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Numerical and Experimental investigation of Heat transfer of triangular ribs in divergent channel

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Abstract
Ribs are famous heat transfer enhancement device used in many heat exchanging channels. This technique of attaching ribs to the flow passages has become one of the wide uses in many industrial applications. Ribs increases the turbulent kinetic energy caused by the flow disturbances, increasesthe rate of heat transfer in the duct. From the past researches, it is also observed that for a smooth straight duct/channel, a small variation in the cross-sectional area may produce significant difference in the local and the average heat transfer patterns. In this study, CFD simulations are presented to assess forced convection heat transfer and pressure drop for the air flow through a divergent duct with triangular ribs in staggered and inline arrangement. Measurements are supposed to be carried out on flat aluminium plate in divergent channel for triangular ribs with aspect ratio of 2 and rib height e= 3 mm with varying p/e ratios, at fixed angle of attack as 45°at Reynolds numbers considered in a range of 4000 to 7000.The CFD results show that there is a significant effect on heat transfer rate over smooth divergent duct due to the presence of rib and concluded that the inline arrangement of ribs gives best heat transfer augmentation than staggered for the same mass flow rate.

Keywords*:Divergent duct, Ribs, Nusselt Number, Heat transfer coefficient, Reynolds Number, pressure drop,CFD.*

1. Introduction

In order to obtain higher power output from the gas turbine engines, the turbine inlet temperature had been increased in the recent engines. This high temperature could lead to overheating of the blades and may result in blade failure.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 and one of the most popular methods is by using rib turbulators. Many other heat transfer augmentation techniques are also used such as fins, ribs, dimpled surfaces, and protruding surfaces that generate vortices in a heat exchanger. Rib turbulators are used in gas turbine airfoils for increasing the heat transfer rate via turbulence, heat exchangers and the mixing of fluids. Rib turbulators have major scope in the applications such as rotating drums, sterilizers, heat transfer ovens, mixing and pelletizing machines, and air de-stratification fans for horticultural and agricultural uses. Rib Turbulators are an efficient and economicalway of heat transfer augmentation. Repeated ribs 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 is enhanced as well as the pressure drop is an important parameter in the analysis of the overall performance of such flows.There are many investigations have been performed to study the effect of ribs in the channel on improvement of heat transfer.

Experimentswere conducted to evaluatethe thermal performance for the straight rectangularchannel with rib turbulators of different cross-sections such as triangular, right-angle triangular and rectangular. Ribs were placed on opposite walls of the channel. Heat transfer coefficients and frictional loss were calculated. The results obtained for all the ducts with different rib shapes proved that the isosceles triangular shaped rib had given best heat transfer performance with in-line rib arrangement PongjetPromvonge, et al(2008).
Investigations are evaluated by conducting the experiment to assess the thermal performance for the rectangular channel fitted with triangular ribs of different heights with in-line and staggered arrays. The flow rate in terms of Reynolds numbers was considered in a range of 5000 to 22,000. They found that the in-line rib arrangement provides more heat transfer and friction loss than the staggered one for the same flow rate. Comparison among ribbed channel and smooth channels is done and they found that the largest e/H of 0.13 rib with inline array performed best in terms of both the Nusselt number and the friction factor C. Thianpong et al(2009). Numerical investigation on turbulent forced convection in a channel withdifferent shapes of ribs such as square, rectangular, trapezoidal and triangular was done using water as the flowing fluid in their experiment.The main aim of said analysis was to assess the heat transfer rate of the straight channel with ribs by the use of fluent code v6.3. The flow rate in terms of Reynolds numbers was considered in the range between 20000 and 60000. It is found that the most significant thermal

performances are provided by triangular ribs with w/e= 2.0 OronzioManca et al (2011). Thermal performance was presented to investigate the heat transfer to the fluid flow through a straight channel with triangular ribs of different angles. The flow rate in terms of Reynolds numbers was considered in a range from 20000 to 60000 by using Ansys ICEM &Fluent V14. It is found that the highest value of average Nusselt number was obtained for triangular ribs of angel 60° compared to the Nusselt number for the ribs of angle 90° and 45° at Reynolds number of 60000TuqaAbdulrazzaq et al (2013). Experimental investigation was carried out to evaluate the thermal performancein a narrow diverging channel with and without ribs with a representative Reynolds number of 28000. This analysis showed ribbed ducts provided higher heat transfer coefficients Justin Lamont et al (2013). Experimental investigation was done to assess heat transfer and pressure drop ofturbulent flows with a fixed rib height through the rectangular convergent and divergent channels with square ribs.The flow rate in terms of Reynolds numbers was considered in a range from 15,000 to 89,000.Comparison of the thermal performance of the ribbed rectangular divergent/convergent channelswith the ribbed square straight channel showed that among the four types of channels, the divergent channel of D2(Dho/Dhi =1.49) performed best at the same mass flow rateM.S.Lee et al(2013).

