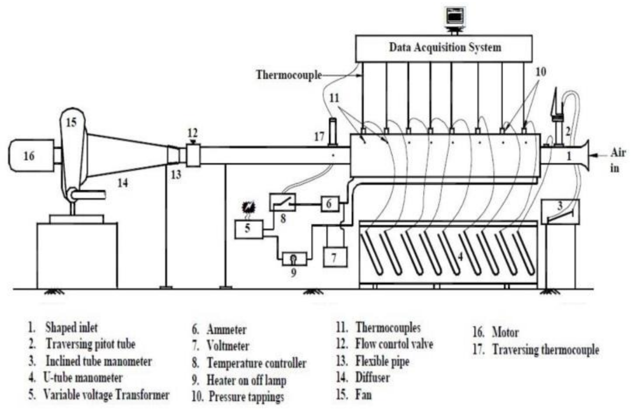

Figure 2.Schematic Diagram of the Experimental setup.

Experimental Facility and Methodology

The experimental facility, "figure 2", consists of Test section, Inlet section, Air supply system and Heating arrangement.

Test Section

Smooth tube of this test section, is a circular brass tube having 70mm inside diameter and 1.5m length. The test section was wrapped with mica sheet, glass fibre tape and insulation ribbon. Over mica sheet Nichrome wire was spirally wound uniformly with 4 mm spacing. The delta winglets inserted by a support rod. Asbestos sheets were placed which act as heat guards in the longitudinal direction.

Inlet Section

An unheated inlet section was made integral to avoid any flow disturbances at upstream of the test section to get fully developed flow in the test section. The pipe shaped inlet is 533mm long.

Air Supply System

Induced draft air flow was created using an electrically operated centrifugal blower. A gate valve placed between the test section and the downstream was used to control the flow rate of air.

Heating System

An electric heater of two heating coil, made of Nichrome wire, was used to heat the test section at constant heat flux. A regulated AC supply with a 5KVA variable voltage transformer through a magnetic contactor and a temperature controller was used as the power supply for heating.

Delta winglet Vortex Generators

Four geometric parameters of Delta winglet vortex generators were varied in this study. The basic configuration was of 5DWVGs at 4.3 pitch ratio, 30º angle of attack, with aspect ratio 1 and 40mm chord length at c/D 0.5714. One geometric parameter was varied at a time keeping others constant. "Figure 3" shows CAD representation (not drawn to scale) of 1DWVG; 2DWVG and 3DWVG of pitch ratio 8.6, 5DWVG of pitch ratio 4.3. "Figure 4" shows DWVGs with an angle of attack of 25º, 30º, 35º and 40º. "Figure 5" shows DWVGs of aspect ratio of 0.8, 1 and 1.2. "Figure 6" shows DWVGs of chord length 40mm at c/D 0.5714, 35mm at c/D 0.5 and 30mm at c/D 0.4285. Each configuration consists of a single pair of DWVG in common flow down arrangement.

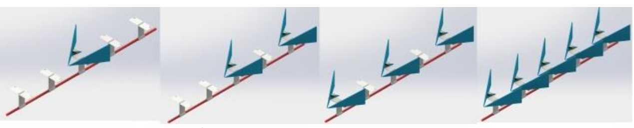

Figure 3.CAD model of Pitch ratio variation.

Figure 4.Angle of attack variation.

Figure 5.Aspect ratio variation.

Figure 6. c/D variation.

Measurement of Experimental Data

Flow of air through the test section was measured using diesel as manometric fluid at the inlet section with the help of a traversing pitot tube. The static pressure tapings were made at the inlet of the test section as well as equally spaced 8 axial locations of the test section. The temperatures at the different axial locations and the air inlet temperature were measured with the help of k-type thermocouples.

