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A SIMULATIVE ANALYSIS FOR HEAT TRANSFER ENHANCEMENT USING RECTANGULAR WING & WINGLET TYPE VORTEX GENERATOR IN A TRIANGULAR CHANNEL

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ABSTRACT

The augmentation of heat transfer through different ways has been developing as an intense area of research since many years. The recent increase in the use of heat exchangers for industrial applications has called for improvement in their design, efficiency & compactness. In general, the thermal resistance offered by the gases (air in particular is pretty large; therefore, performance of heat exchangers with gas as the working fluids becomes practically important. One of the most common techniques for compensating the poor heat transfer properties of gases is that the surface area density of plate heat exchangers be increased by using the secondary fins such as offset fins, triangular fins, wavy fins, louvered fins etc. In addition to this a promising technique for enhancement of heat transfer is use of longitudinal vortex generators. The longitudinal vortices are produced due to the pressure difference generated between the front and back of the vortex generator. The longitudinal vortices facilitate the exchange of fluid near the walls with the fluid in the core and hence, the thermal boundary layer is disturbed. It causes an increase in temperature gradient at surface which leads to heat transfer augmentation. An innovative design of triangular shaped secondary fins with rectangular wing or winglet vortex generator mounted on the bottom of the channel for enhancing heat transfer is proposed. The computational details have been given for analysis of problem in the ANSYS FLUENT 18 which mainly describes about the solution algorithm and solution schemes as well as under relaxed factors required for the recent problems. As the solution is converged after certain number of iterations, the value of pressure-drop and Nusselt number, average temperature, friction factor is calculated for different attack angles and at different locations and compared with plain channel for same parameter.

1. INTRODUCTION

The performance characteristics of heat exchanger for thermal and fluid analysis are quantified with help of certain parameters (Schubauer & Spangenberg, 1960). Certain dimensionless numbers such as re number, nu number etc are used as parameters (Johnson et al., 1969). Re number for example quantifies the nature of

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flow whether it is laminar or turbulent (Webb et al., 1987). Nu number directly gives the idea about the heat transfer characteristics of the flowing fluid (Biswas et al., 1989).

1.1 Reynolds number

When inertial force for flowing fluid is divided by its viscous force Re number is obtained. Hence it quantifies the above two forces for the given conditions of flow. For a characteristic hydraulic dimension of channel, Re is given by

$$\mathrm{Re}=\frac{\rho VD}{\mu} \tag{1}$$

Where for the given cross section flow V is free air stream velocity usually obtained by mass conservation equation, ρ is density; the symbol used for dynamic viscosity is μ.

Basically, whether the flow regime is laminar or turbulent is characterized by Re (Fiebig et al., 1989). Since Re number is directly proportional to velocity and density of flowing fluid, A large value of Re means larger value of inertia force in comparison to viscous force thus suggesting rapid turbulence in flowing fluid (Fiebig et al., 1989). The lower value of Re number means that viscous force predominates over inertia force to keep the flow laminar (Tao et al., 2002). The transition from laminar to turbulent takes place through a critical Re number at which flow becomes turbulent. Different geometrical shapes give different values of Re number.

1.2 Pressure drop

One more physical quantity that is associated with fluid flow through triangular channel with wing or winglet is the pressure drop penalty, which is actually nothing but the difference of pressure between inlet and outlet (Biswas & Chattopadhyay, 1992).
It must be noted that since flow is laminar viscous with obstructions therefore power is needed to keep the fluid flowing through the duct (Lu & Zhai, 2019). The power requires is directly proportional to pressure drop. Thus, use of LGVs for fluid flowing through the channel should not add up to the pumping cost. Therefore, optimization is needed to be done between the benefits of increasing heat transfer weighed against the additional cost of pumping power requirements (Tiggelbeck et al., 1992).

