CFD Analysis & Experimental Investigation to improve Heat Transfer Enhancement in flat plate with W Ribs

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Abstract

Ribs on the opposite walls of internal cooling passages of gas turbine blades are often used for heat transfer Enhancement. Passages can be straight, converging or diverging. Rib Turbulators is an efficient and economic tool in heat transfer enhancement. These In this study, experimental data for local heat transfer coefficients are presented for a diverging channel with square cross section and rib roughening elements. Experiments are conducted to assess turbulent forced convection heat transfer behavior for air flow through a rectangular duct over a flat plate fitted with W shape ribs. Two rib arrangements namely in-line and staggered arrays, are introduced. Measurements are carried out for a rectangular channel of aspect ratio, AR=1.5 and height, H=100mm with single rib height, e=5mm and rib pitch, P=50mm. The flow rate is in terms of Reynolds number based on hydraulic diameter of rectangular duct in range of 57870 to 17362. The experimental result shows a significant effect of presence of ribs on heat transfer rate over smooth flat plate. The staggered rib arrangement provide higher heat transfers than in-line one for a similar mass flow rate. CFD analysis can be done using ANSYS 14.0. From the CFD results it is clear that Maximum heat transfer rate is for staggered arrangement.

Keywords: *Flat plate, Heat Transfer coefficient, Nusselt Number, Reynolds Number, Heat transfer Enhancement CFD, W-Ribs.*

1. Introduction

To obtain higher power output from the gas turbine engines, the inlet temperature of turbine has been increased in the recent engines. Due to increase in inlet temperature of turbine there is possibility of overheating of the turbine blades and it may result in blade failure. This could lead to engine failure and catastrophic effects. In order to prevent such failures, the blade surfaces must be maintained to acceptable limits. So, the cooling of blade surfaces must be considered. There are various methods to cool the turbine blade. For turbine blade cooling, rib turbulators are also used. Rib turbulators are used in gas turbine aero foils for enhancing the heat transfer rate via turbulence. Rib turbulators are widely used in industrial applications such as heat exchangers and the mixing of fluids. Rib turbulators have immense scope in rotating drums, sterilizers, heat transfer ovens, mixing and pelletizing machines, and air destratification fans for horticultural and agricultural uses. Rib Turbulators is an efficient and economic method of heat transfer enhancement. Repeated ribs or Turbulators have been used as the promoters of turbulence to enhance the heat transfer to the flow of coolants in a channel. These roughness elements break the laminar sub-layer of the flow. The heat transfer enhancement as well as the pressure drop, an important parameter in the analysis of the overall performance of such flows. Investigations have been conducted to predict the effect of the arrangement of ribbed walls on heat transfer and friction characteristics over the smooth Flat plate.

2. Literature Review

1. **Arvind Rohan Sampath** presented a detailed investigation of effect of rib turbulators on heat transfer performance in stationary ribbed channels where they examined thermal performance computationally for the stationary channels with rib turbulators oriented at 90 degrees. Ribs were placed on opposite walls and the heat transfer coefficients and frictional loss were calculated. The results obtained for all the channels with different rib configuration proved that the increase in rib width reduced the thermal performance of the channels. By combined effect of rib width, rib spacing and flow parameters, the optimal cooling configuration was obtained.
2. **Navanath G. Ghodake, Prof, MRC. Rao** carried out flow and heat transfer analysis of various ribs for force convection heat transfer. In this they performed cfd analysis of different shaped ribs such as v-ribs (simple and broken v-ribs), triangular and rectangular ribs placed rectangular duct. The work is

carried out in two stage:- 1. Modeling of ribs for different shapes in CATIA, 2. Analysis of flow and predict the best suited rib among the various rib considered and this analysis has been done in ANSYS CFD. from the analysis they conclude that the result obtain by CFD analysis shows that the temperature of 321.102k with the maximum heat flux of 28 w/m^2 and maximum heat transfer coefficient of 78 w/m^2 for rectangular taper rib. This analysis also conclude that broken v (45 degree) rib has highest temperature of 323k,with maximum heat flux of 28 w/m^2 and maximum heat transfer coefficient of 76 w/m^2.