Results and Discussion

Experimental data were calculated to find the local heat transfer co-efficient h_x, local Nusselt number Nu_x, friction factor F_i and pumping power P_m by the following equations.

$$T_{bx} = T_i + \frac{Q'(\pi D x)}{\dot{m} c_p} \quad (1)$$

$$h_x = \frac{Q'}{(T_w - T_b)_x} \quad (2)$$

$$Nu_x = \frac{h_x D}{k} \quad (3)$$

$$F_i = \frac{(-\Delta P/X)D}{\frac{1}{2}\rho V^2} \quad (4)$$

$$P_m = \frac{\Delta P}{\rho}\dot{m} \quad (5)$$

Where, T_{bx} is the bulk temperature,$Q' = Q/A_s$,$A_s = \pi DL$

Bulk and wall temperature

"Figure 7" and "figure 8" below show the bulk & wall temperature distribution at comparable Reynolds Number for different geometric configurations of delta winglets.

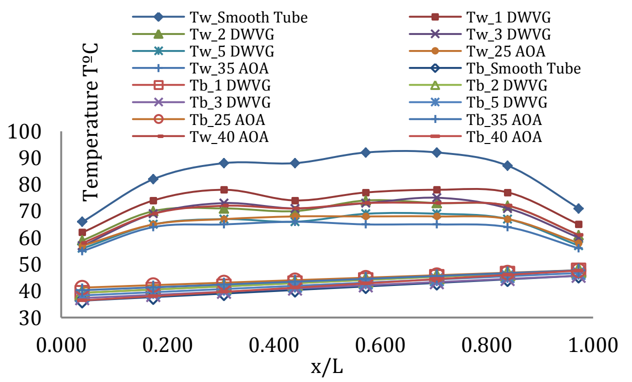

Figure 7.Bulk & wall temperature distribution at comparable Reynolds Number for different PR & AOA

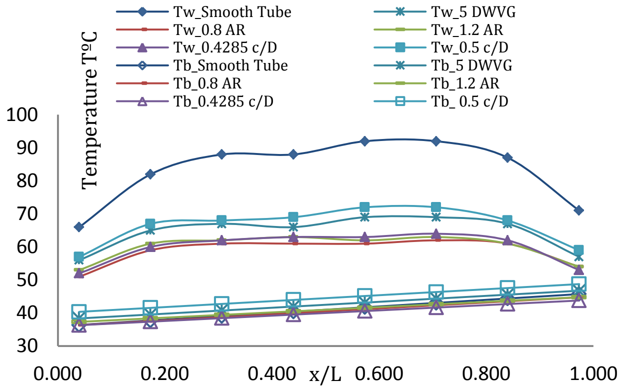

Figure 8.Bulk & wall temperature distribution at comparable Re for different AR ratio & c/D variations.

From these figures it is clear that, the wall temperature increases along the axial length and reaches its maximum value. Then the temperature drops slightly at the downstream due to end effect. End effect is due to the conductive heat loss between the test section and unheated tube downstream. Figures show that bulk fluid temperature increases linearly as air passes through the smooth tube. As the vertical distance between the wall temperature and bulk temperature used to calculate the fully developed heat transfer co-efficient. Keeping the other parameters fixed, the smallest temperature difference in these figures indicates the best heat transfer performance.

Heat Transfer

Figures below show the average Nusselt number vs. Reynolds number for different pitch ratios "figure 9", angles of attack "figure 10", aspect ratios "figure 11"and c/D variations "figure 12". It can be seen that, the pitch ratio of 4.3 for 5DWVG and 40°AOA provides the most heat transfer enhancement over other PRs and AOAs. Surprising improvement in heat transfer in high Reynolds number is found for aspect ratio of 0.8.