1.3 Nusselt number

For the applications involving convective mode of heat transfer, the governing equations is made dimensionless various variables are combined together in non dimensionless numbers (Chimres et al., 2018). Basically, heat transfer coefficient is quantified using non-dimensionless number defined as Nusselt number

$$\mathrm{Nu}=\frac{hL}{k}=\frac{convective\ heat\ transfer}{conductive\ heat\ transfer} \tag{2}$$

Where L is characteristic length
h is heat transfer coefficient for convection
k is thermal conductivity

In the 20th century Wihlem Nusselt made many pivotal contributions to the subject of convective heat transfer, his major contribution was to quantify convective heat transfer coefficient into dimensionless number named after him. Physical importance of Nu number could be understood for a fluid layer of thickness L having a finite temperature differenceΔT. When the fluid layer is stationary, mode of heat transfer is conduction whereas for the fluid involving motion heat transfer occurs by convection

Average Nu number is given by

$$\mathrm{Nu}=\frac{Q\quad 2h}{A\Delta T\, k} \tag{3}$$

Where, ΔT is the temperature difference, A is effective heat transfer coefficient area.

Q is the total heat transfer between solid (including fin and winglet surfaces) and air.

Nu number physically signifies the increment in heat transfer of fluid layer as a result of convection relative to conduction (Fiebig et al., 1993). Thus, more effective convection is achieved at very large Nu number. Pure conduction by the fluid is given at Nu value of unity. The turbulent flow of higher range involving more active convection mode of heat transfer is given by larger Nu number (Sarangi & Mishra, 2017). The NU number is the function of Re number and Pr number for forced convection that is

$$\mathrm{Nu}=f(\mathrm{Re},\mathrm{Pr}) \tag{4}$$

1.4 Prandtl number

When momentum diffusivity of a fluid is divided by its thermal diffusivity Pr number is obtained. Pr number is a dimensionless number which describes the relative thickness of the velocity and thermal boundary layer (Sinha et al., 2016). Pr number is given by

$$\mathrm{Pr}=\frac{\nu}{\alpha}=\frac{\rho C}{k} \tag{5}$$

α is the thermal diffusivity (units in SI system m^2/s)
ν is the kinematic viscosity (units in SI system m^2/s)
k is thermal conductivity (units in SI system W/mK)

C is the specific heat capacity (units in SI system J/kgK)
ρ is the density (units in SI system kg/m^3)

The concept of boundary layer in 1904 was developed by Ludwig Prandtl. The non-dimensional Pr number physically controls the relative thickness for the thermal and momentum boundary layers (Biswas et al., 1994). Lower value of Pr number signifies that heat diffuses more rapidly in comparison to momentum. For heavy oils Pr number is as high as 1000 as compared to liquid metals for which Pr numbers are 0.01. Typically for gasses both the velocity (momentum) and heat diffuse at same rate leading to Pr number of unity (Wang et al., 2015).

For Pr number less than one heat diffuses quickly relative to momentum. This usually happens in liquid metals (Lemouedda et al., 2012).

For Pr number greater than one heat diffuses very slowly as compared to momentum e.g., oils (Borrajo-Pelaez et al., 2011).

The liquid metals have much thicker thermal boundary layer as compared to velocity boundary layer and thermal boundary layer as compared to velocity boundary layer for oils is much thinner (Fiebig et al., 1994).

1.5 Grid independence test

For the triangular duct with rectangular wing/winglet, the grid independence test is done by conducting simulation at various Pr and Re number. Four distinct grid numbers are studied in order to validate the solution independence of the grid numbers (Liitng Tian et al., 2009).

The directions chosen for the grid generation are X, Y& Z. The four distinct values of grid are 33000, 200000, 330000, and 500000 respectively. Figure 1 shows variation of the average temperature with grid number (Zhu et al., 1995).

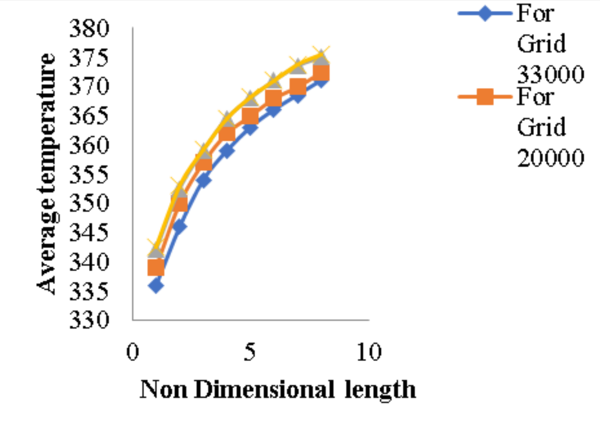

Figure 1. Grid independence test

2.1 Performance of rectangular winglet

2.1.1 Average Nusselt number

The Nu number is a significant dimensionless parameter. Nu is a function of Re & Pr number. The temperature gradient at a surface where heat transfer takes place by convection is represented by Nu number. For pure conduction purposes Nu is unity. Higher value of Nu number means enhanced convection (Wu J. M. et al., 2008).