3. **Ahmed M. Bagabir and Ahmed S. Hassan** , Studied turbulent periodic flow and heat transfer in a square channel with different ribs. A numerical investigation has been carried out to examine turbulent flow and heat transfer characteristics in a three-dimensional ribbed square channels.Fluent 6.3 CFD code has been used. The governing equation are discretized by the second order upwind differencing scheme, decoupling with the SIMPLE algorithm and are solved using a finite volume approach. The fluid flow and heat transfer characteristics are presented for Reynolds numbers based on channel hydraulic diameter ranging from 10^4 to $4* 10^4$. The effects of rib shape and orientation on heat transfer and pressure drop in channel are investigated for six different rib configuration. Rib arrays of 45^0 inclined and 45^0 V-shaped are mounted in inline and staggered arrangement on the lower and upper walls of the channel.

4. **Satyanand Abraham, Rajendra P. Vedula**, presented a similar investigation of heat transfer and pressure drop measurements in a square cross-section converging channel with V rib turbulators. In which Ribs on the opposite walls of internal cooling passages of gas turbine blades are often used for heat transfer enhancement. These passages can be straight, converging or diverging. In this study, experimental data for local heat transfer coefficients are presented for a converging channel with rib roughening elements with the cross-section being maintained square from inlet to exit. The local heat transfer coefficient distribution shows the same qualitative behavior observed for the straight channel.

Priyank Lohiya, Shree Krishna Choudhary, conducted a numerical study on heat transfer of turbulent duct flow through ribbed duct. Ribs have been used as a tool to enhance heat transfer by increasing the level of turbulence mixing in the flow. Rib roughness on the underside of the top wall of a duct has been found to substantially enhance the heat transfer coefficient. A two-dimensional CFD investigation is conducted to study forced convection of fully developed turbulent flow in a rectangular duct having ribs on the underside of the top wall. CFD solutions are obtained using commercial software ANSYS FLUENT v12.1. The working fluid in all cases is air.

5. **Gurav utekar, Vivekanand Navadagi**, investigated performance analysis of solar collector with inline and perforated W shape rib roughened absorber plate for air heating application. Investigation have been carried out by testing the collector under clear sky with available solar radiation intensity with variation in mass flow rate of air passing through collector ranging from 0.01484kg/sec to 0.01726 kg/sec for three different absorber plates. Collector Efficiency has been evaluated for plane absorber plate and compare with absorber plate having inline and staggered shape plate. It is found that instantaneous collector efficiency for staggered w shape perforated fin roughened absorber plate solar collector is 18% higher as compared with plain absorber plate solar collector for mass flow rate of 0.01726kg/sec and 12% higher than the absorber plate with inline w shape rib Roughened absorber plate collector. Enhancement in collector efficiency is due to increase in the turbulence of the air for staggered w shape absorber plate solar collector. **Gap Identified in the literature:**

Ref No	Geometry	Methodology	Finding	Gap
1	Rib with 90^0	Numerical	combine d effect of rib	No Exp
2	Rectangular rib, triangular rib, v-rib	CFD	Rectangular taper rib and v-rib gives maximu m heat transfer coeff.	NO Experimental
3	45^0 inclined and 45^0 Vshaped are mounted in inline and staggered arrangement	CFD	Virib with staggere d arrange ment gives max. heat transfer	No Exp
4	V rib turbulators	Exp	Nu 20 % increses e	No CFD
5	ribbed duct	CFD	Nu 30 % increses e	No Exp
6	W shape rib	CFD	18% higher	No Exp

Thickness = 10mm

3. Nomenclature

Table 1 Nomenclature

Sr. No	Nomenclature	Description
1	Re	Reynolds Number
2	Nu	Nusselt Number
3	V	Flow Velocity, m/s
4	T	Temperature, K
5	H	Convective Heat Transfer Coefficient, W/m^2-K
6	K	Thermal Conductivity, W/m-K
7	D	Diameter
8	Q	Heat Transfer Rate
9	dP	Change in Pressure
10	ΔT	Change in Temperature

From above analysis it can be concluded that w-rib with inline and staggered arrangement have not been experimentally investigated.