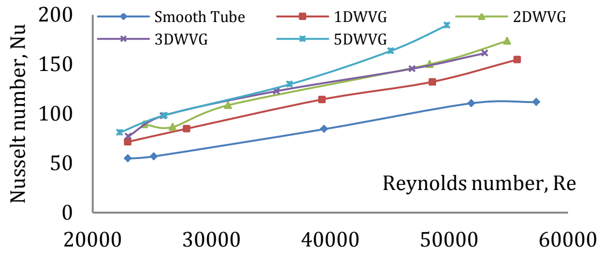

Figure 9. Nusselt number vs. Reynolds number for different Pitch Ratios

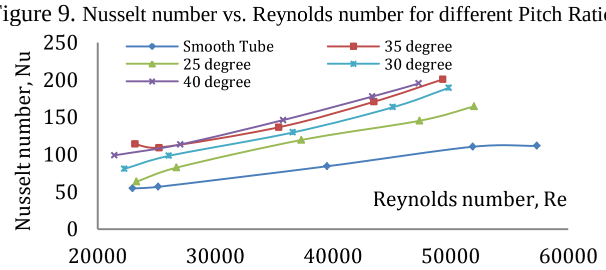

Figure 10. Nusselt number vs. Reynolds number for different AOA

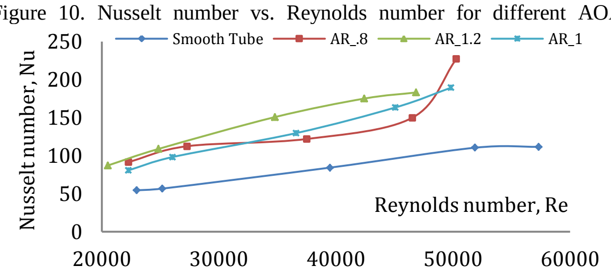

Figure 11. Nusselt number vs. Reynolds number for different ARs

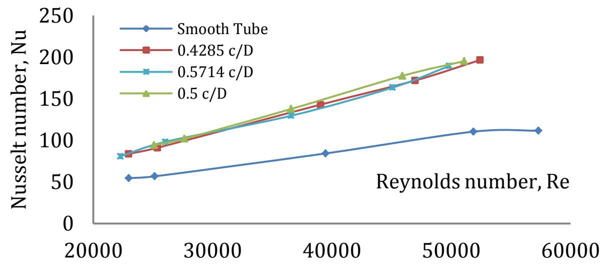

Figure 12. Nusselt number vs. Reynolds number for different c/D.

A very important finding in "figure 12" is that, there was no change in the heat transfer enhancement while the values of c/D were changed. The Nusselt numbers for all configurations of delta winglets were significantly greater than that of the smooth tube.

Pumping Power

Figures below show the Pumping power required vs. Reynolds number for different pitch ratios ("figure 13"), angles of attack ("figure 14"), aspect ratios ("figure 15") and c/D variations ("figure 16"). The 5DWVG configuration and the 40ºAOA needs more pumping power than other PRs and AOAs at different Reynolds number. Surprisingly the highest enhancement giving configuration of aspect ratio of 0.8 (from "figure 11") needs less pumping power than other aspect ratios.

