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Flow Visualization of Air Jet Impingement on Convex Heated Surface - A Review

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ABSTRACT

Flow dynamics of round and slot air jet impinging on convex surface is reviewed by considering free jet flow visualization images. Phenomena of air entrainment, large vortex structure generation, vortex merging, pairing, break up in the flow are responsible for different heat transfer behavior from the hot surface. In this paper an attempt is made to review flow dynamics and flow behavior by round air jet over convex heated surface along with discussion for jet structure under free condition.

Keywords: Air Jet, Convex Surface, Flow Visualization, Impingement, Vortex.

I. INTRODUCTION

Impinging jets are used in number of industrial application due to high rates of heat transfer. The common application areas are cooling of high temperature gas turbines and combustor walls, paper, textile and films drying, annealing of metals, glass manufacturing, thermal control of high-density electronic equipment, Manufacturing optical fiber by outside vapor deposition process (OVD) and many more. To improve the systems performance knowledge of various parameters those affects the heat transfer rate is important. These parameters are flow turbulence, flow confinement, recovery factor, the effects of nozzle geometry, entrainment effect and dissipation of jet temperature. A lot of theoretical and experimental work has been done so far in the field of air jet impingement on flat [1-17] and curved [18-38] surfaces. These studies includes heat transfer by jet impingement to flat surface under normal direction [1-7], effect of flat plate surface roughness [8, 9], Effects of nozzle-inlet chamfering [10] and of natural convection [11] under confined condition, and for oblique impingement [12-14]. The visualization of flow behaviour has been investigated for flat as well for curved surfaces [23, 25, 26, 29] using smoke wire visualization method.

In this paper an attempt is made to review flow dynamics by round air jet over convex heated surface. Before the insight in flow behavior over curved surface, jet structure under free condition is presented.

II. FLOW VISUALIZATION

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Since jet dynamics affects heat and mass transfer from the heated surface, therefore a proper understanding air jet impingement behavior on heated surface is inevitable. Smoke wire flow visualization technique is one of the suitable techniques for this purpose. With this technique visualization of air stream is possible without disruption due to use of a fine wire. Oil coated tungsten wire is placed across the jet at suitable position downstream from the tube exit. Oil droplet in regular interval on the wire produces smoke on electrical heating. This generated smoke is carried away by the flowing air jet. The flowing air pattern is enlighten by a proper light source, which act as flash/spot light, further corresponding images are captured by a high speed camera. Proper selection of light source with sufficient luminous and brightness is prerequisite in this method of visualization otherwise it may lead to problems like unsynchronization with camera, overheating of jet stream and curved surface, problem of reflection and over exposure in images/video etc.

The recorded images are then digitized to get proper quality images for the analysis of jet behavior during impinging on heated surfaces. Some parameters as reported by Fleischer et al. [24] are used for analysis of behavior of jet stream these are:

Vortex initiation distance: This is the distance from nozzle/tube exit where first vortex is formed during jet flow due to jet instabilities.

Vortex spacing: This is the separation distance between two neighboring toroidal vortices from the nozzle/tube exit.

Vortex period: This is the time taken to cover two specified points in the space

Vortex breaks up location: This is the location where core of vortex begins to exhibit instability instead of coherent vortex motion. Xb indicates transition to a turbulent flow that will not support large scale vortices, as turbulent flow enhances heat transfer that's why Xb is important.

Vortex merging or pairing: This is the phenomena when one large vortex overtakes the weak vortex in front of it and two vortexes merges in to one vortex.

Based on these parameters, flow of free jet and jet over flat surface is examined before the review of jet behavior over convex surfaces for the better understanding of phenomena.

III. . FREE JET

Free jet is produces by blowing air with suitable blower through long straight pipe or channel. Air is exited from a pipe of required diameter or from a nozzle attached at the end of pipe or channel. Nozzle used may be of any type i.e. bell or convergent shaped, contour or sharp or saw tooth edge, etc. Internal surface of nozzle should properly machined and polished to ensure a very thin laminar boundary layer and uniform out let velocity profile.