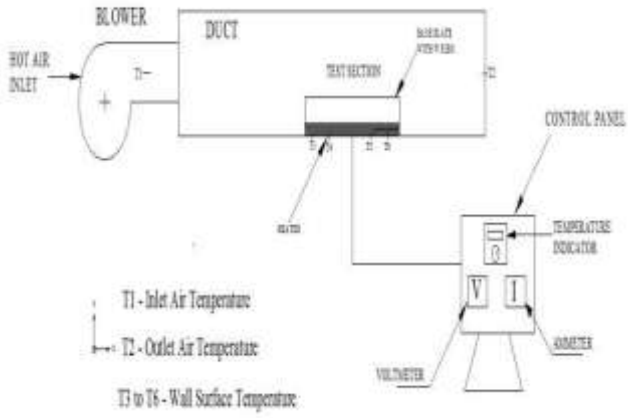


Fig.1 Schematic of Experimental Set up

4. Experimentation

Experimental set up has an insulated rectangular duct, flat plate, blower which is used to regulate mass flow rate of air. An insulated rectangular glass duct is used in which test section i.e. flat plate is accommodated. A heater is placed beneath the aluminum plate for heating of flat plate. There is a temperature sensor along with digital temperature indicator to measure inlet and outlet temperature of air. Thermocouples also measure the surface temperature of flat plate. The schematic diagram of the experimental set up is shown in fig.1 the air is taken from atmosphere and pressurizes when it passes through blower, the pressurized air then flows through valve where flow is regulated. The velocity of air is measured at exit of **Fig.2** Actual of Experimental Set up rectangular duct by anemometer. The air is fed to rectangular duct where it absorb the heat from the flat plate which receives the heat from heater which is kept at beneath of flat plate. The heated air then taken out from the outlet of rectangular duct.

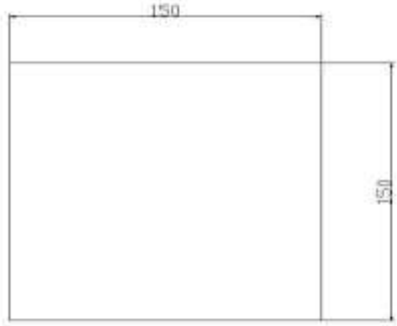


Fig.3 Smooth flat plate

Rectangular Duct:

An insulated rectangular duct of square cross section area having physical parameter as follows- Material of duct= glass

- Width of duct = 150mm
- Height of duct = 100mm

Flat plate:

