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Numerical Investigation of Heat and Flow Characteristic of Air Jet Impingement Over Heated Tube

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Abstract: **This work present the investigation of heat transfer and flow characteristics of air jet impingement over heated tube. Two cases are studied in this investigation, first case is considering isothermal tube at constant temperature of 453 K, and second case is compressed air with inlet temperature of 453 K entering at tube inlet. The velocity profile, and Nusselt number over the tube are evaluated in this study, by comparing the jet slot height, effect of change in Reynolds number, effect of change in distance of jet to impingement tube, effect of splitting of slot into one, two and three slots, and the effect of changing the distance between two slots. The results are proposed in terms of Nusselt number, for the case of isothermal tube. Similarly, for the second case, the results are plotted in terms of drop in temperature of hot air at the exit end of the tube. The comparison is done for the effective cooling by using air jet impingement system.**

Keywords: **Jet, Jet geometry, Nusselt number, Reynolds number, Temperature.**

I. INTRODUCTION

Supercharging is a very common requirement of all high power internal combustion engines. A supercharger is an air compressor that increases the pressure or density of air supplied to an internal combustion engine. This finds wide application particularly in heavy duty diesel automotive vehicles. Supercharged engines are generally provided with an intercooler connected in between the supercharging duct and adapted to cool the air leaving the turbocharger unit before being it is admitted into the intake manifold. Air required for the combustion of fuel, is first compressed in a compressor to increase air density. Due to the compression, density of air increases, which finally leads to improved volumetric efficiency. But with increase in density of air, air gets heated up extraordinarily, which is undesirable for better engine performance. Therefore the compressed air needs to be cool, before it enters into the intake manifold. Conventional air cooled intercooler which was in use for a long period of time, is now not being used due high cooling load of new generation high power diesel engines. The supercharging duct connecting compressor exit to intercooler is extremely hot, which needs a cooling mechanism. Jet air cooling is an effective technique for such application which practiced in several engine systems. Air Jet Impingement system has been an area of interest for electronic cooling, cooling to drying of textiles, continuous and other high heat flux removal applications, and is characterized by high heat transfer, uniformity of heat removal. But the mechanisms by which heat is removed during air cooling are poorly understood. This is due to complexity of mechanism of heat removal. The study of air jet impingement system has various parameters which effect the cooling process. These parameters are jet Reynolds number, mass flow rate of the air, air temperature, jet exit cross sectional area, number of jet used in a system, and jet to target distance.

Several researches have contributed in the development of understanding of heat a fluid flow characteristic of jet flow. Various studies of jet impingement such as jet flow over heated flat surface, circular rod, and concave surface have been done under different operating conditions and geometrical parameters. Gori [1] carried out an experimental investigation on the cooling of an externally finned cylinder with a slot jet of air. Two slots were employed with D/H equal to 2 and 4, where D is the diameter of the cylinder without fins and H the slot height. Local and mean Nusselt numbers were evaluated at several Reynolds numbers and distances from the slot exit. In another experimental investigation, the effect of a slot jet on an electrically heated circular cylinder is studied, by Gori and Bossi [2]. He investigate the effect of Reynolds numbers, the distance of the cylinder from the slot exit, on Mean and local Nusselt numbers. The maximum mean Nusselt number was observed when distance of cylinder was maintained 8 times of slot height. The ratio of cylinder diameter and slot jet height is taken as 4. The maximum mean Nusselt number is measured when the cylinder is set at a distance H, from the slot exit, such that H/S = 8. Gori and Petracci [3] has carried out the

Nomenclature

u	velocity in x direction, m/s	T	temperature, K
v	velocity in y direction, m/s	k	thermal conductivity, W/m K
w	velocity in z direction, m/s	E	rate of deformation
μ	dynamic viscosity, kg/ms	μ_t	eddy viscosity
ρ	density, kg/m^3	ϵ	rate of dissipation of turbulent energy
C_p	specific heat, kJ/kg K	$C_{1\epsilon}$, $C_{2\epsilon}$	constant, value 1.44 and 1.92 resp.
N_u	Nusselt number	R_e	Reynolds number