When the fluid flows over a surface, the first layer of fluid stick to the boundary (No slip condition). This causes the flow to retard in the vicinity of the wall. Moving away from the wall, the effect of this no slip gets smaller until a point where it is no longer felt by fluid. The layer between the wall and this point is what referred to as the boundary layer (Jacobi A. M. et al., 1995).

When for example a cold fluid flows over a hot surface, the first layer of fluid (which gets stuck to the surface) gets heat from the surface by pure conduction. It then gives this newly acquired energy to all of the fluid molecules that it comes in contact with as they pass by it this is convection

For no slip condition

$$Q_{COND}=k\frac{dT}{dY}\text{at}Y=0 \tag{6}$$

This heat flux is taken away through convection by moving fluid.

$$Q_{CONV}=h\Delta T \tag{7}$$

But at interface

$$Q_{COND}=k\frac{dT}{dY}=Q_{CONV}=h\Delta T \tag{8}$$

From above equations Nu number gets defined as

$$Nu=\frac{hL}{k} \tag{9}$$

The variation of the Nusselt number at 45° is more as compare to the 15° and 25° as shown in the Figure 2 and after comparing it with the plain channel it is found that there is increase of 33 %.

And from the Figure 3 it is clear that the winglet position near to the inlet have high Nu number. As we move away from the inlet, there is decrease in the Nu number (Deb et al., 1995).

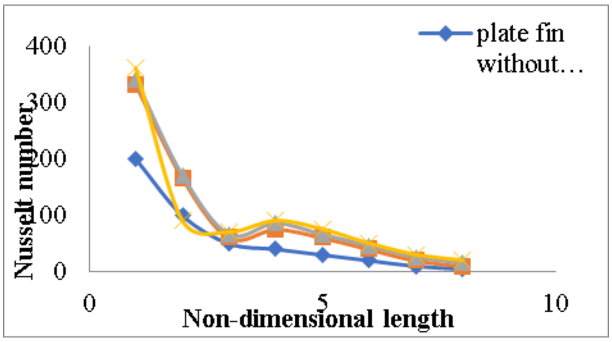

Figure 2. Comparison of Nu number at different attack angles for a winglet

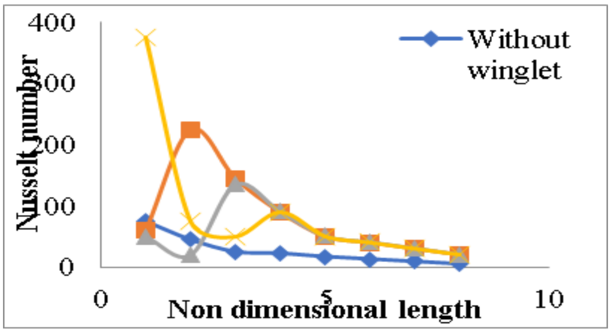

Figure 3. Comparison of Nu number at different positions for a winglet

2.1.2 Friction factor

The formula for friction factor is

$$F = \frac{\tau}{.5 \rho v^2} \tag{10}$$

Equation shows that the friction factor is proportional to the wall shear stress and inversely proportional to the velocity and fluid density under laminar flow conditions. The friction factor is independent of the channel roughness in laminar flow because the disturbances caused by the surface roughness are quickly damped by viscosity. Rectangular winglet vortex generator enhances the heat transfer of the channel as well as result in extra pressure drop due to its form of drag. Rectangular winglet at different angle of attack Vs Non- dimensional length X is shown in Figure 4. Since from the graph it is clear that with the increase in the angle of attack, the friction factor increases (Biswas et al., 1996).