- Material = Aluminum
- Width = 150mm
- Height = 150mm

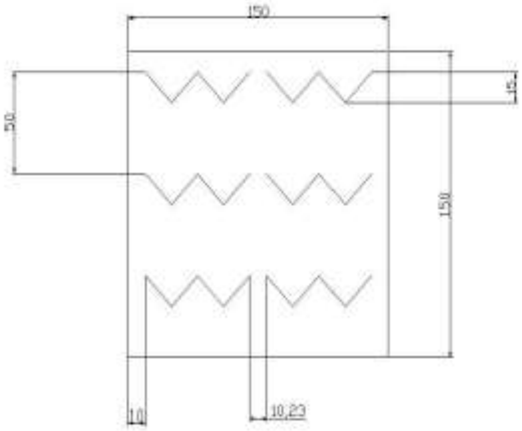


Fig.4 Inline W shape rib on flat plate

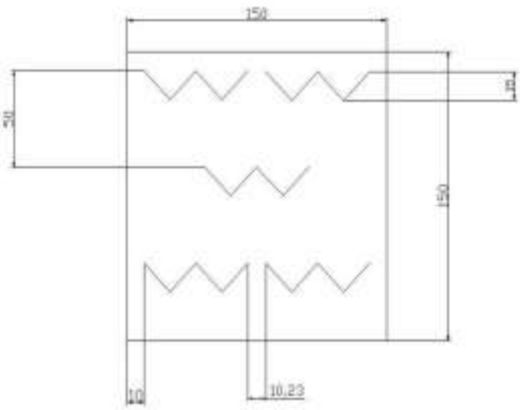


Fig.5 Staggered W shape rib on flat plate

5. Test Methodology

A) Arrangement of W-ribs- The experiment was carried out using In-line and staggered arrangement of W-ribs.

B) Various flow conditions - characterize by Reynolds number (57870 ≤ Re ≤ 17362). The study was conducted using Experimental and CFD methods.

Table 2 Flow Conditions

Sr. No.	Reynolds Number	Velocity, m/s
1	5787	1.0
2	8681	1.5
3	11,575	2.0
4	14,468	2.5
5	17,362	3.0

The experiment was conducted for various operating conditions to develop the complete understanding of the heat transfer mechanism. The flow condition ranging from Re=6,000 to Re = 18,000 was considered. Thermal performance of this study is based on difference between the hot outlet temperature and cold inlet temperature (ΔT).

Table 3 Variation of Temperature Differences

Sr. No.	Velocity m/s	Arrangement of W-rib	Inlet Temp., K	outlet Temp., K	Temp. Difference, ΔT, K
1	1	Smooth plate	314	318	4
		In-line W rib	315	323	8
		staggered	316	328	12
2	1.5	Smooth plate	315	321	6
		In-line W rib	316	326	10
		staggered	315	331	16
3	2.0	Smooth plate	315	326	11
		In-line W rib	316	332	16
		staggered	315	335	20
4	2.5	Smooth plate	315	328	13
		In-line W rib	316	334	18
		staggered	314	333	19
5	3.0	Smooth plate	315	331	16
		In-line W rib	316	338	22
		staggered	314	336	22

C) Heat source - Constant heat supply of 20W (V*I= 40*0.5) is provided at beneath of flat plate using Voltmeter and Ammeter.

The test specimen (smooth flat plate) was placed in rectangular duct and blower operation started. At first, in control panel adjust voltage and current that supply const. heat source (thermal energy) to flat plate then the blower is turn on to supply the air. From the anemometer readings the stability of flow is monitored. Once the flow stability is achieved, the temperature from T-1 to T-12 is to be monitored for the steady state condition. Same method will be repeated for test specimen with in-line and staggered W-rib arrangement.

6. Data Deduction

For data deductions following are the steps required:

1. Heat absorb by air = Q = m × cp × ΔT Watt were imposed on the model. Fluid inlet:

Velocity inlet boundary condition [velocity, static temperature].

2. Change in temperature of air ΔT=To –Ti ^{0}K

3. Temperature of air= Tm= (Ti+To)/2 ^{0}K Adiabatic, No-slip, stationary walls.

4. Heat absorb by air = Q = m × cp × ΔT = h × A × ΔTs

5. ΔTs= (Ts-Tm)

6. Power supply= V × I

7. H = Q/A × (ΔTs) W/m^{2}K

8. Re=ρ × V× D× h/μ

9. $D_h = 4 \times d_{Across}/P$

10. Nu= h×D_h/K

11. Enhancement Ratio is calculated by taking the ratio of Nusselt number of modified plate i.e. w-rib inline and w-rib staggered to Nusselt number of smooth plate

$$E_{Nu} = \frac{Nu_{modified}}{Nu_{smooth}} \quad (1)$$

12. Pressure drop penalty is calculated by taking the ratio of Pressure drop of modified plate i.e. w- rib inline and w-rib staggered to Pressure drop of smooth

plate

$$E_{\Delta p} = \frac{\Delta P_{modified}}{\Delta P_{smooth}} \quad (2)$$

13. Performance Enhancement Factor is calculated by

$$PEF = \frac{\frac{Nu_{modified}}{Nu_{smooth}}}{\frac{\Delta P_{modified}}{\Delta P_{smooth}}} \quad (3)$$