additional experiments in order to investigate the cooling of two smooth cylinders in row by a slot jet of air, in order to study the positions of the two cylinders in row. In the experiments, a slot jet of air is employed with a slot height, S, equal to the cylinder diameter, D, i.e. D/S = 1.0. The first cylinder is set at two distances H from the slot exit, H/S = 4 and 6, while the distance of the second cylinder from the first one, L, is variable from L/S = 2–11. The Reynolds number, Re in the range Re = 11,000–22,200. If the first cylinder is set at the dimensionless distance from the slot exit, which realizes the maximum mean heat transfer on the first cylinder, i.e. H/S = 6, the second one has generally a lower mean Nusselt number. It is also observed that, if the first cylinder is set at the dimensionless distance H/S = 4 the mean Nusselt number on the second cylinder is greater if its distance from the first one is in the range L/S = 3.5–7 for Re = 14,300–22,200. The effects of jet inlet geometry and aspect ratio on local and average heat transfer characteristics of nine confined impinging jet arrangements was investigated experimentally by Koseoglu [4] using thermo chromic liquid crystals. for temperature measurement. In addition, simulations were performed at the same mass flow rate for totally nine jet exit geometries including circular, elliptic and rectangular jets with different aspect ratios for dimensionless jet to plate distances 2, 6, and 12. It is observed from the above study, the effect of aspect ratio on local and average heat transfer decreases with increasing jet to plate distance. McDaniel [5] has experimentally investigated the heat transfer characteristics of circular cylinders exposed to slot jet impingement of air. The study focused on Reynolds numbers in the range 600 to 8000. Both contoured orifice and sharp-edged orifice jet configurations were investigated for cylinder diameter-to-jet width spacing of 0.66, 1.0 and 2.0, and for jet exit-to-nozzle width spacing in the range $1 < z/w < 11$. The average Nusselt number shows stronger Reynolds number dependence for the sharp-edged orifice than for the contoured orifice. A numerical investigation has been performed two-dimensional slot impingement onto two heated cylinders with different diameters turbulent flow conditions, by Varol [6]. Height of slot jet is taken as constant for all cases. The study is performed to see the effects of effective parameters on heat and fluid flow as jet Reynolds number ($11{,}000 \le Re \le 20{,}000$), diameter ratio of cylinders ($0.5 \le D1/D2 \le 1.5$) and ratio of distance between cylinders to slot jet high (L/S). These results were compared with earlier experimental and numerical works and good agreement was obtained. It is found that diameter ratios of cylinders can be a control element for heat and fluid flow. Jacob [7] studied numerical and experimental investigation of the effect of jet impingement on heated copper plate with heat flux maintained at 12000 W/m^2. Studies was conducted to see the effect of the geometrical parameters such as jet diameter, jet to target spacing and ratio of jet spacing to jet diameter on the heat transfer characteristics. The values of Reynolds numbers considered was in the range 7000 to 42000. It is observed that, For a given Reynolds number, the Nusselt number increases by about 28% if the diameter of the nozzle is increased from 1mm to 2mm.

An experimental and numerical investigations of turbulent circular air jet impingement cooling of a circular heated cylinder are presented by Singh [8]. The surface of the cylinder was maintained at constant heat flux condition. The Reynolds number, defined based on the nozzle diameter, was varied from 10,000 to 25,000. The geometric parameters such as the non-dimensional distance between the nozzle exit and the circular cylinder, h/d, and the ratio of nozzle diameter to the diameter of the heated target cylinder, d/D, were investigated for the range of 4–16 and 0.11–0.25. The local Nusselt number variation along the circumferential and axial directions obtained from the experimental studies are reported in this study. Also simulation is done for the various turbulent models like, RNG, SST, k–ε and k–ω. Olsson [9] has investigated the average heat transfer characteristics of the cylinder empirically. Heat transfer from a slot air jet impinging on a cylinder shaped food product placed on a solid surface in a semi-confined area was investigated using

CFD, with the k– ε, k–ω and SST models in CFX 5.5 were compared. The SST model predicts the heat transfer better than the other models and is therefore used in this study. The distribution of the local Nusselt numbers around the cylinder for various Reynolds numbers (23,000–100,000), jet-to-cylinder distances, H/d (2–8), and cylinder curvature, d/D (0.29–1.14) was determined. The results show that the local Nusselt numbers varies around the surface of the cylinder and Nusselt number increases with increasing Reynolds numbers.

