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RESEARCH ARTICLE

STUDY ON COOLING OF AUTOMOBILES USING AIRJET IMPINGEMENT.

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Abstract

Cooling has always been a difficulty faced in the automobile sector. High elevated temperatures have to be achieved and thus there is a requirement for high grade cooling in automobiles. In addition to that, other components in mechanical sector like, gas turbines, compressors, flywheels, etc all require an extensive cooling mechanism. The major contributing factor in any cooling system is the coolant fluid and the heat transfer surface area from which the heat is rejected. The general challenge when concerned with fabrication of any component is its surface finish. Not all surfaces have a smooth contour. Hence, in our project, we will be performing an experimental study on the cooling rate of a metallic component using air impingement cooling. Air impingement cooling is a procedure where, high pressure air is used as a coolant fluid over the whole surface to be cooled. Due to surface finish being a concern, the experiments will be carried out on a copper plate with a rough surface. The major advantage however with a rough surface is the increase in effective heat transfer surface area. The conventional cooling methods include- Air Cooling or Oil cooling at the domestic level. To improve on this, we would like to explore the more advanced process called Impingement cooling. Impingement cooling has the distinctive advantage of being more effective and provides with higher heat transfer rates. It is a common process that is used in the cooling of gas turbine blades and other high temperature, high precision components. Jet impingement is an attractive cooling mechanism due to the capability of achieving high heat transfer rates. This cooling method has been used in a wide range of industrial applications such as annealing of metals, cooling of gas turbine blades, cooling in grinding processes and cooling of photovoltaic cells. Jet impingement has also become a viable candidate for high-powered electronic and photonics thermal management solutions and numerous jet impingement studies have been aimed directly at electronics cooling.The set up includes a copper plate which acts as the metal body (Rough surface), an air compressor's blow off which serves as the Air impinger. The copper plate contains equal spaced holes which makes it a rough surface. This rough surface is then heated using the furnace. Then, the experiment is then conducted by using the Air compressor. At equal intervals of time, the temperature is measured. The experiment is repeated for natural convection too. The temperatures are measured using an IR gun (Infra Red gun).

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Temperatures are seen for both Natural convective cooling and Impingement cooling and a graph is plotted. Then, the results are deducted.

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Introduction:-

This report presents a concise review of the Air Jet Impingement technique on flat surfaces. Impingement is an age old technique which was initially used on gas turbine blades in late twentieth century. This review is aimed at using the technique to a more sophisticated purpose.

Cooling has been an age old technique. We know that there are three basic modes of heat transfer. They are:
Conduction:-
Convection:-
Radiation:-
Phase change is a trending mode of heat transfer which is still in its developing stage. The project revolves around how convection is booming in the present world of Cooling. Convection is of 2 types viz. natural and forced.

Background:-
Our project is based on a type of forced convection called as Impingement. Impingement is a new way of forced convection where the fluid is forced on to the hot surface at a very high force. This method is used in industries for various applications like annealing of metals, cooling of gas turbine blades, cooling in grinding processes and cooling of photovoltaic cells. Jet impingement has also become a viable candidate for high-powered electronic and photonics thermal management solutions and numerous jet impingement studies have been aimed directly at electronics cooling.

Impingement technique has been widely researched for it's high value of heat removal rate and how it behaves. The jet flow characteristics are highly complex and consequently the heat transfer from a surface subject to such a flow is highly variable. Numerous jet configurations have been studied and numerous experimental parameters exist that influence both the fluid flow and the heat transfer.

Jet impingement's most sought after feature is its fluid flow characteristics. Comprehensive studies of the mean fluid flow characteristics of both a free and an axially symmetric impinging air jet have shown that Three zones can be identified in an impinging jet flow.

Firstly, there is the free jet zone, which is the region that is largely unaffected by the presence of the impingement surface; this exists beyond approximately 1.5 diameters from the impingement surface. A potential core exists within the free jet region, within which the jet exit velocity is conserved and the turbulence intensity level is relatively low. Beyond the potential core the shear layer has spread to the point where it has penetrated to the centreline of the jet. At this stage the centreline velocity decreases and the turbulence intensity increases. Second, a stagnation zone that extends to a radial location defined by the spread of the jet. The stagnation zone includes the stagnation point where the mean velocity is zero and within this zone the free jet is deflected into the wall jet flow. Finally, the wall jet zone extends beyond the radial limits of the stagnation zone.

In a jet flow, vortices initiate in the shear layer due to Kelvin Helmholtz instabilities. As the vortices move downstream of the jet nozzle each vortex can be wrapped and develop into a three dimensional structure due to secondary instabilities. A schematic of the breakdown process of toroidal vortices in an axially symmetric jet flow is presented in figure

Vortices, depending on their size and strength, affect the jet spread, the potential core length and the entrainment of ambient fluid. In certain cases jet vortices can pair, forming larger but weaker vortices. With distance from the jet nozzle the vortices break down into random small scale turbulence. In the vortex pairing case, the vortices initiate in the shear layer at a certain frequency. These vortices pass in the shear layer of the jet at the same frequency as the frequency at which they roll up. As the vortices pair off the passing frequency halves.
In this case instabilities in the boundary layer of the flow within the nozzle form vortices once the jet exhausts from

the nozzle. These vortices are typically small and initiate at high frequencies. The vortices grow and merge as they are convected downstream to form larger scale vortices in a process similar to the pairing mentioned previously.

It is known that fluids in motion can separate into regions of high and low temperature and this phenomenon is termed "energy separation". Energy separation involves the re-distribution of total energy in a fluid flow without external work or heating. Energy separation can be initiated within the jet nozzle boundary layer flow and is enhanced later with the onset of vorticity. Because of this the naturally occurring vortex structures of an impinging jet have been the focus of much research. The maximum energy separation peaks at approximately H/D = 0.5 where the strength of the vortex is a maximum. Beyond this, at about H/D = 1 the maximum energy separation decreases until it is no longer discernible at H/D = 14.

Heat Transfer characteristics:-

The heat transfer distribution to an impinging jet varies significantly in shape and magnitude with the various test parameters. The first definition of the convective heat transfer coefficient can be used when the thermal boundary condition is one of uniform heat flux. At heights of the nozzle above the impingement surface that correspond to within the potential core length, the stagnation point heat transfer is relatively low and constant. Nusselt numbers increases with H/D for distances beyond the potential core length until it reaches a maximum at H/D = 8. This increase is attributed to the penetration of turbulence induced mixing from the shear layer to the centreline of the jet. The decrease beyond H/D = 8 is due to the lower arrival velocity of the jet. Similar variation of the stagnation point Nusselt number has been reported by Lee et al. At heights of the nozzle above the impingement surface that correspond to within the potential core length, the stagnation point heat transfer is relatively low and constant. Increases with H/D for distances beyond the potential core length until it reaches a maximum at H/D = 8. This increase is attributed to the penetration of turbulence induced mixing from the shear layer to the centreline of the jet. The decrease beyond H/D = 8 is due to the lower arrival velocity of the jet.

The surface finish of the impingement surface is another parameter for the enhancement of heat transfer to an impinging jet. an array of jets impinging on a dimpled surface was explored. In certain cases, it was found that the heat transfer could be enhanced by up to 50 %, de- pending on the cross-flow condition and on the height of the jets above the impingement surface.

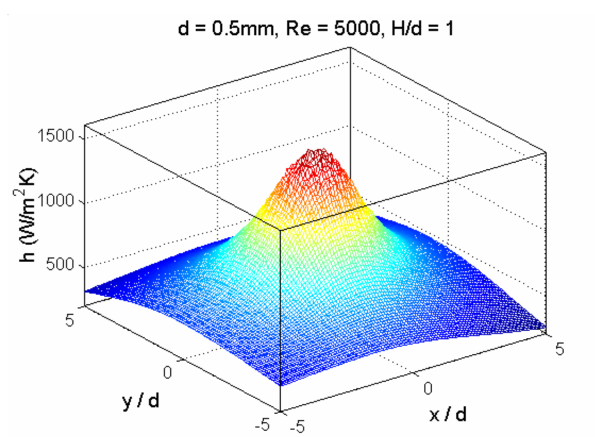


Fig 1.1:- Heat Concentration on the plate with increasing enthalpy.

Research Objectives:-

The current research investigates the fluid flow and heat transfer for a submerged, un-confined axially symmetric impinging air jet, for a range of impingement parameters. Mean and fluctuating heat transfer distributions are compared with local velocity measurements. Of particular interest to the current investigation are the secondary peaks that occur in the mean heat transfer distribution when the jet nozzle is placed within 2 diameters of the impingement surface. An important objective of the current research is to reveal the convective heat transfer mechanisms that influence the magnitude and location of these peaks.