And after comparing it with the plain channel then it is found that there is increase of 30% in the Friction Factor and from the Figure 5 it is clear that the winglet position near to the inlet have more Friction factor as compare to the positions far from inlet (Gentry & Jacobi, 1997).

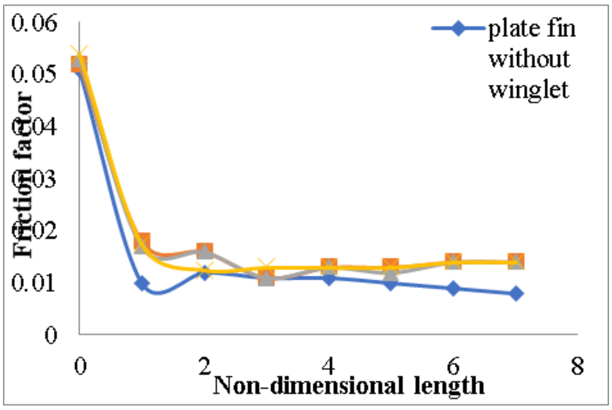

Figure 4. Comparison of friction factor at different angles of attack for a winglet

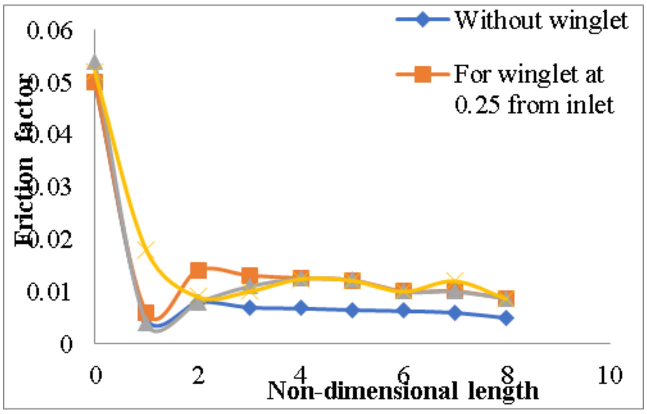

Figure 5. Comparison of friction factor at different locations for a winglet

2.1.3 Pressure drop

In order to obtain the heat augmentation with the rectangular winglet, the price has to be paid. The average pressure at any section has been determined by taking the ratio of the area integral of the pressure at that section to the cross-sectional area. Figure 6 shows the comparison of the pressure drop for the winglet at an angle 15°, 25° and 45° for Reynolds number 200 (Lee et al., 1999).

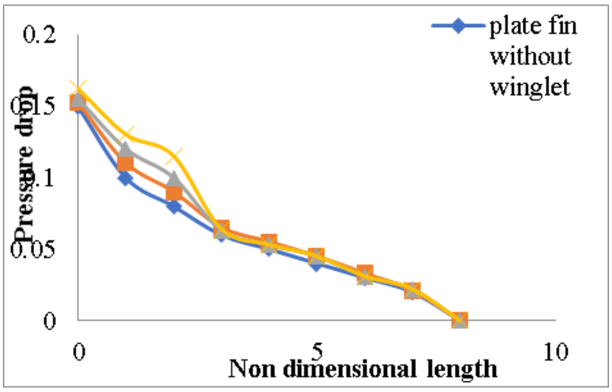

Figure 6. Comparison of pressure drop at different angles of attack for a winglet

The drop in pressure drop is steep where the winglet is placed. This pressure drop is due to the spiraling flow of relatively less vortex strength. The strength of the vertical motion is reduced due to the movement of fluid from the built-in portion. Increase in the angle of attack has the effect of increasing vortex strength which in turn increases resistance and consequently a higher pressure is obtained (Lau et al., 1999). Hence from the graph it is clear that the pressure drops at 45° is more as compare to the 15° and 25°. After comparing with the plain channel, the pressure drop reduces to 33 %. Whereas the case of comparison of the pressure drops, the position of winglet near to the inlet have good results as compare to the positions away from inlet as shown in Figure 7 (Guo et al. 1998).