Yang [10] carried out a numerical investigation, to study flow field and heat transfer characteristics of a slot turbulent jet impinging on a semi-circular concave surface under uniform heat flux. The turbulent governing equation was solved by a control-volume-based finite-difference method with a power-law scheme and k–ε turbulence model. Effect of Reynolds number on several combination of geometrical parameters were investigated by varying heat flux. It is observed that, the variations of local Nusselt numbers along the semi-circular concave surface decrease monotonically from its maximum value at the stagnation point. Craft [11] done the computations of the flow and heat-transfer from a row of round jets impinging onto a concave semi-circular surface, designed to reproduce important flow features found in internal turbine blade cooling applications. Linear and non-linear eddy-viscosity models are applied, with wall-functions to cover the near-wall layer.

II. PROBLEM DEFINITION AND NUMERICAL SETUP

A. Problem Definition:

Present work consists of cooling of heated tube by air jet slot. Impinging jets of air have been proposed as cooling method inside the engine of heavy trucks. In this work, heated tube diameter considered as 16mm, with thickness is 1mm, and length is 250mm. It is cooled by the jet slot of width 106mm, whereas jet height is varied as 4.25mm, 8.5mm, and 17mm. Inside tube temperature is maintained constant at 453 K. The air from the jet exit is maintained at temperature of 343 K, with Reynolds number R_e, varied as 4800, 10500, and 17,750, i.e. respective air jet velocity considered to be 6.24m/s, 13.65m/s, 23.08m/s. The distance between the nozzle exit and the heated tube is kept at 17mm, 42.5mm, 72.25mm. The diameter of the tube is kept constant throughout the investigation. The investigation is done considering following two cases.

(1) Isothermal tube at constant temperature of 453 K, and

(2) Compressed air with inlet temperature of 453 K entering at tube inlet

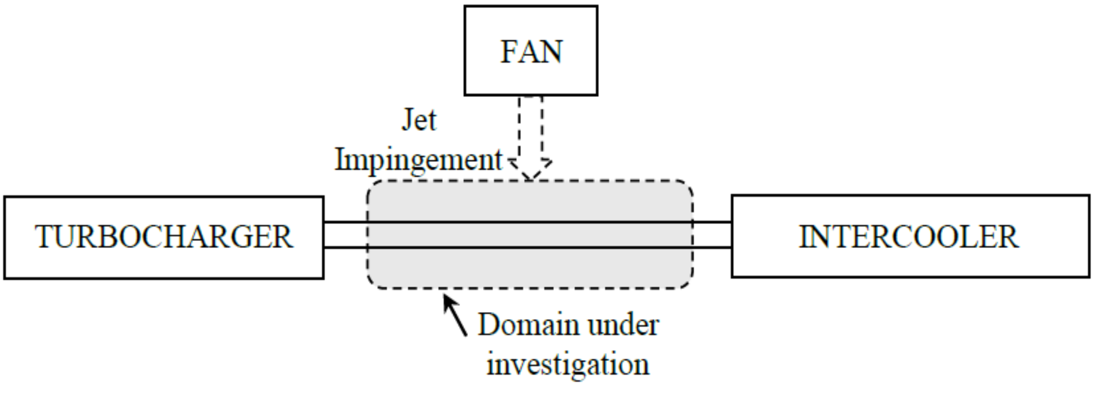

Fig.1: Schematic diagram of problem under investigation

B. Mathematical Model:

The problem under investigation has been modeled under following assumptions.

1. The flow is considered to be incompressible, steady and three dimensional.

2. Flow is turbulent.

Governing Equations:

The governing equations consist of continuity and momentum and energy equations, which are in differential form. There is no transient term as the flow is considered to be steady state. The equations are as follows.

Mass conservation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad \text{(i)}$$

Momentum conservation in X direction

$$u\frac{\partial u}{\partial x}+v\,\frac{\partial u}{\partial y}+\,w\frac{\partial u}{\partial z}=\mu\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right] \qquad \text{(ii)}$$

Momentum conservation in Y direction

$$u\frac{\partial v}{\partial x}+v\,\frac{\partial v}{\partial y}+\,w\frac{\partial v}{\partial z}=\mu\left[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right] \qquad \text{(iii)}$$

Momentum conservation in Z direction

$$u\frac{\partial w}{\partial x}+v\,\frac{\partial w}{\partial y}+\,w\frac{\partial w}{\partial z}=\mu\left[\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right] \qquad \text{(iv)}$$

Energy conservation

$$\rho C_p\left(u\frac{\partial T}{\partial x}+\,v\frac{\partial T}{\partial y}+\,w\frac{\partial T}{\partial z}\right)=\,k\left[\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}+\frac{\partial^2 T}{\partial z^2}\right] \qquad \text{(v)}$$