Comparison of heat transfer and pressure drop between smooth and divergent rectangular ducts with different heights of ribsof e=3, 6 and 9 mm was done experimentally and concluded that the 3 mm height rib performed best than 6, 9 mm rib height and the pressure drop for 6 and 9 mm rib height was higher than 3 mm Dr. Natarajan et al (2014). Experimental investigation was carried out to assess the thermal performancein divergent and convergent ducts with square ribs arranged in staggered arrangement at the inner surface of duct for the range of velocity from 3.2 to 16 m/s. (Reynolds's number: 5000-25000) and compared with plain divergent duct. He observed that the thermal performance of divergent duct with ribs was higher than the plain divergent duct and increased by 34% due to the presence of ribsK. R. Chavan et al(2015).

3. Concept of Rib turbulators:

Attaching of ribs to the flow passages has become one of the most widely used mean of heat transfer enhancement techniques and has many industrial applications such as cooling passages of gas turbine blade, compact heat exchangers, fuel elements in advanced gas-cooled reactor, electronic cooling devices, etc. The flow disturbances due to the rib arrays greatly increase the production of turbulent kinetic energy which enhances the turbulent heat transfer in channel.

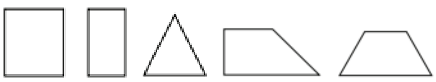

Fig.1 different Shapes of Ribs promoters

The shape of rib cross section affects the formation of separation bubble behind the rib and amount of turbulent kinetic energy production, thus the rib shape is the major factor that determines the heat transfer performance of rib.

3.1 Terminology used for rib turbulators:

- Roughness height (e/D): Roughness height (e/D) is defined as the ratio of rib height to channel hydraulic diameter. It is also called the blockage ratio which is a characteristic of a kind of roughness.
- Roughness pitch (p/e): Roughness pitch (p/e) is defined as the ratio of distance between two consecutive ribs and height of the rib.
- Angle of attack (α): Angle of attack is defined as the inclination of rib with direction of air flow in duct.
- Aspect ratio: It is defines as the ratio of duct width to duct height. This factor also plays a very crucial role in investigating thermo-hydraulic performance.

4. Test Geometry Model:

Fig. 2 shows thegeometry which has been considered in this simulation to study effect of ribs on heat transfer. The total length of channel is 500mm. Three pitch by height ratios are presented (p/e=8, 10&12) with Reynolds number range from 4270 to 6398.