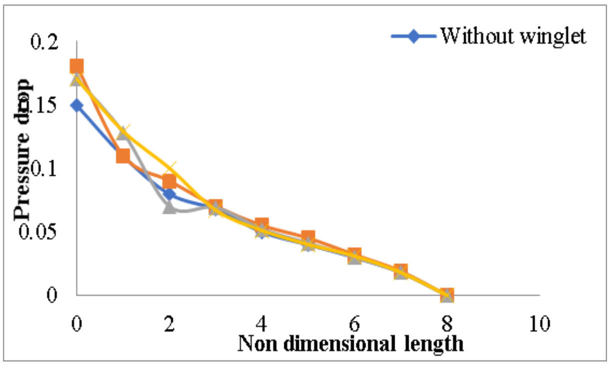

Figure 7. Comparison of pressure drop at different location for a winglet

2.1.4 Average temperature

The mean temperature of the working fluid is more at 45°angle of winglet with the bottom as compare to the 20° and 30° as shown by Figure 8.

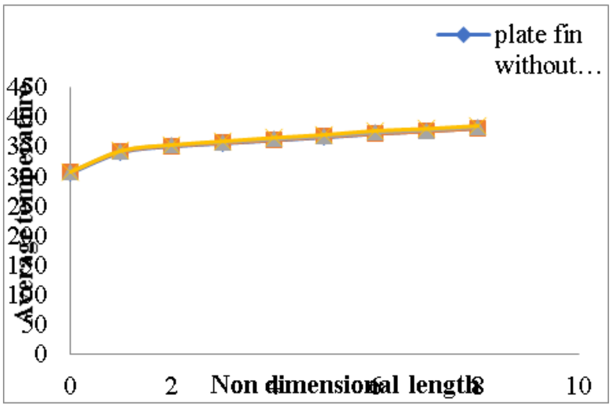

Figure 8. Comparison of average temperature at different angles of attack for a winglet

After comparing with the plain channel, the temperature in the channel with 45° increases with 29%. Also expected, the increment is sudden near the inlet because of high heat transfer in this region due to higher temperature differences between wall surface and the fluid, which is shown in Figure 9

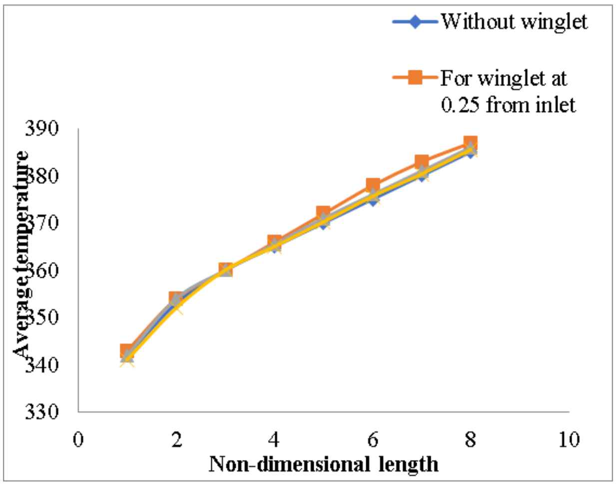

Figure 9. Comparison of average temperature at different positions for a winglet

2.1.5 Heat flux

Figure 10 shows the variation of the span-wise local heat flux, for Re = 300. In the areas surrounding the vortices away from the bottom wall up wash is generated but there is down wash flow developed by winglet in the central region of the channel (Liou et al., 2000).

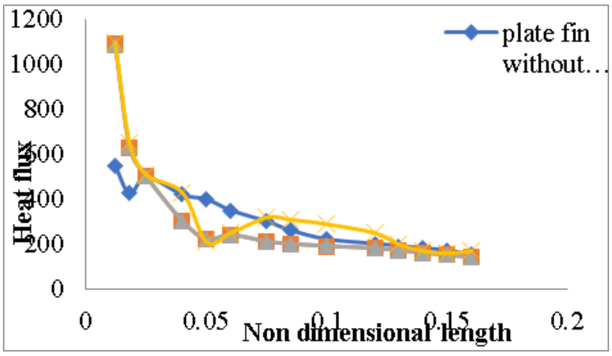

Figure 10. Comparison of heat flux at different angles of attack for a winglet

The strength of the boundary layer is such that it is much diminishes in the middle in the middle region however thickness of boundary layer near the channel wall is much appreciable in the triangular channel, the average local heat flux for the triangular channels with rectangular winglet is higher in comparison with that of the base case of the plate triangular fin channel without rectangular winglet. In comparison to the base case for the position between x/H = 2 and x/H = 2.75, the span-wise local heat flux of the channel with the rectangular winglet also has a higher value (Yang et al., 2001).