K- epsilon Turbulent Model

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\frac{\mu_t}{\sigma_k}\frac{\partial_k}{\partial x_j}\right]+\,2\mu_t E_{ij}E_{ij}-\rho\epsilon \qquad \text{(vi)}$$

$$\frac{\partial(\rho\epsilon)}{\partial t}+\frac{\partial(\rho\epsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_\epsilon}\frac{\partial_\epsilon}{\partial x_j}\right]+C_{1\epsilon}\frac{\epsilon}{k}\,2\mu_t E_{ij}E_{ij}-C_{2\epsilon}\rho\frac{\epsilon^2}{k} \qquad \text{(vii)}$$

Boundary Conditions:

The boundary conditions for the jet inlet taken as velocity inlet, and domain outlet is set as pressure outlet.

The side walls consider as outflow, which is at atmospheric pressure. No slip condition is used on tube surface, to have zero velocity of fluid at tube surface.

C. Computational Domain

Computational domain is main factor while investigating the problem of flow over the tube, because it needs definite boundary up to which hydrodynamic and thermal effect must be captured. The selected domain should be at a distance, from there back flow of the fluid must be zero, or its effect should be minimum. In the current investigation, the jet to tube distance is varied as 17mm, 42.5mm and 72.25mm. The outside tube diameter is 17mm. To have minimum effect of back flow because of side walls, i.e. upper and lower side is kept at a distance of more than 5 times of the tube diameter, i.e. kept at a distance of 100mm in upper side and bottom side. Similarly, to avoid back flow at the outlet side, domain is kept at a distance of more than 10 times of the tube diameter.

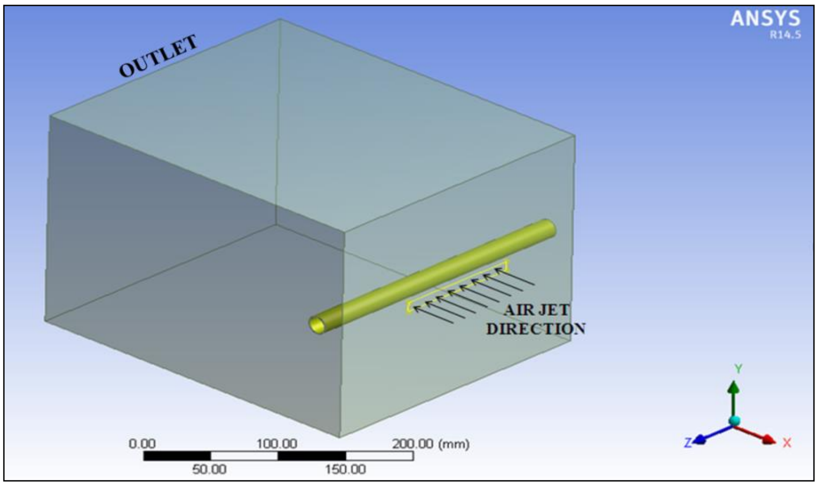

Fig.2: Computational Domain of Jet Impingement System

D. Geometry Creation and Mesh Generation:

The above geometry is created in Ansys Fluent 14.5. The tube diameter is 16mm with thickness 1mm, and 250mm in length. The material of tube is selected as aluminium. The domain selected is to avoid back flow. The mesh is generated with inflation boundary at outer side of tube, with 5 layers and growth rate kept is 1.2. Inflation boundary is used to capture near tube heat transfer effect. Relevance is set to zero, with relevance centre as fine. The tetrahedron mesh generated. The total nodes obtained are 57792 and element formed are 253867. The grid independence is done by changing the relevance size, to check the effect of grid size on Nusselt number.

E. Numerical Setup and Solver:

The computational domain used in the present study is shown in Fig. 2. The computational domain walls are maintained at surrounding condition, i.e. at 313 K. Air jet flow direction is as shown in Figure 2. The energy equation is kept on to captured the temperature change throughout the domain. The standard k-epsilon model is selected, with near wall treatment as Enhanced wall treatment. The interface is created at tube outer surface. The SIMPLE scheme is used as solution method, with Least squares cell based gradient. In under relaxation factors, momentum is kept 0.7, turbulent kinetic energy is 0.5 and turbulent dissipation rate is kept at 0.6. The solver is set up based on pressure based type and absolute velocity formulation. The residue monitor convergence absolute criteria is set to 0.001. The standard initialization is done, and computed from jet velocity inlet.