Control of the vortex development in the shear layer of the free jet and its influence on heat transfer has been a major area of interest in this field in recent years. It has been shown that by exciting the jet, acoustically or otherwise, the vortex development can be controlled and this has a consequence for heat transfer. Another objective of this research is to understand the influence that various stages within the vortex development have on the convective heat transfer in the wall jet.

One important application of jet impingement is the cooling of a grinding process. To date this has been achieved using flood cooling with a traditional coolant such as an oil and water mixture. For both environmental and economic reasons, it would be preferable to cool the process using air. The final objective of this research is to investigate the convective heat transfer mechanisms that occur in an air cooled grinding process, with a view to determining an optimal jet set-up.

Literature Review:-

This chapter presents previous research results and conclusions that are necessary in understanding the characteristic behavior of impinging jet flow. The first section explains the qualitative flow behavior of the jet before and during impingement. The second section presents experimental works that explain the effects of changing certain physical criteria such as nozzle-to-surface distance or jet Reynolds number; effects of different surface shapes, effects of multiple jets, as well as the effects of system rotation on the flow behavior. The third section presents simulation works in predicting jet impingement flow.

Convective heat transfer to an impinging air jet is known to yield high local and area averaged heat transfer coefficients. The current research is concerned with the measurement of heat transfer to an impinging air jet over a wide range of test parameters. mean and fluctuating surface heat transfer distributions up to 6 diameters from the geometric centre of the jet are reported. The time averaged heat transfer distributions are qualitatively compared to velocity flow fields. Simultaneous velocity and heat flux measurements are reported at various locations on the impingement surface to investigate the temporal nature of the convective heat transfer.

At low nozzle to impingement surface spacings the heat transfer distributions exhibit peaks at a radial location that varies with both Reynolds number and H/D. It is shown that fluctuations in the velocity normal to the impingement surface have a greater influence on the heat transfer than fluctuations parallel to the impingement surface. At certain test configurations vortices that initiate in the shear layer impinge on the surface and move along the wall jet before being broken down into smaller scale turbulence. The effects of these vortical flow structures on the heat transfer characteristics in an impinging jet flow are also presented. Specific stages of the vortex development are shown to enhance vertical fluctuations and hence increase heat transfer to the jet flow, resulting in secondary peaks in the radial distribution.

Air jet cooling of a grinding process has been investigated as large quantities of heat must be dissipated to avoid high temperatures that have an adverse effect on the workpiece and the grinding wheel itself. Convective heat transfer distributions

along the axis of cut are compared to local flow characteristics for a range of jet and grinding wheel configurations. It has been shown that the jet velocity must be significantly higher than the tangential velocity of the grinding wheel in order to penetrate the grinding wheel boundary layer and effectively cool the arc of cut.

Anatomy of Jets:-

Structure of Free jets:-

The behavior of free jets and impinging jets on flat surfaces using a smoke wire visualization technique was investigated in the year 1999 and the following visuals were presented

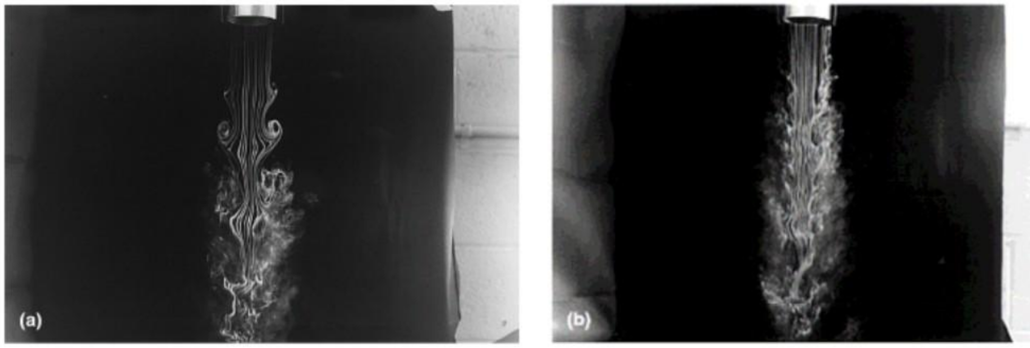


Fig. 2.1:- Visualization pictures showing effect of increasing Reynolds number Re = 6,000 to (b) Re = 10,000 on free flow structures

The above figure shows the visualization results of free jets issuing from a nozzle of diameter D = 47.2 mm at two different Reynolds numbers of Re = 6,000 and 10,000. It is seen that at lower Reynolds number a large, well-defined, vortex structures were observed, which were no longer present at the higher Reynolds number. This was attributed to the increase in the turbulence intensity value at the nozzle edges from 9% to 14%. Thus, it was concluded that at lower Reynolds numbers, where the turbulence intensity level of the shear layer at the jet edge was less than 10%, large vortex structures would form, but no vortex structures would be present at higher Reynolds numbers, where the turbulence intensity level was greater than 14%. With low levels of turbulence intensity at the nozzle's edge, entrainment of surrounding fluid into the jet causes enough instability to create small disturbances in the flow, resulting in the formation of small vortices which roll up and grow in size as they are convected downstream and as more surrounding fluid is entrained into the jet. Eventually, these vortices grow big enough to reach the jet centreline at the end of the potential core, where the vortices will meet up before breaking down, creating high levels of turbulence. For the higher Reynolds number case, the higher levels of turbulence intensity resulted in an earlier transition to turbulent flow, which occurred closer to the jet exit nozzle than for the lower Reynolds number flow.

Structures of jets impinging on flat surfaces:-

In 1999, a few scientists obtained flow visualizations of jet impingement on a Flat Surface which is shown in the following figure.

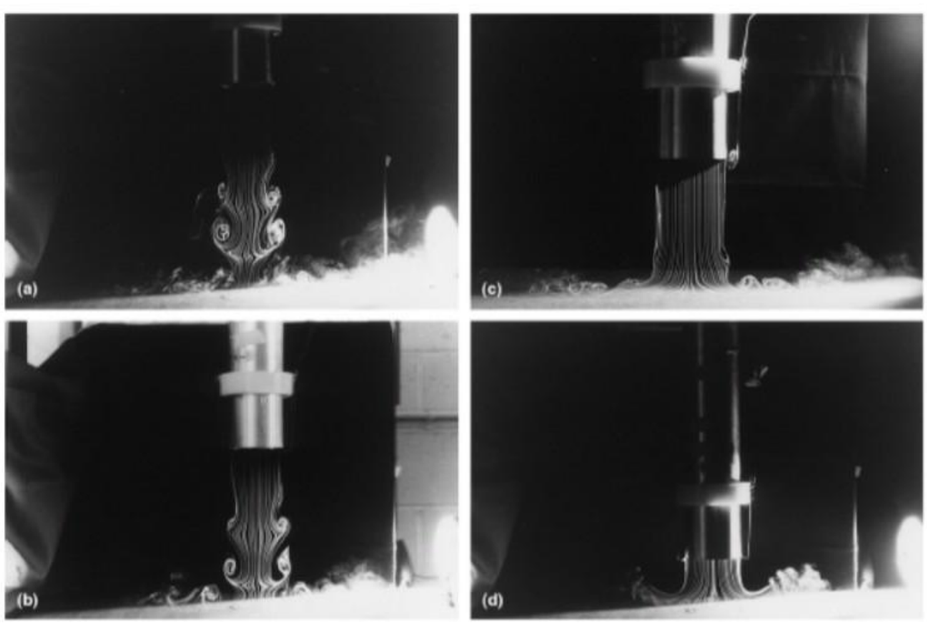
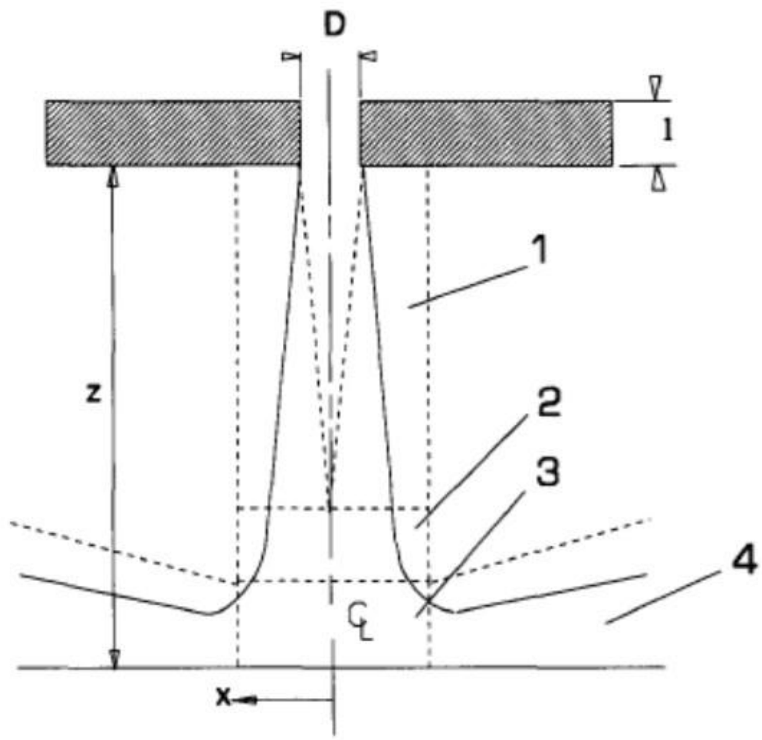