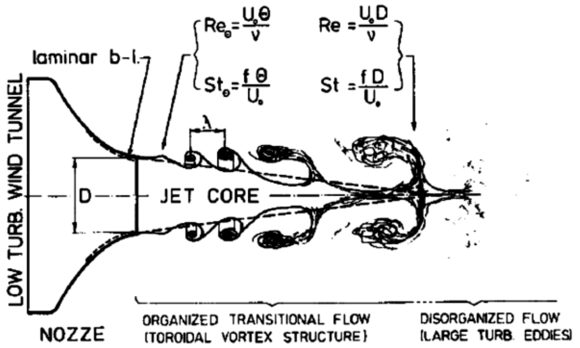


Fig 1 Vortex structure of free jet [25]

Many studies shows free jet has a vortex structure starts in the form of an instability wave in the laminar shear layer as shown in fig (3), this vortex is amplified and then rolled up into a sequence of different toroidal vortices and move down stream along shear layer, surrounds conical potential jet core. Such structure is characteristic of low turbulence and uniform velocity profile. Beyond jet potential core length the mechanism of stagnation heat transfer is affected by large 3D vortex structures which are related to upstream vortex shear layer development. Low turbulence intensity in the shear layer of jet edge at the tube exit is related to the development of organized vortex structure in the free jet shear layer, while high turbulence intensity in the sear layer at the jet edge inhibits the development of organized vortex structure.

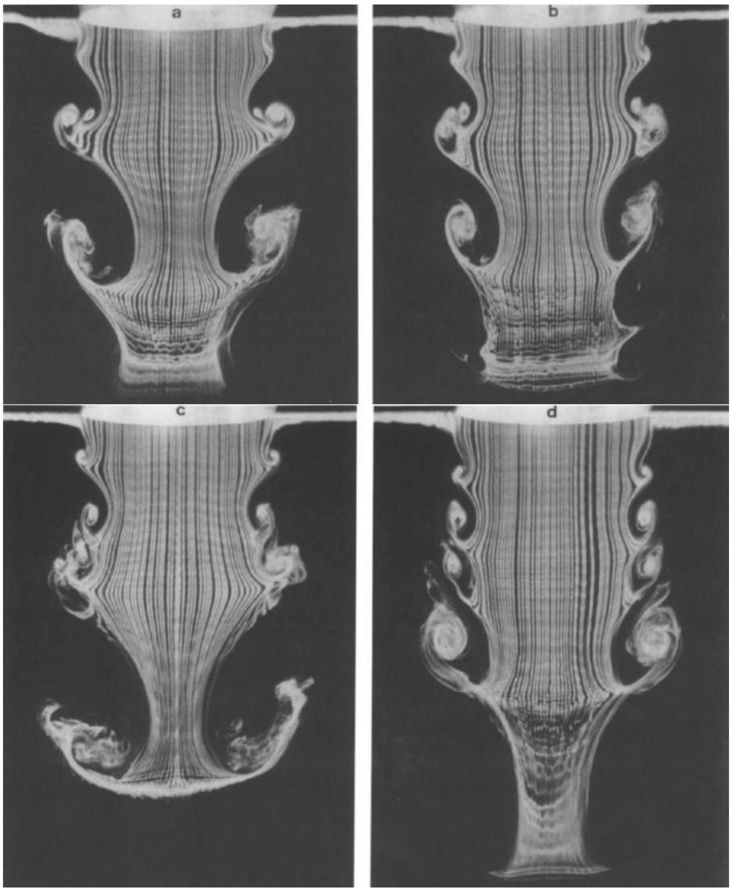
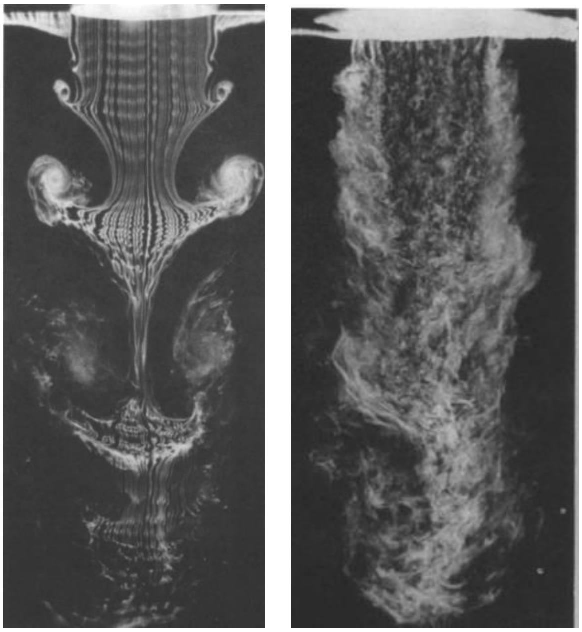


Fig 2. Torodial Vortex Initiation and Development [25]

Flow visualization Images obtained by Popiel [25] and Cornaro et al [22] for free jet (fig 2), shows filament line pattern of the jet at the first two diameters and following stages of vortex formation in the vicinity of the nozzle mouth. Low-turbulence stream of air leaving the trailing edge of the nozzle is surrounded by a thin unstable laminar shear layer. The laminar shear layer leaving the nozzle immediately forms waves with increasing amplitude (Fig. 2a). In the same figure a small lump of vorticity containing fluid, which separates following top (crest) of a sinusoidal wave, convecting downstream and starts to roll up (Fig. 2b). This lump grows in size and form the toroidal vortex. When the already formed and developing strong vortex is convected downstream at a sufficient distance from the nozzle, a new vortex is begin at a small distance from the nozzle mouth in the naturally disturbed free jet (Fig. 2a). The last formed vortex causes a significant contraction of the potential jet core, probably producing a slight pulsation in the pressure of the fluid at the nozzle mouth. This is some kind of" vortex action upstream" that synchronizes the appearance of a new instability wave and as a result vortex generates around the entire circumference.