III. RESULTS AND DISCUSSION

CASE: I - Isothermal Tube at Constant Temperature at 453K:

The following results are obtained by considering the constant temperature at inside surface of tube. It is considered as 453 K, which is the available temperature of turbocharged or compressed air. The investigated results are described as follows. The present study investigated as the effect of jet height, effect of Reynolds number, effect of jet to target distance, effect of number of split jet slot, effect of distance between two slots, when same slot is split into two slots and three slots, in terms of Nusselt number.

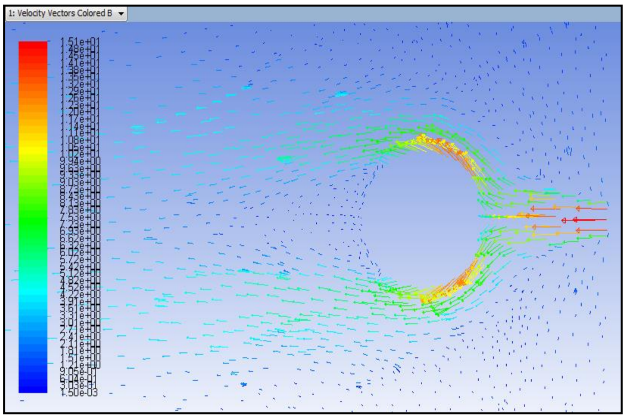

Fig.3 (A): Velocity Vector along Z - axis

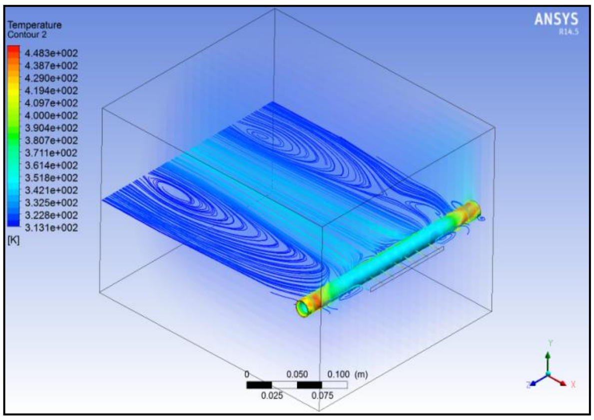

Fig.3 (B): Temperature contour over tube

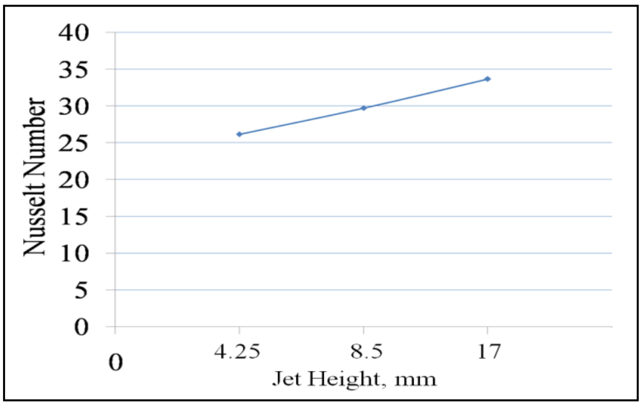

Fig.4: Effect of jet height on N_u

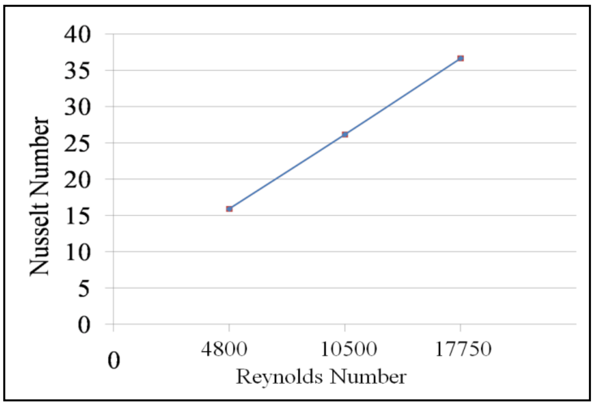

Fig.5: Effect of Reynolds Number on N_u

Fig.6: Effect of jet to target distance on N_u

Fig.7: Effect of No. of split jet slot on N_u

Fig.8: Effect of dist. between two slots on N_u

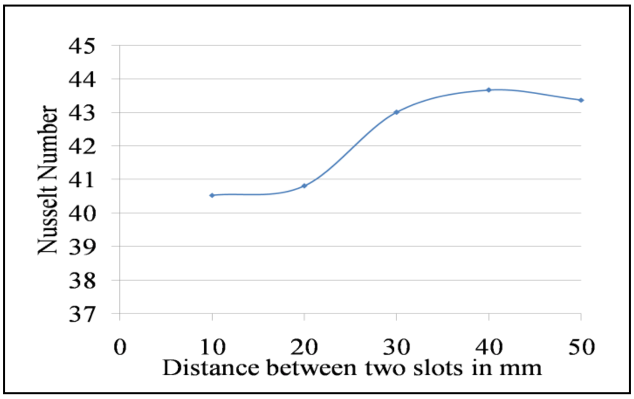

Fig.9: Effect of dist. between three slots on N_u.

A. The Effect of Jet Height:

The study of effect of jet height and jet Reynolds number is carried out, and results are plotted as shown in Fig. 4. The jet height is taken as 4.25mm, 8.5mm, and 17mm. It is observed that, as the jet height increases, heat transfer rate increases. It is clearly seen that, 17mm jet height gives the maximum heat transfer rate, compared to 8.5mm and 4.25mm jet height. Higher jet height will results into more mass flow rate, hence increase in heat transfer rate.

B. The Effect of Reynolds Number:

Also higher the Reynolds number indicate the higher velocity of air. Reynolds number is varied as 4800, 10500, and 17750. It is observed from Fig. 5, maximum heat transfer rate is observed for maximum Reynolds number. Higher Reynolds number is results into high velocity, hence increase in value of Nusselt number.

C. The Effect of Jet to Target Distance:

Jet impingement system is mainly depends upon the distance of jet to target. It is observed from the Fig. 6, for the maximum distance of jet to target, i.e. at 72.25mm, we get minimum cooling effect. For distance of 17mm, we get maximum heat transfer rate.

D. The Effect of Number of Split Jet Slot:

The next study is carried out by comparison of single jet with two slots jet and three jet slots, keeping the cross sectional area of jet exit is same. It is observed in Fig. 7, using the three slots gives higher cooling effect, compared to single slot and two slots of jet. It is because of kinetic energy of fluid is properly distributed over the tube, for using three slots, as compared to use of single jet slot and use of two slot of jet.

E. The Effect of Distance between Two Slots:

The above study is done by changing the distance between the two slots, in case of using the two slots of jet. The distance between two slots is varied as 10mm, 20mm, 30mm, 40mm and 50mm. It is observed from the Fig. 8, 40mm distance between two jet slots will give more value of Nusselt number, in using two slots of jet.

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F. The Effect of Distance between Three Slots:

The above study is done by changing the distance between the two slots, in case of using the three slots of jet. The distance between two slots is varied as 10mm, 20mm, 30mm, 40mm and 50mm. Using three slots of jet, the maximum Nusselt number is obtained at a distance between two slots is 40mm, as shown in Fig. 9.

CASE: II - Compressed Air at Inlet Temperature of 453K Entering at Tube Inlet:

In the second stage of present work, investigation of slot jet impingement is done, by considering the flow of heated air through the tube. Turbocharged air is at the temperature of 453 K, entering at fluid entry, and leaving at fluid exit end, as shown in Fig. 2. Air jet Reynolds number is varied in the range of 500 to 2000. The study has been carried out by changing the Reynolds number of air flowing inside of the tube, changing the jet height, jet Reynolds number, effect of number of split Jet slot, effect of distance between two slots, when same slot is split into two and three slots.