Fig. 2.2:- Flow structures of a jet impinging on a flat surface (a) H/D = 4 (b) H/D = 3 (c) H/D = 2 (d) H/D = 1

At H/D = 4 (Figure 2.2 (a)), the impingement occurs just at the end of the potential core resulting in the vortex structures breaking down at the impingement point. Because of this, no large vortex structures were observed radially along the flat surface after the impingement point. At H/D = 3 (Figure 2.2 (b)), the vortex structures formed in the free jet continued radially along the flat surface after impingement because jet impingement occurs within the potential core region, and the transition to fully turbulent flow occurs further downstream from the stagnation point, resulting in the flow vortex structures retaining their form for a longer duration. At H/D = 2 (Figure 2.2 (c)), no large vortex structures were observed along the jet because the structures have no time to form before impingement takes place, although small vortex structures did develop radially along the flat plate after the impingement. At H/D = 1 (Figure 2.2 (d)), due to the close proximity of the jet nozzle to the surface, the strong axial flow resulted in a subsequent strong radial deflection with no large vortex structures forming at all, before or after impingement.



The Jet impingement flow structures are divided into four zones as shown in the figure below.
Fig. 2.3:- Flow zones of an impinging jet

In this figure, Zone 1 is the developing zone, which encompasses the jet nozzle exit up to the end of the potential core. The potential core is the region where the fluid velocity is almost equal to the nozzle exit velocity. It was suggested that the end of the potential core is reached when the axial velocity falls to 95% of the jet exit velocity. The reduction of the jet velocity is due to the entrainment of fluid into the jet forming a mixing or shear layer which surrounds the potential core.

Zone 2 is the established jet zone. If the nozzle-to-surface distance is sufficiently long, the flow will progress beyond the potential core length. This region will subsequently be fully turbulent and the centreline axial velocity will continually reduce as the flow moves away from the nozzle exit. the reduction of the centreline velocity is inversely proportional to the square root of the axial development distance for slot jets whilst for circular jets it is inversely proportional to the distance.

Zone 3 is the deflection zone. This region is also called the impingement zone or the stagnation zone. This is the region where there is a rapid decrease in axial velocity and an increase in static pressure. The extent of this zone is approximately nozzle diameters from the impingement surface. Zone 4 is the wall jet zone. The deflected flow from Zone 3 follows and spreads over the surface, creating a wall jet. The wall jet momentum will eventually decay due to the effects of wall friction at the surface and the mixing with the surrounding fluid.

Experimental studies of impinging jets:-

Single Jet Impinging on Flat Surfaces:-

An early experimental work on impinging flows done by Gardon & Carbonpue (1962) investigated the effects of various nozzle-to-surface (H/D) distances on the heat transfer rate. They found that the maximum stagnation heat transfer rate occurred at nozzle-to-surface distances of between 6 to 7 jet diameters.

The lateral variation of heat transfer coefficient at various Reynolds numbers for a nozzle-to-surface distance of H/D = 2 is shown in the graph below. The profiles show that the overall heat transfer coefficient increases with an increase in Reynolds number. A number of heat transfer coefficient peaks were also observed. Two peaks were observed at Reynolds numbers between 14,000 to 28,000, at lateral positions of x/D = +0.5 and +1.9. At Reynolds numbers between 2,800 and 10,000, up to three peaks were observed at lateral positions of x/D = +0.5, +1.4 and +2.5.

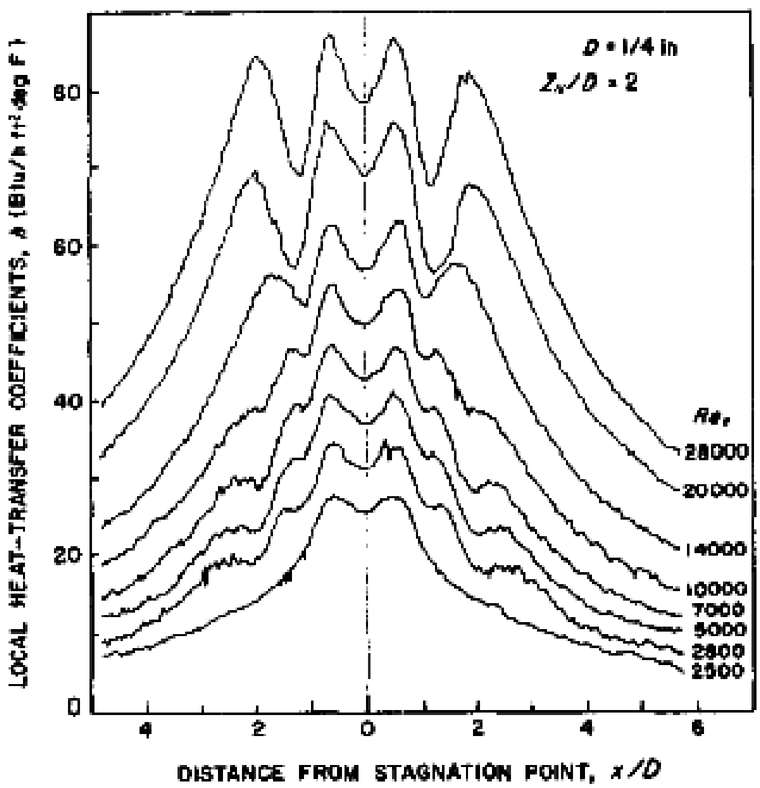


Fig. 2.4:- Lateral variations of local heat transfer coefficients

The conclusions said that the first peak is not caused by the effects of turbulence but by the mechanism of the axisymmetric impinging jet flow, regardless of whether the flow is laminar or turbulent. Also, he first peak is caused by the rapid increase in lateral velocity as the flow accelerates in the deflection region. Next, the second peak, at x/D = +1.9, is caused by the transition from laminar to turbulent boundary layer flow. Then, the third peak at x/D = +2.5 for flows between Re = 2,800 and 10,000 is caused by the toroidal vortices as observed. the local heat transfer coefficients exhibit local minimum values at the stagnation point.

Computational studies of Impinging jets:-

Modelling of impinging jets:-

Many of the widely used turbulence models for predicting momentum and heat transfer have been developed by reference to flows parallel to walls, such as simple boundary- layer flows. To use these models in complex flows, it is important that they can perform accurately regardless of the flow orientation relative to the bounding surfaces. In particular, for impinging jets, the models should be able to predict correctly both flows parallel to and normal to the walls. There are a number of significant differences between shear and impinging flow characteristics, which the models must be able to reproduce.

Due to these differences in the flow behaviour, many turbulence models such as linear k-ε models, and even some stress transport models, give incorrect predictions of impinging flows. n advanced low Reynolds number second moment closure model with reasonable success on impinging jet flow and flow through ribbed passages. However, second moment closure models use a lot of computational resources because of their complexity.

Further development of the eddy viscosity approach has resulted in non-linear eddy viscosity models (NLEVM) which introduce additional non-linear terms into the stress- strain relation. a cubic stress-strain relationship into the two- equation k-ε eddy viscosity model tested over a range of applications including flow in a curved channel, through a rotating pipe, transitional flow over a flat plate, impinging flow and flow around a turbine blade. In each of these cases, the model produced a significant improvement in results compared with the linear model, requiring only 10% more computing time. Particularly in the case of flat plate impinging jet simulations

Table 2.1:- Differences between impinging flow and shear flow

Impinging Flow	**Shear Flow**
Turbulence energy is dominated by normal straining near the impingement region.	Turbulence energy is generated by the shear effects.
RMS fluctuating velocity normal to the wall is larger than that parallel to the wall at the impingement zone.	Stress component normal to the wall is small compared with other components.
Turbulence length-scales near the wall are strongly affected by those of the incoming jet.	Turbulence length-scales are determined by the distance from the wall.
Convective transport of turbulence energy is important near the stagnation point.	Convective effects are negligible whilst the generation and dissipation processes are roughly balanced.