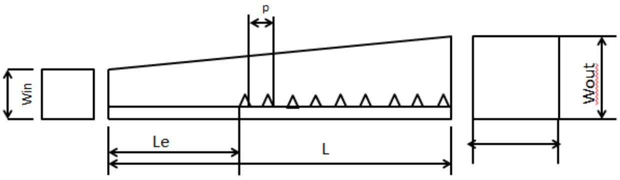

Fig.2 Test Geometry

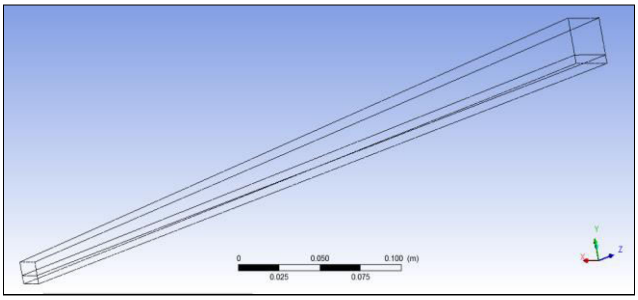

Fig. 2.a. plain divergent duct

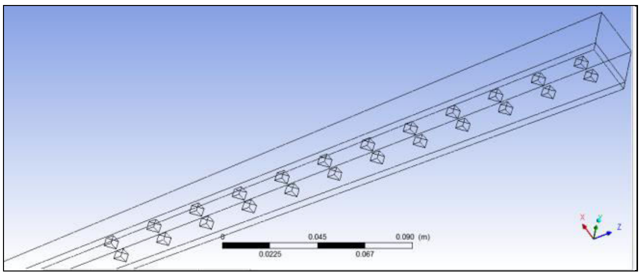

Fig. 2.b. Divergent duct with ribs inline arrangement

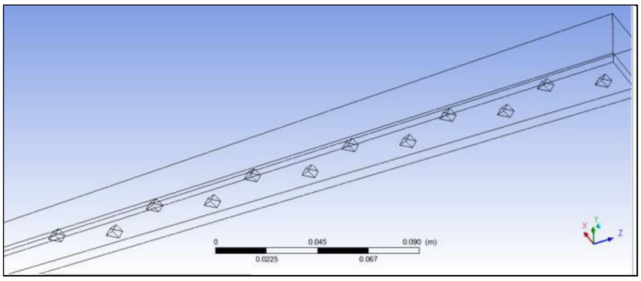

Fig. 2.c. divergent ribbed duct with staggered arrangement

5. Experimental Set up

Experimental set up mainly consists of an insulateddivergent duct, flat plate, blower which is used to regulate mass flow rate of air. A divergent duct made up of Acrylic material in C section is used in which the test section i.e flat plate with triangular ribs is accommodated. A heater is placed beneath the aluminum plate for heating of flat plate. Temperature sensors along with digital temperature indicator are used 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 as shown in fig.3. Air is taken from atmosphere pressurizes when it passes through blower, the pressurized air then flows through a flow control valve where flow is regulated. The velocity of air is measured at exit of divergent duct by anemometer. The air is fed to the duct where it absorbs the heat from the flat plate which receives heat from heater which is kept at beneath of flat plate. The heated air then taken out from the outlet of divergent duct.

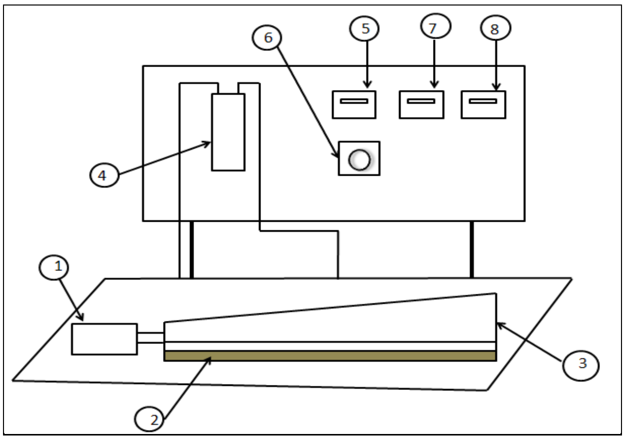

Fig. 3Experimental Setup

From Fig.3: (1) Blower (2) Plate type Heater (3) Test section (4) U- tube manometer, (5) Digital temperature indicator (6) Control valve, (7) Voltmeter (8) Ammeter

6. Data Reduction:

For data reductions following are the steps required:

1. Heat Extracted by the air = $Q = mCp\Delta T$
2. Change in temperature of air = $\Delta T = (To - Ti)$ K
3. Bulk mean temperature air = $Tf = (To + Ti)/2$
4. Temperature difference $\Delta Ts = Tw - Tf$
5. Heat transfer rate = $Q = hA\Delta T$ Watts
6. Coefficient of heat transfer = $h = Q/(A\Delta T)$
7. Hydraulic diameter = $Dh = 4Acs/P$
8. Reynolds Number= $\mathrm{Re} = (\rho VDh)/\mu$
9. Nusselt Number = $Nu = hDh/K$
10. Enhancement Ratio
    $ENu = Nu(\mathrm{mod}\,ified)/Nu(smooth)$
11. Friction factor = $(2Dh\Delta P)/(LU^2)$
12. Enhancement ration in terms of friction factor=
    $Ef = (f\ \mathrm{mod}\,ified\ /\ fsmooth) \wedge (1/3)$
13. Performance Enhancement Factor= PEF= ENu/Ef

7. CFD Methodology

3-Dimensional, Steady-state CFD simulations are performed using ANSYS FLUENT V15.0. A second order upwind scheme for momentum and energy equations are considered with SIMPLE coupling for couple velocity and pressure drop. This project work includes the convection heat transfer from the solid surfaces to the adjacent air; and the conductive heat transfer in the triangular ribs.

The pressure based solver is chosen for the simulations with the 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 is applied for the simulation.

6.1 Boundary conditions:

The following appropriate boundary conditions were imposed on the model.