14. Friction Factor f=2×D×h×Δp/ρ×v^2 in Lc

7. CFD Methodology

3-Dimensional, Steady-state CFD simulations were performed using ANSYS FLUENT V16.0. In this project Work includes the convection heat transfer from the solid surfaces to the adjacent air and the conduction heat transfer in the smooth plate. This combined mode heat transfer is called 'conjugate heat transfer'. The 'pressure based solver' was chosen for the simulations With includes he consideration to the low speed flows in this problem. Air density and other properties such as viscosity, specific heat will be considered as constant values. The Realizable k-epsilon turbulence model was applied for the simulation as per the suggestions from the literature. Based on the literature survey, the following appropriate boundary conditions

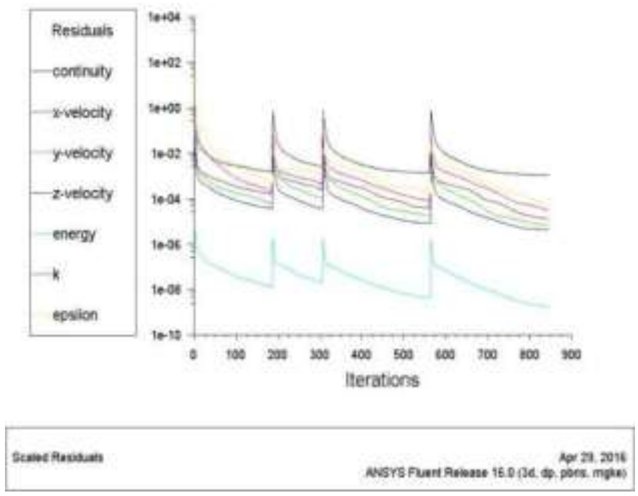


Fig.6 Scaled Residuals

The simulation was defined as converged based on the following criteria

1. Governing equation residual reduction

2. Conservation of fluid flow mass between flow inlet and flow outlet 3. Conservation of energy

This approach is applied for all the simulations in this project work.

Fig.7 & Fig. 8 shows velocity contours & Temperature contours for Smooth flat plate, Inline & Staggered W rib on flat plate. For air velocity of 3 m/s.

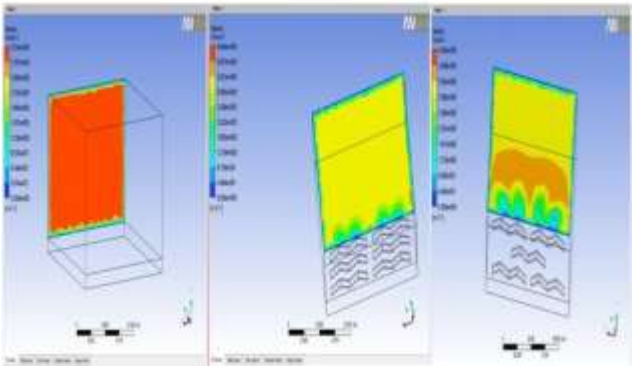


Fig.7 Velocity contours for Smooth flat plate, Inline & Staggered W rib on flat plate.

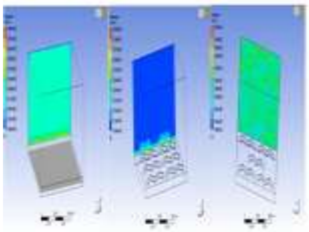
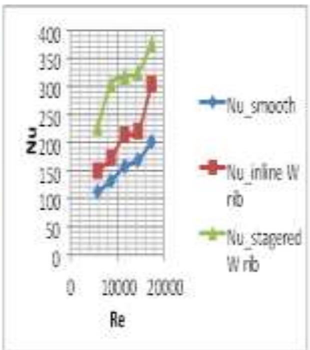


Fig.8 Temperaturecontours for Smooth flat plate, Inline & Staggered W rib on flat plate.