Research Methods:-

Current research in improving impingement jet performance and predicting jet behavior falls into two categories, experimental and numerical. Where possible, researchers use experimental results to assist in the development and validation of numerical tools for predicting flow and heat transfer behavior.

Impingement heat transfer experiments focus on measuring the flow field characteristics and the surface heat transfer coefficients. In an experiment a single jet or jet array is constructed and positioned above a solid target such as a plate or cylindrical surface. A pump or blower forces fluid onto the target plate while instrumentation collects information about fluid proper- ties and target surface properties. Most impinging jet industrial applications involve turbulent flow in the whole domain downstream of the nozzle, and modeling turbulent flow presents the greatest challenge in the effort to rapidly and accurately predict the behavior of turbulent jets. Numerical modeling of impinging jet flows and heat transfer is employed widely for prediction, sensitivity analysis, and device design. Finite element, finite difference, and finite volume computational fluid dynamics (CFD) models of impinging jets have succeeded in making rough predictions of heat transfer coefficients and velocity fields. The difficulties in accurately predicting velocities and transfer coefficients stem primarily from modeling of turbulence and the interaction of the turbulent flow field with the wall.

The computation grid must resolve both the upstream and downstream flow around the nozzles or orifices and must extend sufficiently far to the side of a single jet or array (typically eight to ten diameters) to provide realistic exit conditions. Zero- gradient and constant-static-pressure conditions have been used at the far-field model boundaries. Successful, stable modeling using both of these conditions can depend on properly shaping the boundary at the edge of the model domain.

Turbulent impinging jet CFD he variety of numerical models has grown and computational research has taken on a larger importance in predicting the physical behavior of impinging jets. The continuing increase in computing power has enabled more rapid computation including optimization by parametric variation. An inexpensive desktop computer may solve precise, high-resolution two-dimensional models within a day. Three- dimensional models and unsteady models are now possible without the use of super- computers, and have execution times ranging from several days to several weeks. The examples in the following review are primarily from impinging jet numerical modeling conducted since the original review by Polat et al.

Useful as a theoretically simple approach, the direct numerical simulation (DNS) method is the most complete and physically exact numerical method employed to predict the impinging jet flow field and transfer rates. This method solves the full Navier–Stokes, continuity, and energy/mass diffusion equations using discrete units of time and space, but requires an extremely small grid to fully resolve all the turbulent flow properties, because the microscopic turbulent length scales involved in jet impingement are far smaller than the macroscopic lengths involved (e.g. D_0 or H). The consequently long computation time practically limits the use of DNS to Reynolds numbers much lower than those in the gas turbine impingement heat transfer application. Since the DNS computational time to resolve turbulent eddies grows with the local turbulent Reynolds number (R_t) to the third power, this modeling method may be of academic interest for laminar flows but will remain impractical for turbulent jets for the foreseen future. Typical DNS CFD studies, using supercomputers, were limited to Reynolds numbers of the order of 10,000. To represent practical application successfully, the majority of DNS computations were limited to Reo1,000, with even lower limits for highly complex flows.

In an attempt to remedy this situation, some CFD models use Large Eddy Simulation (LES). The time-variant LES approach tracks flow properties with the full equations down to some user-defined length scale (typically the grid spacing), and then uses additional sub-grid-scale equations to describe turbulent flow behavior at smaller scales. The LES method has shown encouraging results and clarified the understanding of formation, propagation, and effects of flow eddies upon the velocity fields and jet transfer characteristics, but it requires high resolution in space for accuracy, may require high resolution in time for stability and accuracy, and therefore still needs a great amount of computing power or time to produce satisfactory solutions for the transitional and turbulent flows of interest here.

Summary:-

An investigation of documented research results has been performed regarding jet impingement cooling on flat surfaces. Both experimental and numerical studies have been surveyed, as well as situations with multiple jets and rotation effects, in addition to impingement on both concave and convex surfaces. Based on the investigation, an understanding of the flow behavior and characteristics has been achieved.

Through visualization results of low Reynolds number jet flows, it was found that large vortices develop within the surrounding mixing layer of the jet before impingement and these vortices are translated to the impinged surface, resulting in increased turbulence and heat transfer levels. The vortices will eventually disperse downstream due to momentum loss. For curved surfaces, the centrifugal forces created by the surfaces act to destabilize the flow for a boundary layer developing on a concave surface and stabilize the flow for the corresponding convex surface case. In both cases, experimental results suggest that the heat transfer rate is increased compared with that of flat plate impingement.

Generally, increasing the Reynolds number, Re, will increase the heat transfer rate at the impinged surface. The main peak in the heat transfer profile is caused by the deflection of the flow near the stagnation point resulting in a rapid lateral velocity where the flow follows the impinged surface. Increasing the nozzle-to-surface distance H/D to a position just beyond the jet's potential core will generally increase the heat transfer rate because at that relative high H/D, the flow reaching the surface is already fully turbulent. At lower H/D, secondary peaks are observed in the heat transfer profiles caused by the transition of the wall jet from laminar to turbulent flow. In some cases, a minima is observed at the stagnation point because, due to the low H/D, the flow reaching the surface is within the non-turbulent potential core region.

Predictions using the two-equation k-ε linear eddy viscosity model have proved to be inaccurate for simulations involving flat plate jet impingement and rotating flows. This is because the linear k-ε model fails to capture correctly the normal stress anisotropy in impingement flow and the effects of Coriolis forces in rotational flow. However, for jet impingement on a concave surface, the k-ε linear model did show reasonable correlation with experimental results. For flat plate impingement and rotating flow, predictions using two-equation k-ε non-linear cubic eddy viscosity models can give reasonably good results due to the inclusion of additional non-linear terms in the stress-strain relation. Second moment closure models generally gave better predictions for jet impingement and rotating flows but at the cost of higher computational time and resources due to their complexity.

Jet Impingement:-

Impinging jets have attracted much research from the viewpoint of the fluid flow characteristics and their influence on heat transfer. The jet flow characteristics are highly complex and consequently the heat transfer from a surface subject to such a flow is highly variable. Numerous jet configurations have been studied and numerous experimental parameters exist that influence both the fluid flow and the heat transfer. The overall objective of the current research is to conduct a fundamental investigation of the heat transfer mechanisms for an impinging air jet. Much of the research presented in this chapter has been conducted as independent investigations into jet impingement fluid flow and impinging jet heat transfer.

This chapter is divided into 3 parts. The first showing the jet fluid flow characteristics which includes all the aspects of the flow that have been shown to influence the heat transfer. Second section describes the various parameters which influence the heat transfer. Third part shows some novel techniques that enhance Heat transfer to an impinging air jet.

Fluid Flow Characteristics:-

This section presents some of the latest research on impinging jet fluid flows that has a consequence for heat transfer and has not been presented in the previous reviews of mean characteristics of jet flow.

Jet Flow Characteristics:-

Three zones can be identified in an impinging jet flow. Firstly, there is the free jet zone, which is the region that is largely unaffected by the presence of the impingement surface; this exists beyond approximately 1.5 diameters from the impingement surface. A potential core exists within the free jet region, within which the jet exit velocity is conserved and the turbulence intensity level is relatively low. A shear layer exists between the potential core and the ambient fluid where the turbulence is relatively high and the mean velocity is lower than the jet exit velocity. The shear layer entrains ambient fluid and causes the jet to spread radially. Beyond the potential core the shear layer has spread to the point where it has penetrated to the centreline of the jet. At this stage the centreline velocity decreases and the turbulence intensity increases. he stagnation zone includes the stagnation point where the mean velocity is zero and within this zone the free jet is deflected into the wall jet flow. Finally, the wall jet zone extends beyond the radial limits of the stagnation zone.