- Inlet: Velocity inlet boundary condition [velocity, static temperature].
- Outlet: Pressure Outlet [atmospheric pressure].
- Heat source: constant heat flux
- Walls: constant Adiabatic, No-slip, stationary wall

Test geometry Meshing tool ICEM 15 has been used and these are shown as following:

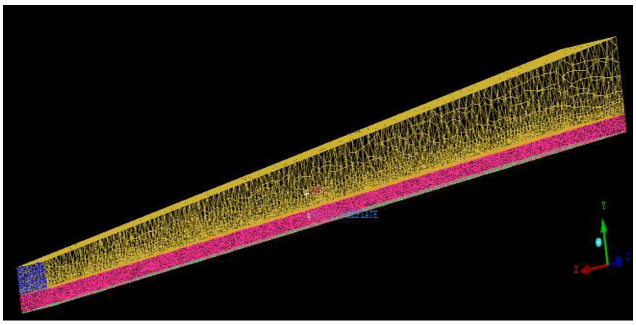

Fig. 4meshing for plain divergent duct

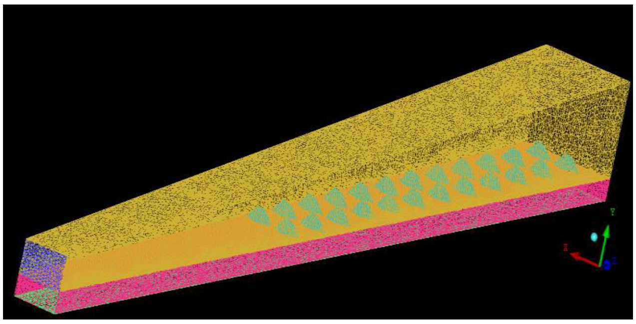

Fig.5 meshing for ribbed divergent duct with inline arrangement

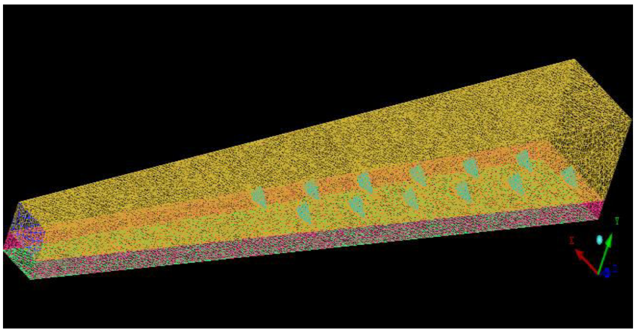

Fig.6meshing for ribbed divergent duct with staggered arrangement

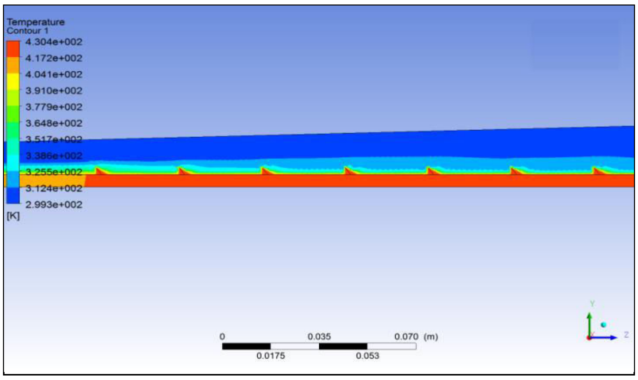

Fig. 8 Temperature Contour for ribbed divergent duct

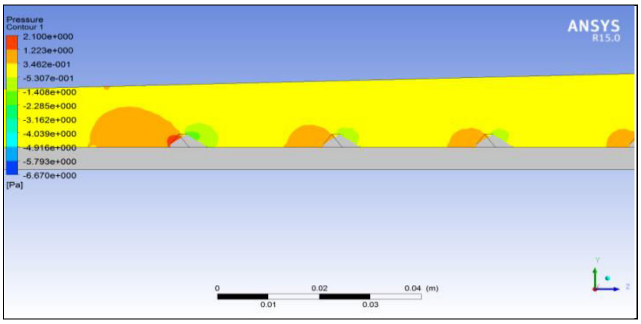

Fig. 9 pressure contour for ribbed divergent duct

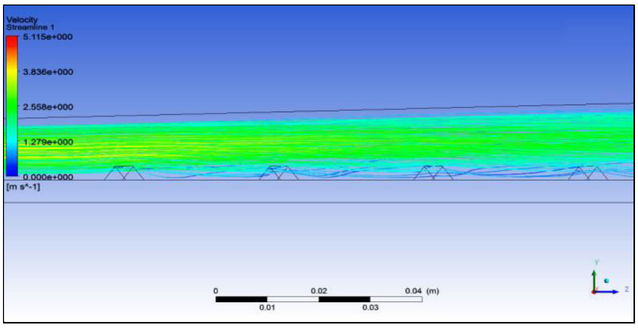

Fig.9 Velocity Streamline for ribbed divergent duct

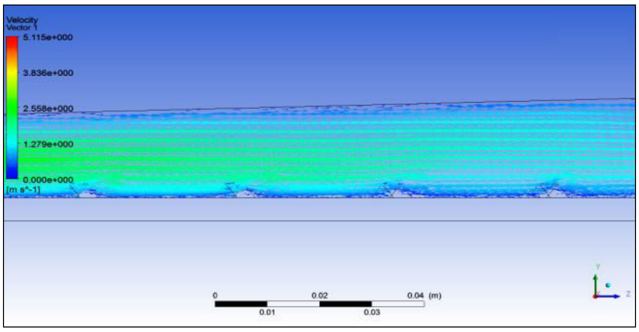

Fig. 10 Vector Velocity for ribbed duct

8. Results and Discussion:

Figure 11shows variation of heat transfer coefficient with Reynolds Number. This graph indicates that there is higher heat transfer coefficient for inline rib with p/e=8 than staggered ribs and plain duct. It varies from 25% to 50% than plain divergent duct.
Figure 12shows variation of Nusselt number with Reynolds Number. This graph indicates that there is higher heat transfer enhancement in terms of Nusselt number for inline rib with p/e=8 than staggered ribs and plain duct. It varies from 20% to 45% than plain duct. Figure 13. Shows the variation of friction factor with Reynolds number and it is found that staggered arrangement of triangular rib shows higher values compared to inline rib arrangement.