8. Result and Discussion

Figure 9 shows variation of heat transfer coefficient to Reynolds Number. This graph indicates that there is higher heat transfer coefficient for staggered w rib than inline and smooth plate. It varies from 86% to 103 % than smooth plate. If staggered w rib and inline rib are compared there is increase in heat transfer coefficient from 23% to 52%. Figure 10 shows variation of Nusselt to Reynolds Number. This graph indicates that there is higher heat transfer enhancement for staggered w rib than inline and smooth plate. It varies from 86% to 103 % than smooth plate. If staggered w rib and inline rib are compared there is increase in heat transfer enhancement from 23% to 52%.

Figure 11 shows variation of enhancement factor to Reynolds Number. This graph indicates that there is higher enhancement factor for staggered w rib than inline and smooth plate. If inline w rib and smooth plate are compare then enhancement factor varies from 1.33 to 1.52 whereas staggered w rib to smooth plate it varies from 1.8 to 2.31.

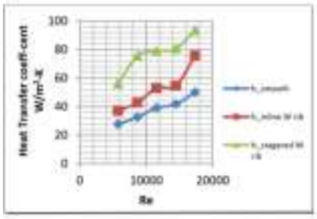


Fig.9 Variation of heat transfer coefficient to Reynolds Number.

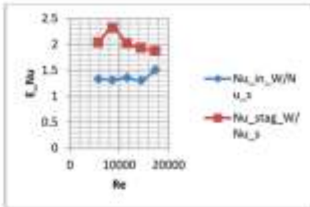


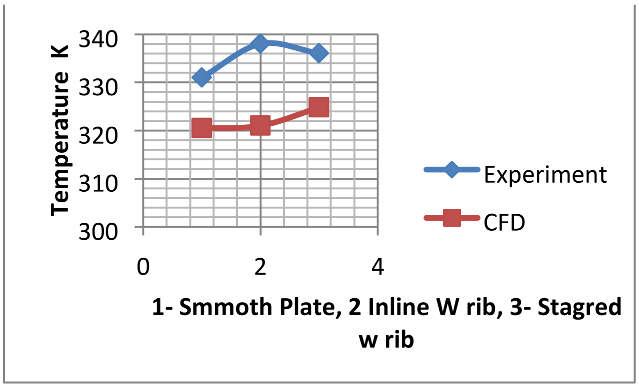
Fig.11 Variation of Enhancement factor to Reynolds Number.

Hence from above graphs it is concluded that staggered w- ribs are gives higher heat transfer enhancement than inline w-rib and smooth plate. So such type of configuration one can use for different cooling system such as electronics cooling system.

Table 4 Comparison of experimental & CFD results for 3m/s air velocity

Sr, No.	Outlet temperature of air Temperature, K			
1	Test specimen	Experi ment	CFD	%Differ ence
2	Smooth plate	331	320.5	3.32%
3	Smooth plate with In-line w ribs	338	321	5.029%
4	Smooth plate with staggered ribs	336	324.8	3.27%

Fig.12 Deviation of Temperature of CFD and Experimental result



9. Conclusion

Experimental investigation on inline w-rib and staggered w rib are compared with smooth plate with Reynolds number from 5787-17362. Following are the conclusions of this work.

CFD simulation for smooth plate, w inline and staggered ribs are performed and w inline and staggered ribs shows effective fluid mixing and development of secondary flow which helps in to improvement of heat transfer enhancement.

Heat transfer coefficient varies from 86% to 103 % than smooth plate. If staggered w rib and inline rib are compared there is increase in heat transfer coefficient from 23% to 52%.

The enhancement factor for inline w rib to smooth plate varies from 1.33 to 1.52 whereas staggered w rib to smooth plate it varies from 1.8 to 2.31.

The deviation of CFD results from the experimental data was with-in acceptable limits and serves as a validation for this research work as shown in Fig 12.

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