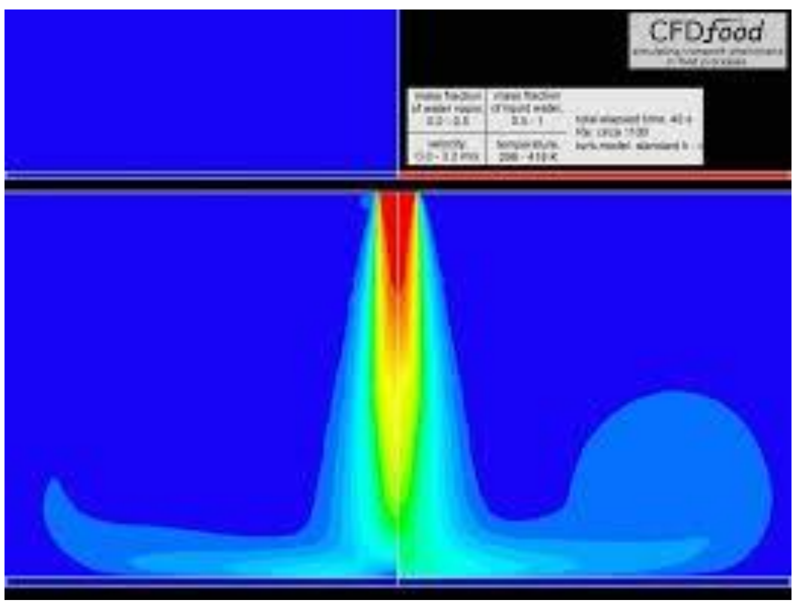


Fig. 3.1:- Jet flow characteristics.

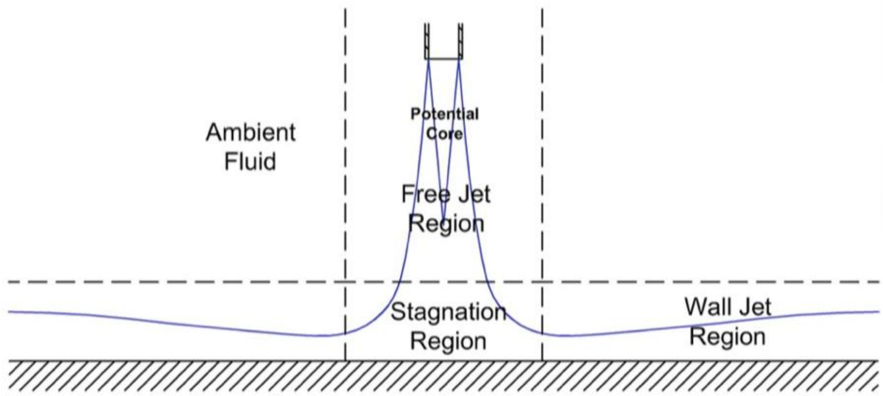


Fig. 3.2:- Impinging Jet zones.

The jet emerges from a nozzle or opening with a velocity and temperature profile and turbulence characteristics dependent upon the upstream flow. For a pipe- shaped nozzle, also called a tube nozzle or cylindrical nozzle, the flow develops into the parabolic velocity profile common to pipe flow plus a moderate amount of turbulence developed upstream. In contrast, a flow delivered by application of differential pressure across a thin, flat orifice will create an initial flow with a fairly flat velocity profile, less turbulence, and a downstream flow contraction (vena contracta). Typical jet nozzles designs use either a round jet with an axisymmetric flow profile or a slot jet, a long, thin jet with a two-dimensional flow profile.

After it exits the nozzle, the emerging jet may pass through a region where it is sufficiently far from the impingement surface to behave as a free submerged jet. Here, the velocity gradients in the jet create a shearing at the edges of the jet which transfers momentum laterally outward, pulling additional fluid along with the jet and raising the jet mass flow.

In the process, the jet loses energy and the velocity profile is widened in spatial extent and decreased in magnitude along the sides of the jet. Flow interior to the progressively widening shearing layer remains unaffected by this momentum transfer and forms a core region with a higher total pressure, though it may experience a drop in velocity and pressure decay resulting from velocity gradients present at the nozzle exit. A free jet region may not exist if the nozzle lies within a distance of two diameters (2D) from the target. In such cases, the nozzle is close enough to the elevated static pressure in the stagnation region for this pressure to influence the flow immediately at the nozzle exit.

As the flow approaches the wall, it loses axial velocity and turns. This region is labeled the stagnation region or deceleration region. The flow builds up a higher static pressure on and above the wall, transmitting the effect of the wall upstream. The non-uniform turning flow experiences high normal and shear stresses in the deceleration region, which greatly influence local transport properties. The resulting flow pattern stretches vortices in the flow and increases the turbulence. The stagnation region typically extends 1.2 nozzle diameters above the wall for round jets

After turning, the flow enters a wall jet region where the flow moves laterally outward parallel to the wall. The wall jet has a minimum thickness within 0.75–3 diameters from the jet axis, and then continually thickens moving farther away from the nozzle. This thickness may be evaluated by measuring the height at which wall- parallel flow speed drops to some fraction (e.g. 5%) of the maximum speed in the wall jet at that radial position. The boundary layer within the wall jet begins in the stagnation region, where it has a typical thickness of no more than 1% of the jet diameter. The wall jet has a shearing layer influenced by both the velocity gradient with respect to the stationary fluid at the wall (no-slip condition) and the velocity gradient with respect to the fluid outside the wall jet. As the wall jet progresses, it entrains flow and grows in thickness, and its average flow speed decreases as the location of highest flow speed shifts progressively farther from the wall. Due to conservation of momentum, the core of the wall jet may accelerate after the flow turns and as the wall boundary layer develops. For a round jet, mass conservation results in additional deceleration as the jet spreads radially outward

Vortex Development:-

In a jet flow, vortices initiate in the shear layer due to Kelvin Helmholtz instabilities. As the vortices move downstream of the jet nozzle each vortex can be wrapped and develop into a three dimensional structure due to secondary instabilities.

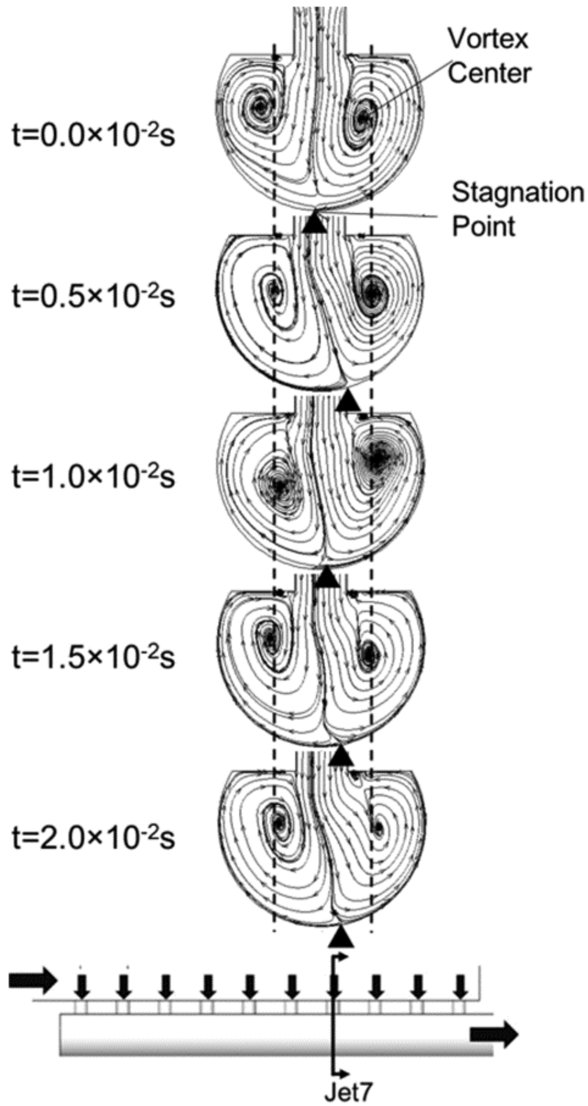


Fig. 3.3:- Vortex development

Vortices, depending on their size and strength, affect the jet spread, the potential core length and the entrainment of ambient fluid. In certain cases jet vortices can pair, forming larger but weaker vortices. With distance from the jet nozzle the vortices break down into random small scale turbulence. In the vortex pairing case, the vortices initiate in the shear layer at a certain frequency. These vortices pass in the shear layer of the jet at the same frequency as the frequency at which they roll up. As the vortices pair off the passing frequency halves. In general, turbulent jets have a fundamental frequency at which the pairing process stabilizes and this is determined by the turbulence level of the jet.

Fig. 3.4:- Vortex Separation

In this case instabilities in the boundary layer of the flow within the nozzle form vortices once the jet exhausts from the nozzle. These vortices are typically small and initiate at high frequencies. The vortices grow and merge as they are convected downstream to form larger scale vortices in a process similar to the pairing mentioned previously.