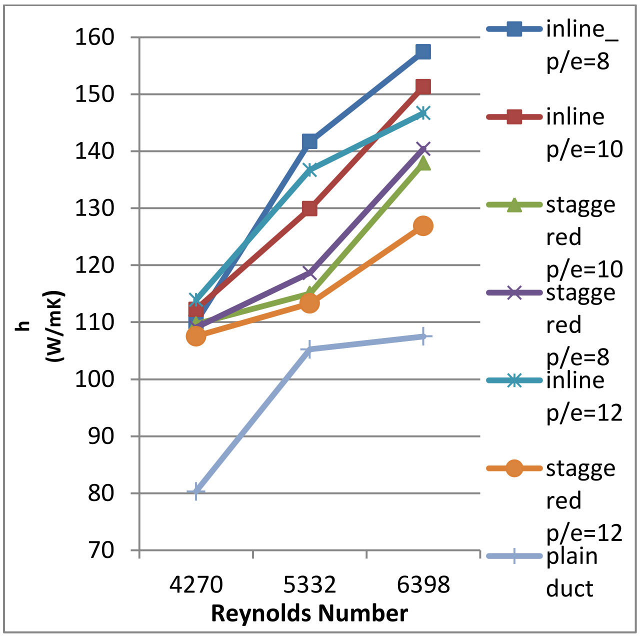

Fig. 11 Variation of heat transfer coefficient with Reynolds Number

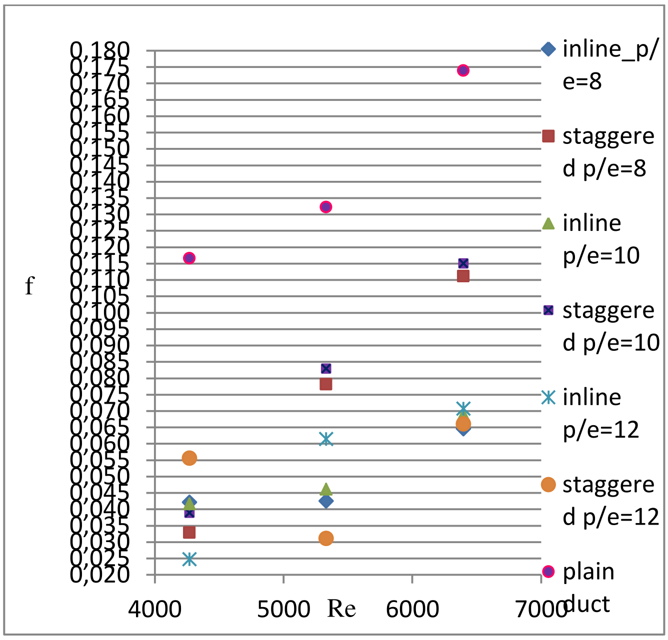

Fig. 13 Friction factor

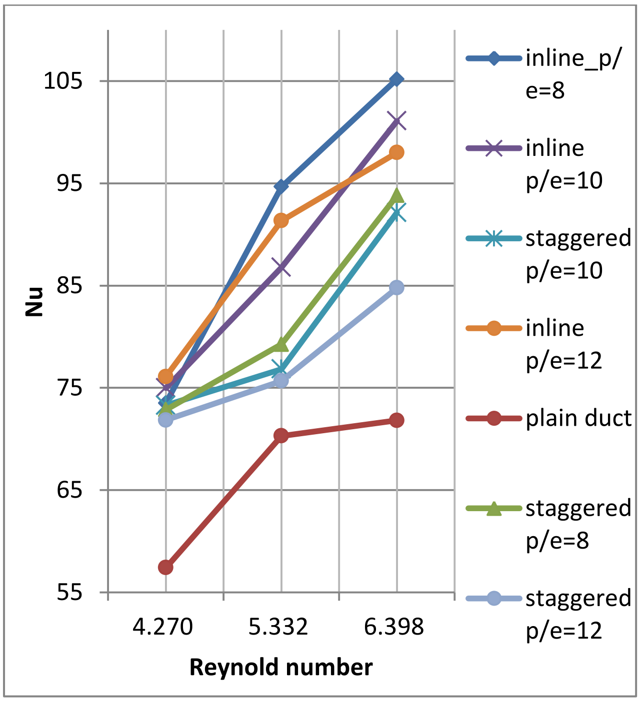

Fig. 12 Variation of Nusselt Number with Reynolds Number

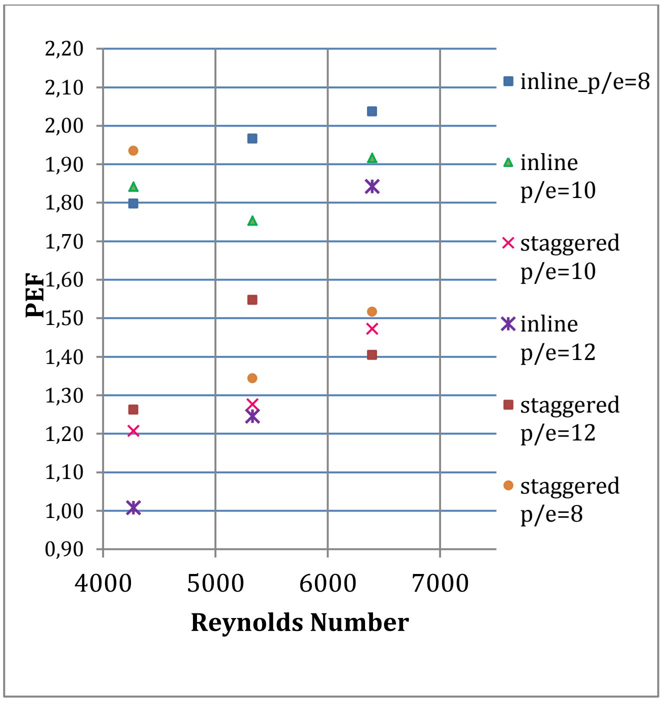

Fig. 14 Performance enhancement factor

9. Conclusions

CFD simulation study onheat transfer to air flow in the divergent channel with triangular ribs with inline and staggered rib arrangements is conducted and compared with smooth divergent channel in the present study. Following are the conclusions of this work.

1. The resultsindicate that the Nusselt number increases with increase in Reynolds Number for all cases
2. The greatest improvement of heat transfer is observed at the Reynolds Number of 6398 for the inline arrangement of triangular ribs with p/e ratio of 8.
3. Highest value of Performance Enhancement factor is found to be PEF =2.04 for the inline rib arrangement and optimum p/e ratio is found to be at p/e=8

NOMENCLATURE

Win	width of duct at inlet, m
Wout	width of duct at outlet, m
L	Total Length of duct, m
Le	Entrance length, m
e	Ribheight, m
p	pitch of rib, m
Cp	Specific heat, J/kg k
Nu	Nusselt number
P	Pressure, Pa
Re	Reynolds number
Dh	Hydraulic diameter, m
Ti	Temperature of air at inlet, K
To	Temperature of air at onlet, K
ΔT	Temperature difference, K
Tf	Bulk mean temperature, K
ΔP	Pressure drop, Pa

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