If the toroidal vortex birth is triggered too early may be by large-scale turbulence peak or by some internal or external disturbances. This vortex is weaker and is usually very soon surrounded by the earlier formed large vortex, this process termed as vortex pairing.



a b

Fig 3 Free round jet a.) Natural b) Highly Turbulent[25]

Vortex pairing process is an inherent phenomenon in the development of the free jet and occurs irregularly. The contraction and swelling of the free jet core near the nozzle does not occur regularly in time due to triggering of vortex initiation which occur in irregular interval and random in nature. However the average passing frequency of the primary vortex structures expressed in the form of Strouhal number, based on momentum thickness of the boundary layer at the nozzle mouth, which is nearly constant. Beyond a distance of about 1.5d the developing toroidal vortex grows in scale to become comparable with the nozzle radius and passing frequency of large toroidal vortices reduces, as observed in Figs. 2 and 3a. Because of this decrease, some toroidal vortices may combine to maintain the same average convective velocity. In this region length scale for the vortex flow is proportional to the diameter of the jet. Therefore, a new preferred vortex passing frequency based on the jet nozzle diameter is used. On putting a rough screen in the way of free round jet, jet loses its regular vortex structure and becomes highly turbulent. Beyond a distance 1.5d this highly turbulent jet becomes unstable and starts to wave motion fig (5b).

A. Entrainment Process

Entrainment of fresh fluid from the surroundings in a free jet has a strong influence on the jet characteristics with the increasing in the mass flow. The toroidal vortices moving downstream grow in size due to the rolling-up action in which the jet core and ambient fluids are involved and supported by the opposite viscous forces applied to the external and internal diameters of the toroids. The growth of toroidal vortices does not changes their main diameter significantly but strongly contracts the jet core, results stretched fluid elements along the jet axis. The jet core fluid elements between the large toroidal vortices are instead strongly shortened in the axial direction and stretched in the radial direction. The developed vortices draw a large amount of ambient fluid into the jet. The trailing edge of each vortex causes a transfer of ambient fluid toward the jet axis, while on the leading edge the nozzle fluid is transferred to the external side of the mixing layer of jet. At the final stage of vortex development the main part of the entrained fluid enters the middle part of the jet and separates the toroidal vortex from the squeezed nozzle fluid.

At this stage the vortex cores are usually turbulent, containing diffused smoke due to the earlier pairing processes (Fig. 3a) and the vortices undergo a strong circumferential secondary instability. Far downstream the jet loses its order, and fluctuations in the jet become more chaotic due to the appearance of higher-order instabilities. At a distance of $x/d > 3\text{-}5$, the smoke traces become difficult due to high diffusion. According to

Fondse et al [36] measurements of entrainment rate is considerably higher for a laminar exit boundary layer compare to turbulent.

During entrainment process free jet behavior is reported by Carnaro et al [22] for distinct Re, different flow situation occur for same Re but for different jet dia. Large vortex structure is present at low (Re) due to low turbulence intensity level. These vortices vanishes at high (Re) for smaller diameter jet due to higher turbulence level in the shear layer at jet edge. The spacing between smoke streak line is reduces where ring vortex rotates towards the jet centre line and is expanded where the ring vortex rotates away from jet centerline. Such expansion and contraction is responsible for axial velocity oscillation in the potential core region. With the contraction of vortex structure fluid is accelerated and with expansion fluid is retarded. Axial velocity distribution variation for low Re but for high Re no such variation is observe due to high turbulence level in shear layer at jet edge.

B. Vortex Spacing

As mentioned earlier axial velocity oscillations form an instability in the low turbulence shear layer which results in small vortices, these vortices rolls up and grow in size as they moves downstream. The vortices start to break down at the end of the potential core where the oscillation of the jet is high. Cornaro et al [22] reported vortex spacing is a function of both (Re) and jet diameter. With increase in Re and jet diameter vortex spacing reduces.