The main reason for this is the formation of the horseshoe vortices at the junction of the upstream face of the rectangular winglet and the lower channel wall (Gentry et al., 2002). The span wise local heat flux goes on diminishing with increasing distance from the vortices (Tao et al., 2002). Location wise placing the winglet near to the inlet has much pronounced result for heat flux in contrast to the locations away from the inlet as shown in Figure 11.

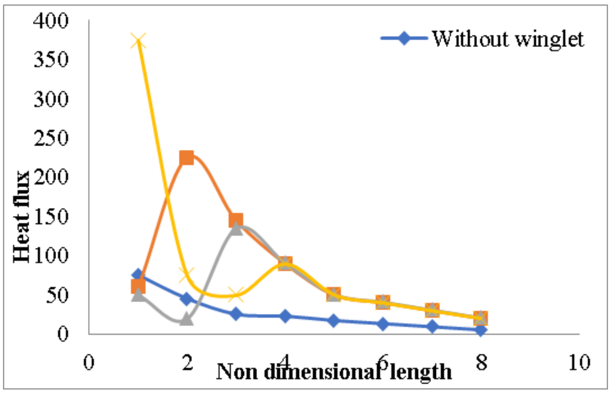

Figure 11. Comparison of heat flux at different locations for a winglet

2.2 Performance of rectangular wing

2.2.1 Average Nusselt number

The temperature gradient near the constant temperature walls decreases as result of formation of boundary layer thereby decreasing the average span wise Nu number. For X<2 along the length, Nu number is very high since temperature difference is high (Tao et al., 2002). The fluid gets churned near the wing and hence a temperature gradient is set as such Nu gets increased. Plots from figure 12 and 13 show the variation of Nu number for different angles of attack and at different positions (Chen & Shu, 2004).

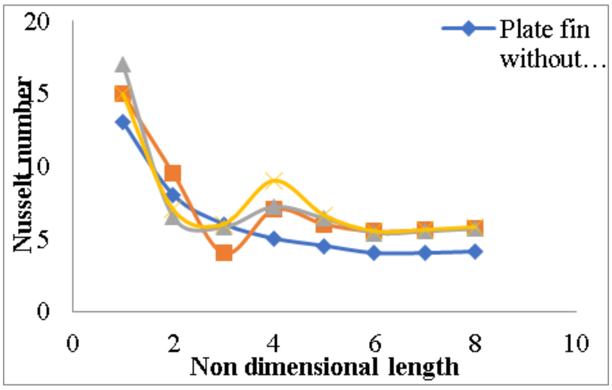

Figure 12. Comparison of Nusselt number at different angles of attack for a wing

The decrease in Nu number is due to formation of wake region which decreases the gradient of temperature (Pesteei et al., 2005).

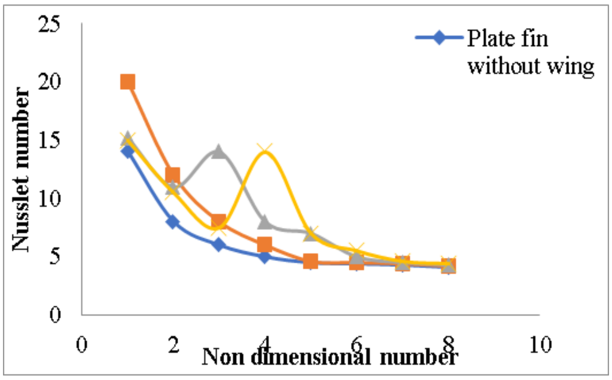

Figure 13. Comparison of Nusselt number at different locations of attack for a wing

2.2.2 Friction factor

Figure 14 shows that the friction factor increases with increase in angle of attack and is maximum for attack angle of forty- five degrees (Ferrouillat et al., 2006).