Energy separation:-

It is known that fluids in motion can separate into regions of high and low temperature and this phenomenon is termed "energy separation". Energy separation involves the re-distribution of total energy in a fluid flow without external work or heating. Energy separation can be initiated within the jet nozzle boundary layer flow and is enhanced later with the onset of vorticity. Because of this the naturally occurring vortex structures of an impinging jet have been the focus of much research. Heat transfer Characteristics The heat transfer distribution to an impinging jet varies significantly in shape and magnitude with the various test parameters. This section focuses primarily on differences between various investigations available in the literature. This includes the effects of some parameters that have not been considered in the current research. In general, the heat transfer distribution is presented as the variation of the local Nusselt number with radial position.

Enhancement techniques:-

Several techniques have been investigated with a view to enhancing the heat transfer to an impinging air jet. These include increasing the turbulence in the jet, the addition of swirl or artificially exciting the jet. This section identifies some of these techniques, explains the principles behind them and then briefly describes some of the findings of the various research conducted.

Nozzle geometry:-

The jet nozzle geometry is believed to have a significant effect on the heat transfer to the impinging air jet. Several studies attribute inconsistencies between reported data and their own research to slight differences in the nozzle geometries. For this reason, the effect of nozzle geometry on heat transfer has attracted much research. One of the most important aspects of the nozzle geometry is confinement. A long pipe nozzle issuing a jet into a open space is considered to be unconfined, however in many cases, a nozzle is machined into a plate. This situation is considered to be semi-confined.

Nozzle Shape:-

The effect of nozzle inlet chamfering, with a view to enhancing the ratio of area averaged heat transfer coefficient to the pressure drop across the jet nozzle. This was done by finding the optimum inlet chamfering angle. It was concluded that while the inlet chamfer angle has a large effect on the pressure drop across the nozzle; the effect on the heat transfer coefficient was not significant. A chamfer angle in the vicinity of approximately $60^{\pm}$ was shown to be the optimum set-up as this removed a sharp corner at the inlet which reduced the effect of a vena contract within the nozzle. Both smaller and larger angles were more similar to a sharp edged orifice.

For a semi-confined jet orifice, the effect of jet exit chamfering on the heat transfer to the impinging air jet. It has been shown that for a sharp edged orifice the maximum turbulence intensity is greater than that with less chamfering or no chamfering (square edged). The nozzle exit chamfering has been shown to induce more jet expansion than the sharp edged orifice. Results reported in their investigation were also compared to previous investigations that employed both contoured nozzles and fully developed flow from long pipe jets. All the data presented by Lee and Lee [62] have shown enhancements in the heat transfer by 25

° 55 % and 50 ° 70 % with respect to the fully developed pipe jet and the contoured nozzle respectively, at low H/D = 2. This enhancement is attributed to the higher turbulence intensity of the orifice jets. The nozzles investigated included a semi- confined hyperbolic shaped nozzle, a semi-confined orifice and an unconfined jet. In general, the pressure distribution along the impingement surface decreases from a maximum at the geometric centre with increasing radial distance. However, at low $H/D < 2$ the pressure is reported to be sub-atmospheric between $0.6 < r/D < 2.2$.

Jet Excitation:-

Jet excitation has been shown to have the potential to significantly influence heat transfer to an impinging jet. A jet has a natural frequency at which vortices form and develop and it is thought that this naturally occurring frequency has an effect on the heat transfer distribution. Artificial excitation can control the development of vortices in the jet flow and therefore has the potential to enhance the heat transfer from the surface. This is the most recent enhancement technique investigated by researchers.

The impinging air jet acoustically and reported on the resulting flow and heat transfer distributions. It has been shown that, depending on the frequency of excitation, the area averaged heat transfer can be enhanced or reduced at low nozzle to impingement surface spacings. In the case where the jet is excited at a sub harmonic of the natural frequency of the jet, the heat transfer is reduced. This frequency has the effect of strengthening the coherence of the naturally occurring frequency. It is thought that the energy separation due to a more coherent flow structure has an adverse affect on the heat transfer to the jet. The jet was also excited at a frequency higher than that of the natural jet frequency. In this case the excitation had the effect of producing intermittent vortex pairing. This results in a break down of the naturally occurring vortex. Consequently, the effects of energy separation are reduced and transition to small scale turbulence effectively increases the heat transfer to the impinging air jet.

Acoustic excitation was applied to the shear layer of the jet also. Two naturally occurring frequencies were identified in the spectrum of the velocity data acquired in the free jet. The larger occurred at approximately 1kHz and this corresponds to the fundamental frequency of vortex generation. A subharmonic of this frequency at 500Hz is present and is due to the frequency of vortex pairing. Three shear layer excitation frequencies were applied to the jet, (1950,2440,3250Hz). When the jet is excited at a multiple of the natural jet frequency, the vortex is maintained at larger distances downstream. This is because the excitation frequency suppresses the effects of vortex pairing. Results have shown that while the frequency of the jet flow is affected strongly by the acoustic excitation of the jet it has a less significant effect on the vortex frequency. At higher excitation frequencies, the vortex frequency is increased marginally. In general, the excitation frequency has the potential to change the potential core length, depending on whether the excitation frequency encourages or discourages vortex pairing. Therefore, the heat transfer rate can be affected by changing the location of the impingement surface relative to the jet development stages without changing its location relative to the nozzle exit. When the excitation frequency was equal to, or close to being equal to, a harmonic of the natural frequency of the jet, vortex pairing was suppressed. This elongated the potential core of the jet. Otherwise the jet excitation facilitated vortex pairing and reduced the potential core length.

The difference between main- stream jet excitation and shear layer excitation was investigated. Essentially no significant difference was noted between the two excitation techniques. Results were presented for a range of Strouhal numbers and for two different excitation power levels from 80dB to 100dB. Only slight differences in the jet structure are noticed to vary with excitation technique. When the main flow was excited the potential core is reported to be slightly shorter and the turbulence intensity to be elevated slightly. It has been shown that a significant excitation power level (approx. 90dB) is required to have an appreciable effect on the jet velocity or turbulence intensity. Once again however, the power level is a factor that amplifies the effect that a particular excitation has. Finally, for a heated plane jet that when the excitation frequency is within 4.5Hz of the natural frequency of the jet, the vortices are strengthened by the excitation.

Other techniques:-
Several other techniques have been employed with a view to enhancing the overall heat transfer to an impinging jet flow. Some of these techniques are:

Intermittency:-
An intermittent jet flow has been used to provide enhancement of the convective heat transfer to a free surface water jet. Depending on the location on the impingement surface the heat transfer could be enhanced by up to 100 %. This is explained on the basis that the intermittent flow forces renewal of the hydrodynamic and thermal boundary layers that form along the wall jet. An investigation presented results for another self-oscillating jet. Results were presented for oscillation frequencies from 20Hz to 100Hz. A significant enhancement in the heat transfer to the jet of up to 70 % was reported for the specific range of heights (H/D >=24) and Reynolds number of 14000. In another investigation, different sort of nozzle geometry, that of a precessing jet effectively the precessed jet motion is that of self-sustained unsteadiness. It was found thatfor the range of parameters studied, however, the heat transfer to the jet was reduced. Effectively there are two main competing effects. The first is that the interaction of the jet with the ambient flow increases the mixing and turbulence of the flow along the plate. However, this interaction has the consequence of reducing the arrival velocity of the impinging jet. It is thought that the heat transfer is highly sensitive to the amplitude and frequency of the oscillations and therefore the enhancement

Turbulence Promoters:-
In an attempt to enhance the heat transfer by increasing the turbulence in the jet flow, installed mesh screens across the nozzle exit with various mesh solidity. The mesh screen has the effect of increasing turbulence in the stagnation zone. It also reduced the pressure in this zone and this resulted in enhancement of the heat transfer coefficients by up to 4 % at low H/D and a mesh screen solidity of 0.83.

Surface Finish:-
The surface finish of the impingement surface is another parameter for the enhancement of heat transfer to an impinging jet. In an investigation] an array of jets impinging on a dimpled surface was explored. In certain cases, it was found that the heat transfer could be enhanced by up to 50 %, de- pending on the cross- flow condition and on the height of the jets above the impingement surface.

The literature to date has shown that the heat transfer to an impinging air jet is highly sensitive to each of the many experimental parameters that exist. The shape of the heat transfer distribution in particular varies considerably with height of the jet nozzle above the impingement surface. While abrupt increases in turbulence in the wall jet are used to explain the location and magnitude of secondary peaks in heat transfer the literature fails to provide an in depth explanation of the heat transfer mechanism that causes this increased heat transfer.