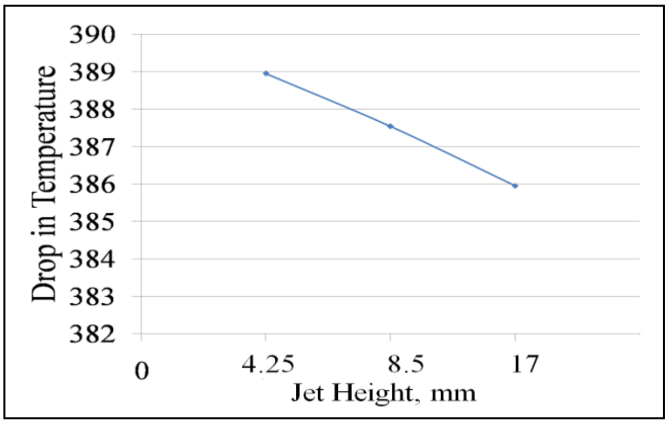

Fig.10: Effect of jet height on drop in air temp

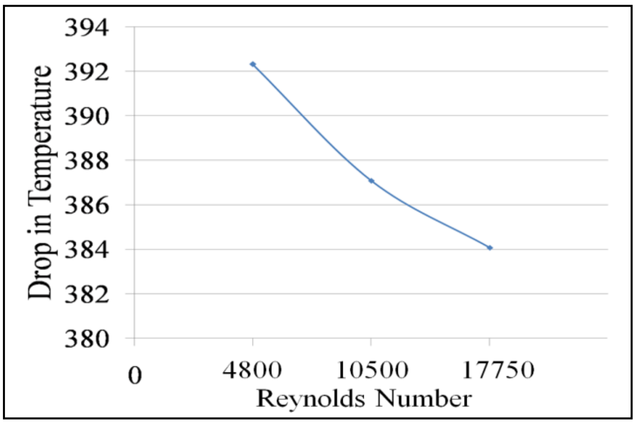

Fig.11: Effect of jet R_e on drop in air temp

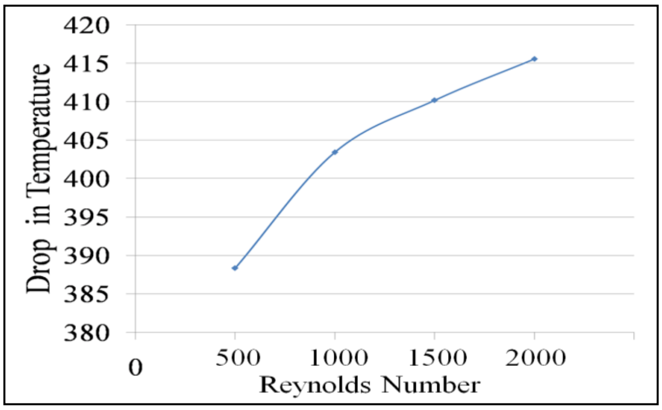

Fig.12: Effect of inner R_e on drop in air temp

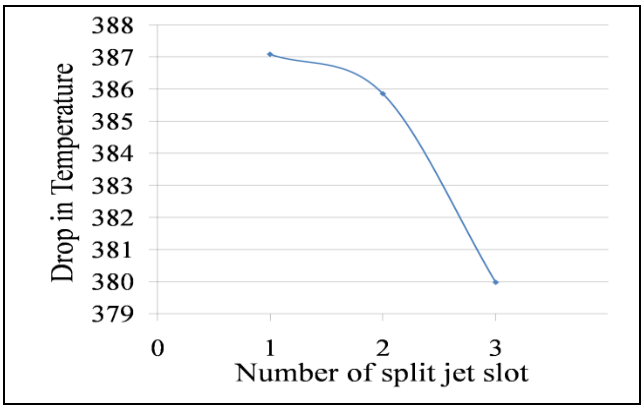

Fig.13: Effect of No. of split of slot on drop in air temp

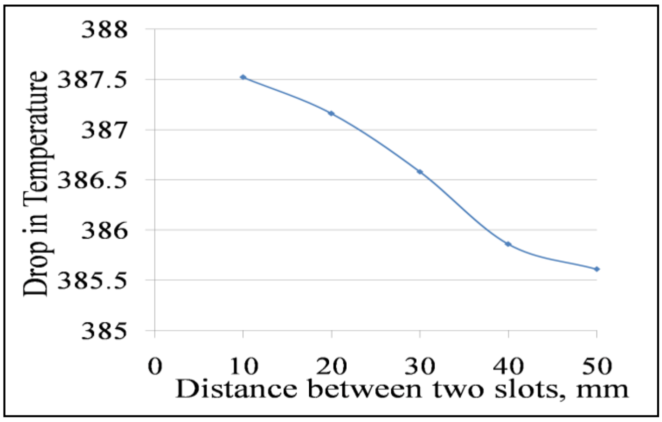

Fig.14: Effect of dist. between two slots on drop in temp

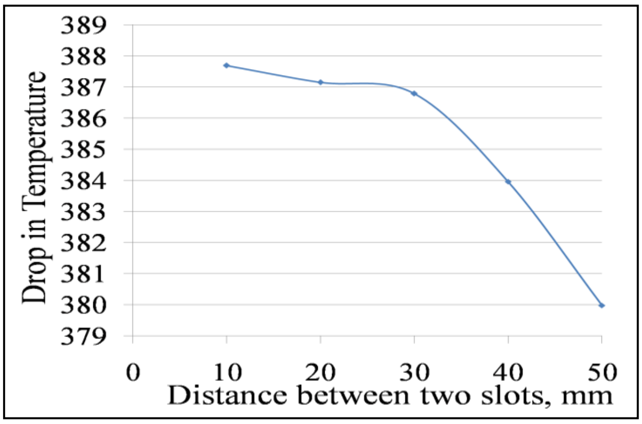

Fig.15: Effect of dist. between three slots on drop in temp

A. The Effect of Jet Height:

This results are plotted for the drop of temperature of heated air, at the exit end, which is entering at 453K. Higher the slot height, higher is the Nusselt number, and therefore more cooling and higher temperature drop of air is observed for the slot height of 17mm, compared to 8.5mm, and 4.25mm. Therefore the graph shows negative variation, as shown in Fig. 10.

B. The Effect of Jet Reynolds Number:

The effect of change in Reynolds number is shown in Fig. 11. This again shows negative variation of drop in temperature of heated air, with increase in value of Jet Reynolds number. At the higher value of Reynolds number, we have maximum value of Nusselt number, and therefore more cooling of heated air, for the Jet Reynolds number of 17750, compared to 10500 and 4800 Jet Reynolds number.

C. The Effect of Change in Inner Fluid Reynolds Number:

Effect of variation of change in inside heated air Reynolds number is obtained, for the different Reynolds Number, as shown in Fig. 12. High Reynolds number indicate high air flow rate, ultimately time of passing the air through the tube, for constant length, is minimum. So minimum time is available for high value of Reynolds number. Therefore, for the maximum value of heated air Reynolds number, we observed less cooling effect, i.e. drop in temperature at the exit end is minimum.

D. The Effect of Number of Split Jet Slot:

The study is carried out by comparison of single jet with two slots jet and three jet slots, keeping the cross sectional area of jet exit is same. It is observed from the Fig. 13, using the three slots gives maximum drop of exit temperature of heated air, compared to single slot and two slots of jet. It is because of kinetic energy of fluid is properly distributed over the tube, for using three slots, as compared to use of single jet slot and use of two slot of jet, therefore cooling effect is maximum for using three slots of same cross sectional area of jet.