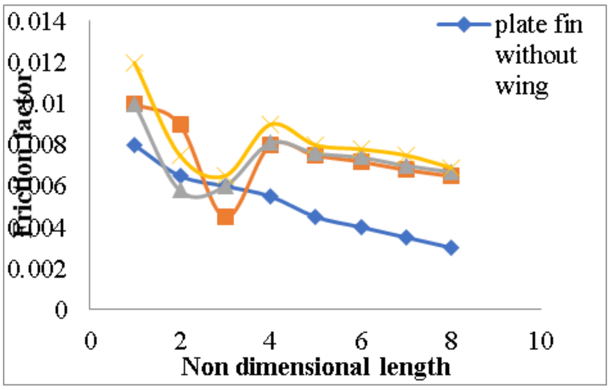

Figure 14. Comparison of friction factor at different angles of attack for a wing

The cause of pressure loss is the convergent & divergent movement of air near wing. The wake generation behind the wing results in development of black flow regions. These areas are responsible for higher pressure drop. For different positions, as shown in figure 15 the friction factor is higher when wing is nearer the inlet (Wang et al., 2007).

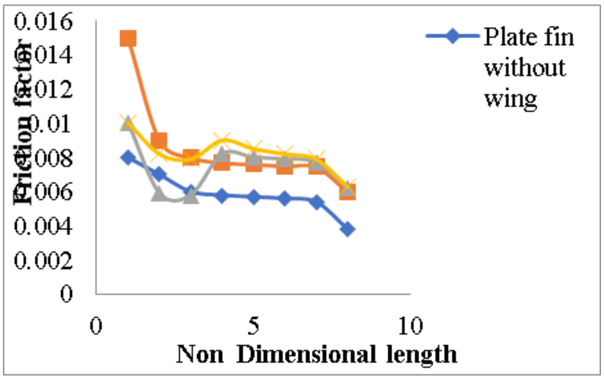

Figure 15. Comparison of friction factor at different locations for a wing

2.2.3 Pressure drop

For continuous flow of fluid through the channel pumping force is required. The pumping power is proportional to pressure drop. As evident from the figures 16& 17, the LVGs act as obstructions to the flow, thus there is sudden decrease in pressure.

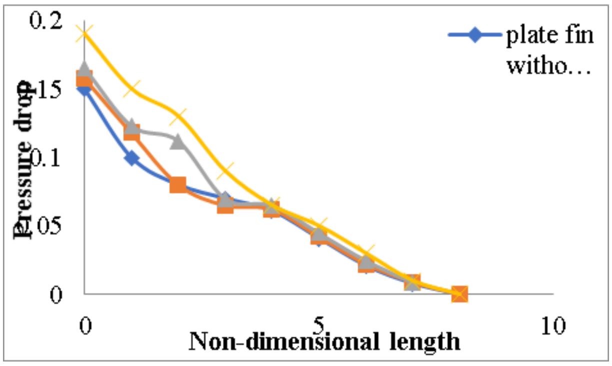

Figure 16. Comparison of pressure drop at different angles of attack for wing

The pumping power increases with increase in angle of attack. There is an increase of about 15% in pressure drop penalty for channel with wing in comparison to channel without wing (Yang et al., 2007).

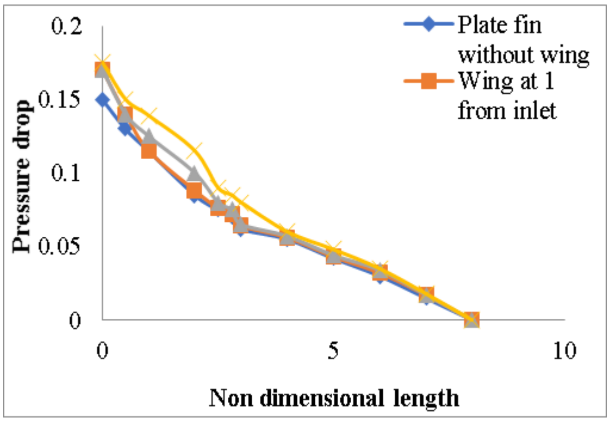

Figure 17. Comparison of pressure drop at different locations for a wing

2.2.4 Heat flux

The LVG creates down wash flow towards bottom wall in the middle area and an up-wash flow outside vortices for a triangular channel mounted with rectangular wing. When x/H< 1, the strength of boundary layer is such that thermal boundary layer is wider in outside region and thinner in central region and in comparison, with case of channel without wing the heat flux for the channels with rectangular wing configuration is on higher side (Sohankar et al., 2007). It is interesting to note that in the position between x/H = 1 and x/H = 1.3 (as shown in figure 18), compared with the base case, the heat flux of the channel with the rectangular wing also has a higher value, the reason for this is the formation of the horseshoe vortices at the junction of the upstream face of the rectangular wing and the bottom channel wall. As one goes away from the region of the vortices, the heat flux goes on diminishing (Michael J. L. et al., 2008).