In more recent years, attention has been focused on the potential of vortices within an impinging jet flow to enhance the heat transfer. It has been revealed that vortices serve to enhance energy separation within the flow. Research has also shown that the development of a vortex can be influenced by artificial excitation of the jet flow and that, depending on the excitation frequency, the time averaged heat transfer can be enhanced. An understanding of the heat transfer mechanisms at various stages within the vortices' development is not available however.

Finally, it is apparent that the jet nozzle has a significant effect on the overall heat transfer. Discrepancies between studies have been attributed to slight differences between nozzle geometries. The jet exit flow condition is dependent on the nozzle shape and therefore each investigation is nozzle specific. The current investigation presents data for the most common nozzle type found in the literature, i.e. a hydro- dynamically fully developed jet that issues from a long pipe.

Experimental Set up and measurement techniques:-
In this chapter, we describe the experimental rig design and the measurement techniques employed. The experimental rig has been designed to allow for the variation of parameters beyond the scope of this project and these are detailed in this chapter. The specifics of the fluid flow and heat transfer measurement techniques used are also detailed in this chapter. Finally, the acquisition hardware and software are described.

Experimental rig:-

The experimental rig is to be used for both the impinging air jet and for the study of air jet cooling. The rig consists of an Air Compressor connected to a shower which acts as an impinger, Copper plate which acts as a rough surface and a table fan to measure the fundamental investigation.

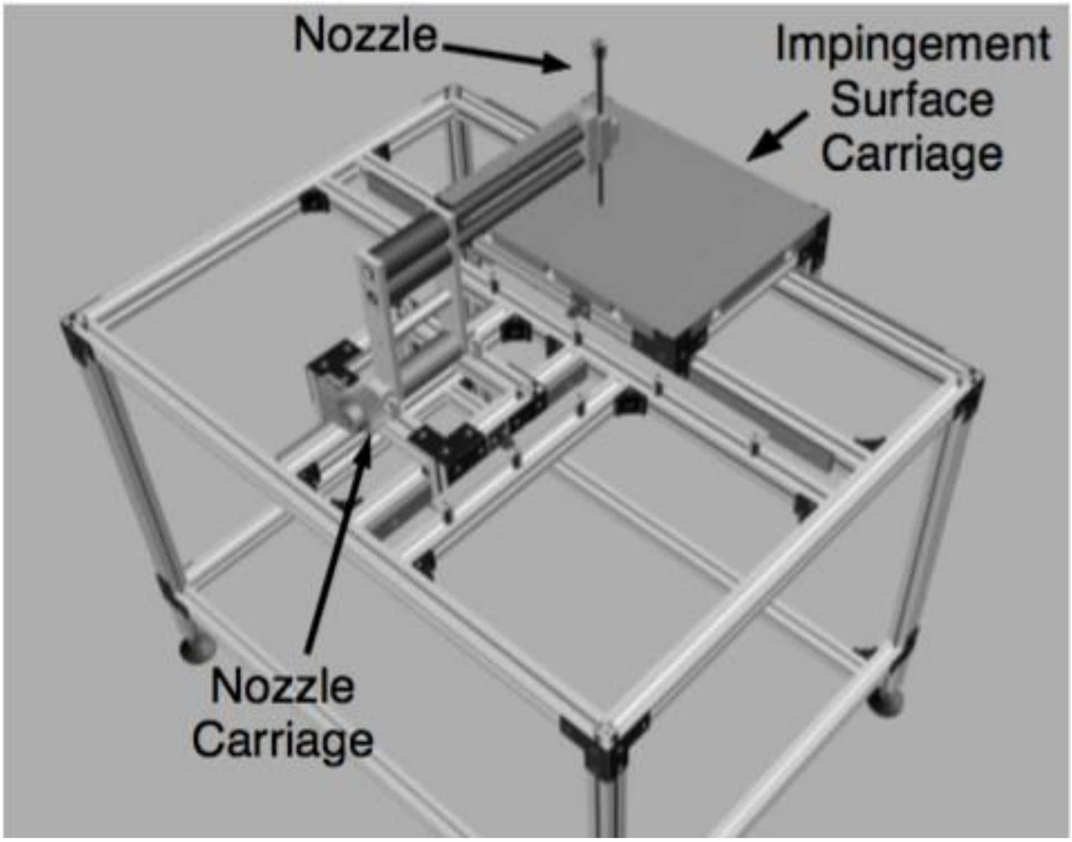


Fig. 4.1:- Schematic diagram of set-up

Experimental Equipment:-

The experiment consists of the following equipment.

Shower:-

Fig. 4.2:- Stainless Steel Shower

The Stainless steel Shower is used for impingement cooling of the plates. The Shower is connected to the flexible pipe and the other end of the flexible pipe to the outlet of the air compressor. The shower is placed right above the

Heated plates and air impacts the hot plates at right angles.

Copper Plates:-

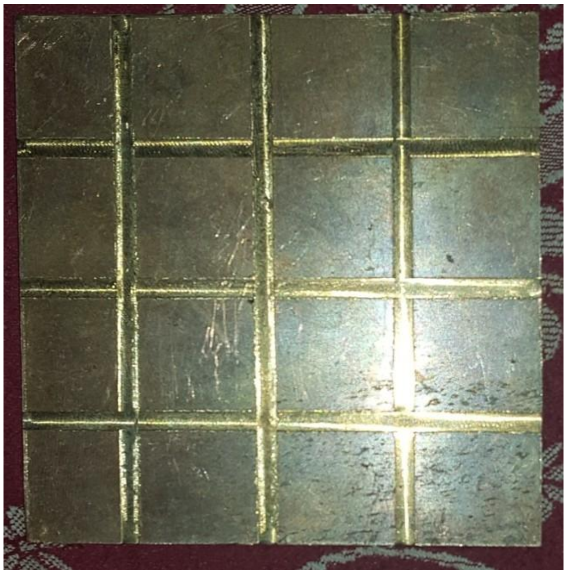


Fig. 4.3:- Copper plate of thickness 0.1in

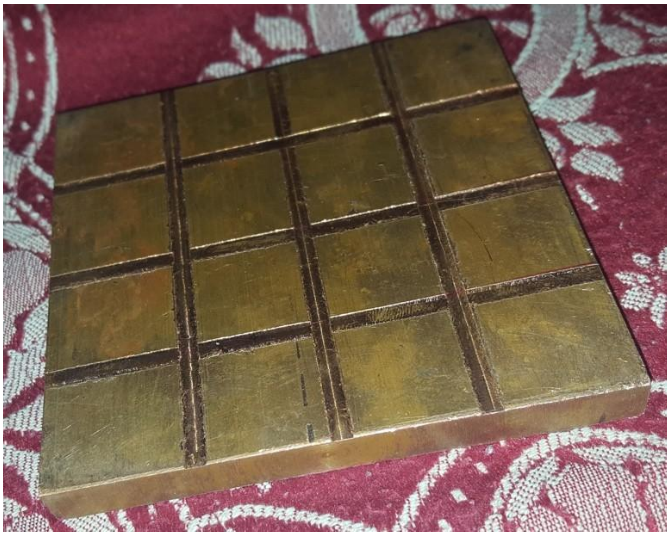


Fig. 4.4:- Copper plate of thickness 0.5in

The above are the copper plates on which the experiment is conducted. There are two copper plates which are used. One of thickness 0.1in and the other of thickness 0.5in.

Air Compressor:-

Fig. 4.5:- Air Compressor.

Infra Red Thermometer:-

Fig. 4.6:- Infra Red Thermometer.

The Infra Red Thermometer uses Infra Red waves to detect temperature. When the laser light is incident on the plate, the infra red waves reads the temperature and displays the temperature.

Set-up for Fundamental investigation:-

The main elements of the experimental rig are a nozzle and an impingement surface. Both are mounted on independent carriages that travel on orthogonal tracks. The flat impingement surface is instrumented with two single point heat flux sensors and the ability of the carriages to move in this way enables the jet to be positioned relative to the sensors at any location in a two dimensional plane.