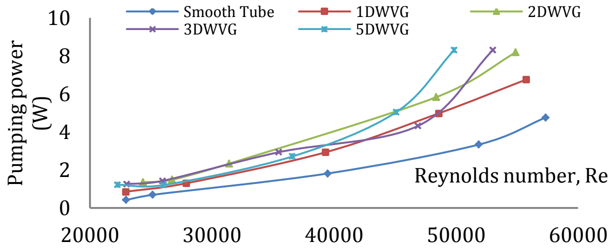

Figure 13. Pumping power vs. Reynolds number for different Pitch Ratios

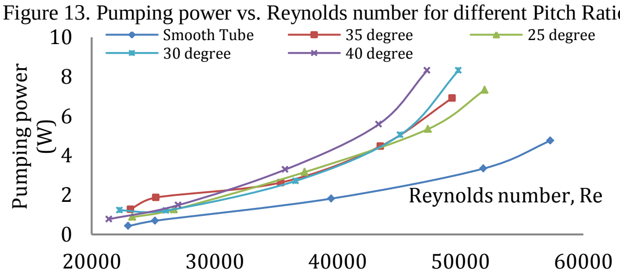

Figure 14. Pumping power vs. Reynolds number for different AOA

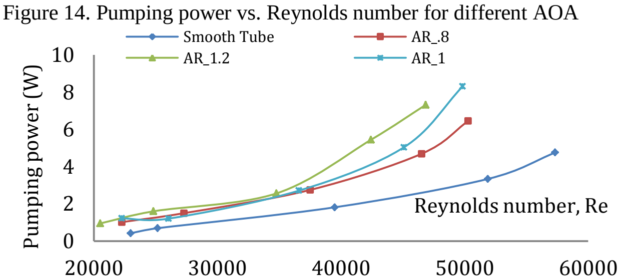

Figure 15. Pumping power vs. Reynolds number for different ARs

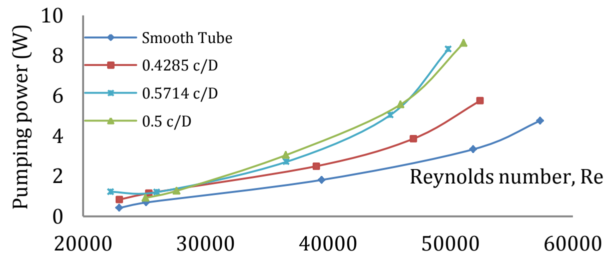

Figure 16. Pumping power vs. Reynolds number for different c/D

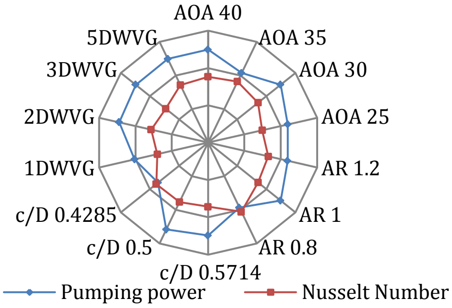

Figure 17. Nu and P_m for all configurations wrt. smooth tube.

Another important finding is that, though the heat transfer enhancements do not change while changing chord length (figure 12), the pumping power decreases with decreasing c/D value. This may be because of the small flow obstruction for 0.8 aspect ratio and 30mm chord length at c/D 0.4285, as the projected areas are comparatively lower. This may permit the generated vortex to go further downstream. The spider graph of "figure 17" shows the relative increase in pumping power in blue line and Nusselt number in red line over smooth tube for all configurations considered in this investigation. The configuration having the smallest radial distance are preferable over others, as this means higher enhancement at lower pumping power.

Correlations

A correlation was developed for the Nusselt number at different delta winglet configurations.

$$Nu = .003785RePr^{.4} - (75.82 + 3.0232PR - 2.683AOA - 28.42AR + 8.266\,c/D)Pr^{.4} \quad (6)$$

The Nu predicted from this correlation "equation (6)", agreed well with the experimental values as seen in "figure 18".

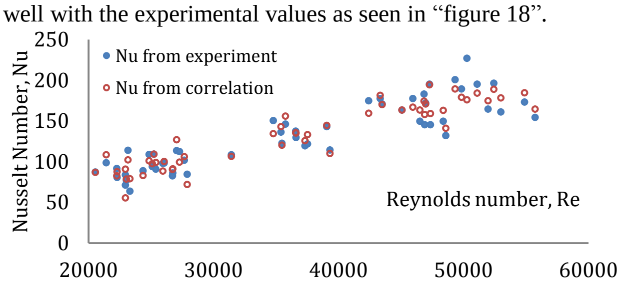

Figure 18. Nusselt number vs. Reynolds number.

Conclusions

The major findings of this present study are summarized as follows:

- The heat transfer enhancement increased by 171.5% of that of smooth tube, for pitch ratio of 4.3 with 5 DWVGs, at 248.9% increase in the pumping power required.
- For 35ºAOA, heat transfer enhancement was 181.8% of that of smooth tube, with pumping power required increased only by 207.1%. Though 40ºAOA provided more heat transfer enhancement, 35ºAOA is considered optimum, for its low requirement of pumping power.
- Delta winglets of aspect ratio 0.8 gave a remarkable heat transfer enhancement of 205.7% of that of smooth tube, at a mere 193.3% increase in pumping power required.
- The pumping power dropped to 172.2% while using delta winglets of 30mm chord length at c/D 0.4285. And the heat transfer enhancement was 178% of that of the smooth tube.

Delta winglets of low pitch ratio, low aspect ratio, small c/D value with an optimum angle of attack might be considered for heat transfer enhancement at minimum pumping power.

Recommendations

Future works may be performed using delta winglets of conventional two row pairs, two pair "V" array, three pair "V" array and of perforated geometry.

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