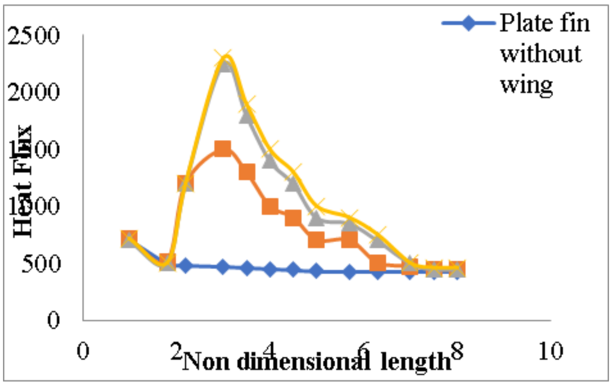

Figure 18. Comparison of heat flux at different angles of attack for a wing

From the figure 19, it is clearly shown that the variation is maximum for angle of 45°. As the value of angle of attack increases, the variation in the heat flux also increases due to increase in the strength of the vortices (Joardar & Jacobi, 2008).

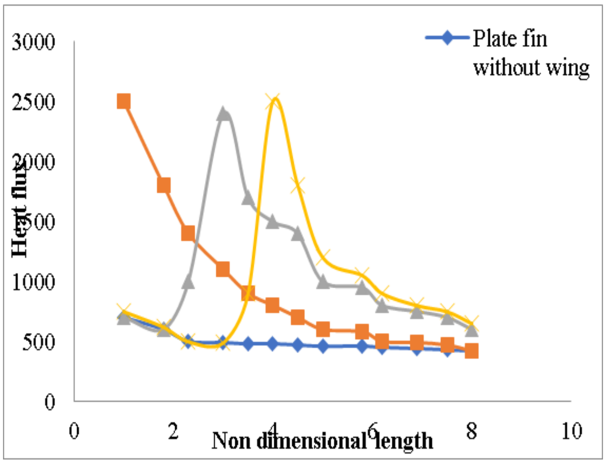

Figure 19. Comparison of heat flux at different locations for a wing

3. CONCLUSIONS

Numerical simulation was done for a wing & winglet. The effects of parameters like different angles of attack and different positions of LVGs were explored in order to see to what extent, the heat transfer and fluid flow structures get influenced by these parameters. The following are the conclusions drawn from simulative analyses:

- The rectangular wing or winglet when mounted on triangular fins disturbs flow structure and create longitudinal vortices. Heat transfer on extended gets augmented by using rectangular wings and winglets as LVGs.
- Span wise average Nu number is considerably increased with increase in angle of attack. In

case of rectangular wing there was almost an enhancement of 10.25 %, 15% and 33% in span wise average Nu number for angles of attack 15,25 and 45 degrees respectively in contrast with the channel devoid of any wing.

- The average heat flux also increased with increasing angle of attack. Similarly, the average temperature value increases for distinct attack angles are 11% for 20 degrees and 275 for 45 degrees.
- The pressure drop penalty increased with increase in angle of attack. The pressure loss must not burden the pumping power required to keep the fluid flowing through channel. The friction factor also gets affected in the similar fashion by angle of attack.
- The average Nu goes on increasing when the wing is placed nearer to inlet, suggesting that the wing can be mounted closer to inlet thereby reducing length of channel and thus material cost.
- The vortex generator for an approach angle of forty-five degrees gives better augmentation in contrast to relatively smaller angles. Thus, for both wing and winglet placed in triangular duct, the heat transfer parameters attain a maximum value for an angle of forty-five degrees. The wing must be mounted closer to inlet for economical design.

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