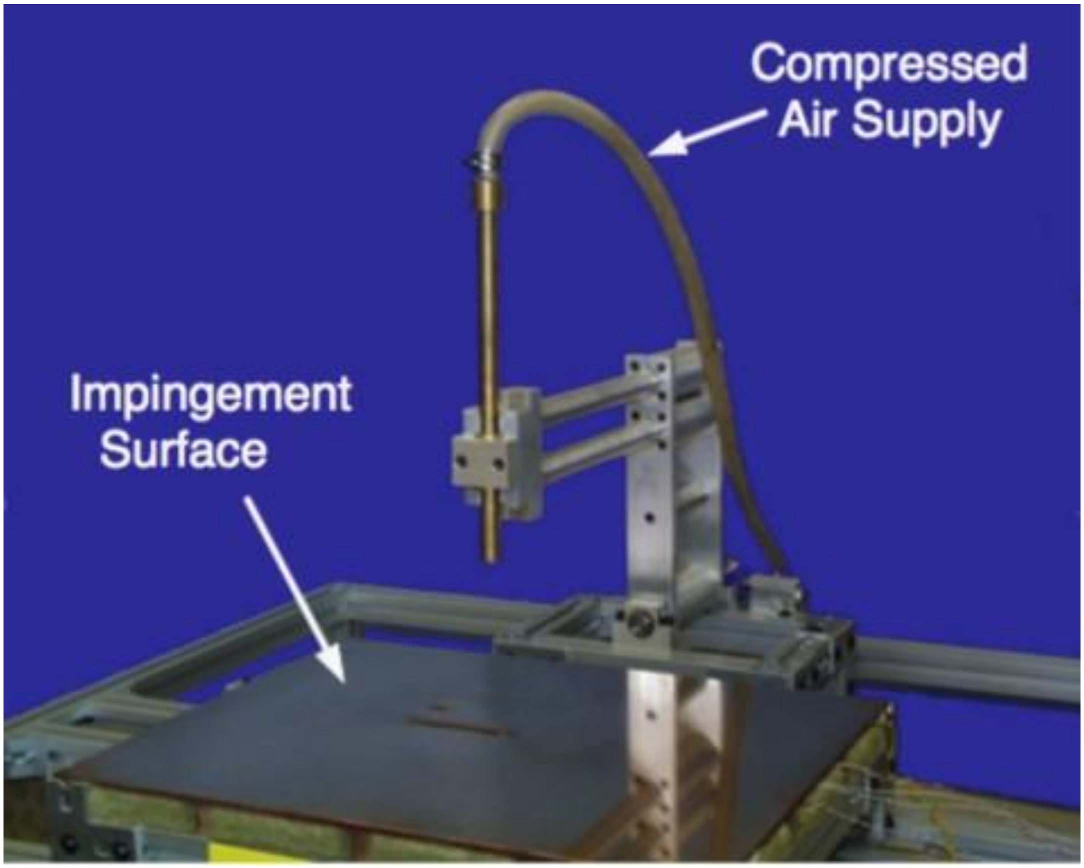


Fig. 4.7:- Actual set up.

Measurement Technique:-

There are 3 experiments being conducted. First by natural convection, second by forced convection and finally by impingement. Each of the experiment has a separate measurement mode. They are listed below:

For Natural Convection:-

The copper plate is heated by using the furnace to a temperature of about 450 C. The temperature is measured using an Infra Red gun. This metal plate is then carefully taken from the furnace and kept in the open to undergo natural convection. The temperature is noted down at every 15 minutes and the experiment is repeated with the second metal plate.

For Forced Convection:-

The copper plate is heated by using the furnace to a temperature of about 450 C. The temperature is measured using an Infra Red gun. This metal plate is then carefully taken from the furnace and kept under a table fan for forced convection to occur. The temperature of the plate is checked at every 15 minutes and the experiment is repeated with the second metal plate.

For impingement:-

The copper plate is heated by using the furnace to a temperature of about 450 C. The temperature is measured using an Infra Red gun. This metal plate is then carefully taken from the furnace and kept under the shower of the air compressor for impingement to occur. The temperature of the plate is checked at every 15 minutes and the experiment is repeated with the second metal plate.

Tables of Data.
On Copper plate of thickness 0.5in.

Natural Convection.

Table 5.1:- Temperature-Time values for Natural Convection.

Time (Minutes)	Temperature (□ C)
0	454
15	446
30	431
45	416
60	408
75	396
90	381
105	364
120	350
135	331
150	306
165	297
180	271
195	255
210	231
225	212
240	198
255	177
270	142
285	120
300	103
315	93
330	80
345	71
360	47
375	44

Forced Convection:-

Table 5.2:- Temperature-Time values for Forced Convection

Time (minutes)	Temperature (□ C)
0	448
15	418
30	391
45	360
60	339
75	307
90	288
105	267
120	243
135	219
150	193
165	172
180	140
195	122
210	98
225	78
240	54
255	48

Impingement cooling:-

Table 5.3:- Temperature-Time values for Impingement cooling

Time (minutes)	Temperature (C)
0	459
5	390
10	328
15	241
20	178
25	119
30	98
35	73
40	42

On Copper plate of thickness 0.1in

Natural convection

Table 5.4:- Temperature-Time values for Natural Convection.

Time (minutes)	Temperature (C)
0	453
15	442
30	429
45	411
60	401
75	391
90	376
105	359
120	343
135	327
150	306
165	291
180	269
195	241
210	219
225	198
240	171
255	140
270	119
285	98
300	76
315	54
330	51

Forced Convection:-

Table 5.5:- Temperature-Time values for Forced Convection

Time (minutes)	Temperature (C)
0	455
15	418
30	387
45	351
60	332
75	301
90	279
105	251
120	229

135	201
150	175
165	143
180	122
195	95
210	56
225	52

Impingement cooling:-

Table 5.6:- Temperature-Time values for Impingement cooling.

Time (minutes)	Temperature (° C)
0	452
5	381
10	311
15	233
20	151
25	95
30	48

Conclusions:-

The main objective of this thesis is to explore the technique of Air Jet Impingement as a technique for cooling automobiles. With it's existing uses it has been seen that Impingement cooling can be a method to cool Automobile Engines at a very fast rate.

However, before the experiment was conducted, simpler computational domains were taken into account. Such as, Flat plate with uniform roughness was used. Also, copper plates were used due to it's high conductivity. The temperature of the plates were not allowed to go beyond 450° C and the pressure from the Air compressor was maintained at a constant pressure.

A comparison of the types of present cooling techniques viz. Natural Convection, Forced Convection and Impingement cooling is done and the best method is identified.

The following conclusions can be derived from these numerical investigations involving both the copper flat plates.

1. The ambient temperature of the environment had a major role to play in cooling the surfaces. Temperature during the experiment was around 46° C, hence the higher time for cooling during cooling.
2. For the conditions investigated the RMS velocity or turbulence intensity is a maximum in the wedge made between the grinding wheel and the grinding surface.
3. The Angle of incidence on to the plate had a major role to play.
4. It has been seen that a high speed jet effectively penetrates the boundary layer flow around the grinding wheel providing good cooling of the grinding zone.
5. Vortices that roll-up naturally in the shear layer of the free jet, close to the nozzle exit, have been shown to merge forming larger yet weaker vortices, before being broken down into smaller scale random turbulence. Stages within the merging processes have been identified to occur at various distances from the jet nozzle.
6. The effect that the actual vortex structure has on surface heat transfer has attracted little attention. It has been shown here that axial velocity fluctuations close to the impingement surface have a far greater influence on the heat transfer than fluctuations parallel to the surface. Vortices that impinge upon the surface determine the magnitude and frequency of the fluctuations in both directions. Because of this, the various stages of the vortex merging process influence the mean and RMS Nusselt number distributions at low H/D.
7. Vortices that impinge at later stages in their development are weaker and therefore as they breakup in the wall jet, the magnitude of the velocity fluctuations normal to the surface is reduced. This does not enhance the heat transfer in the wall jet, to the same degree as stronger vortices do. In general, the breakdown of strong vortices (in the early stages of the vortex development), has a favorable effect on the heat transfer in the near wall jet. Enhancement of the heat transfer in this region could be achieved by exciting the jet so that strong coherent vortices impact on the heated surface.

Further Work:-

The current research on impinging jet flow has been concerned with the effect of vortices at different stages in their development on the surface heat transfer. Recent studies have shown that jet excitation has the potential to control the development of vortices in a jet flow. With the knowledge gained from the current research, further work would include the artificial excitation of the impinging jet flow. This would facilitate an in depth investigation of the effect of the vortical jet flow on the surface heat transfer, for a wider range of parameters to include the vortex strength, passing frequency, etc.

Also. With impingement on the rise, it would be of a great intensity if it enters the Automobile Industry to cool the Automobile Engines as that would lead it to Higher vehicle life, higher engine usage, low cost of maintenance and higher profit rates.

Acknowledgement:-

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