E. The Effect of Distance between Two Slots:

The above study is done by changing the distance between the two slots, in case of using the two slots of jet. The distance between two slots is varied as 10mm, 20mm, 30mm, 40mm and 50mm. It is observed from the Fig. 14, 40mm - 50mm distance between two jet slots will give more cooling effect, i.e. maximum temperature drop of air is observed, as we kept the distance between two jets is 40mm - 50mm.

F. The Effect of Distance between Three Slots:

The above study is done by changing the distance between the two slots, in case of using the three slots of jet. The distance between two slots is varied as 10mm, 20mm, 30mm, 40mm and 50mm. It is observed from the Fig. 15, using three slots of jet, the maximum cooling is obtained at a distance of 50mm.

IV. CONCLUSION

Numerical investigation is done for rectangular slot jet of air is used as cooling system of an heated tube with the goal of finding the slot with high rate of heat transfer and high Nusselt number, increasing the volumetric efficiency of engine of heavy duty truck . The conclusions for the local Nusselt numbers are the followings. The Nusselt numbers increase with the slot height and the Reynolds number, and decreases with the angle from the impingement. As the distance of jet from the impingement surface is increases, we get minimum heat transfer rate and hence minimum value of Nusselt number we get. Keeping the cross sectional area same, comparison is done for splitting of jet into one, two, three slots. The distribution of kinetic energy of flow over the tube is maximum for three slots jet, therefore we get high rate of heat transfer for using jet with three slots, compared to one slot and two slots of jet. It is also observed that, at 40mm distance between slots, we have maximum value of Nusselt number and high rate of heat transfer. Increasing the Reynolds number of inside hot fluid, Nusselt number is calculated. Higher the Reynolds number will have minimum time to pass through the tube, hence less drop in temperature of inside fluid.

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