It is assumed that vortex spacing (λ) (Average separation distance between two neighboring toroidal vortices from the nozzle) is proportional to the distance (y) from nozzle. A relation was proposed for measured value of (λ) with (y) as

$\lambda/d = 0.55y/d$ the value of (λ) is also expressed as

$\lambda/d = Uc/f_d = (Uc/Uo)/St$

where Strouhal number (St) based on preferred passing frequency of large toroidal vortices and is given as St = 1.2(y/d)-1.

IV. IMPINGEMENT JET ON CONVEX SURFACE

Impingement jet on curved surface is categorized in two way impingement over convex and over concave surfaces. Visualization images shows flow over concave surface is more unsteady than convex surfaces [22]. Effect of centrifugal forces stabilizes the flow over convex surfaces while this force destabilizes the flow over concave surfaces and lead to a type of instability called "Taylor-Görtler" vortex [29]. Effect of surface curvature, nozzle to surface spacing and Re is more or less similar on both types of surfaces. Therefore only visualization of flow over convex surface is reviewed here. Impingement jet flow remains same as free flow before impingement but presence of different impingement surface affects vortex generation and structure. Cornaro et al [22] observed that presence of convex surface reduces vortex spacing for low Re and jet diameter compare to free jet. For large nozzle to surface distance equal to potential core length, radial oscillation of stagnation point on convex surface is stronger than flat plate. The radial oscillation of the jet enhances the breakdown of the vortices that reaches the surface and destroys the symmetry of the jet upstream of the surface. As the (z/d) decreases clear vortex structure is observed in jet shear layer and rolled down on surface until dissipate in unsteady flow situation with less stagnation point oscillation and symmetric upstream vortex structure. At z/d =1 radial oscillation ceases and strong oscillation in axial direction is observed with distorted smoke filament. This axial oscillation carries the vortex structures periodically on and off the surface

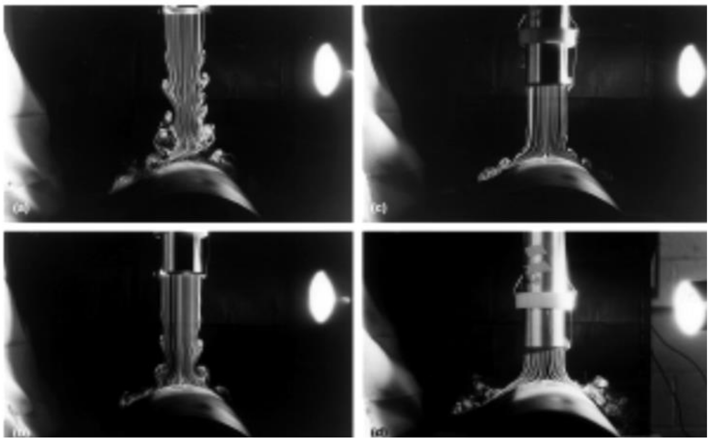


Fig 4 Round jet on convex surface effect of (z/d) [22]

similar to flat plate condition (fig 4).

Curvature effect on vortex structure is shown in fig (5). For z/d=2 a transition from laminar to unsteady flow along the surface is observed for lowest curvature, when curvature increases, flow remains laminar along the

Table 2 [AC 11]

surface, delays in transition to turbulence as the flow along the surface remains stable and shows well-formed vortex structures. This is due to flow stabilization by centrifugal force; result in more time for laminar flow at high d/D. With further increase in (z/d) situation remains same but at high d/D vortices break down rapidly. At very high and low value of (z/d) curvature effect is reduces due to radial oscillation at high z/d and axial oscillation at low z/d. At 90° orientation, section parallel to the axial axis of the cylinder the flow shows similar vortex structure (fig. 6).

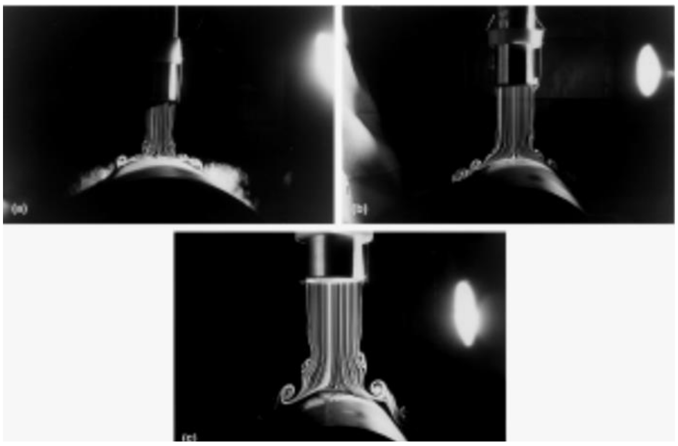


Fig 5 Round jet over convex surface effect of curvature [22]

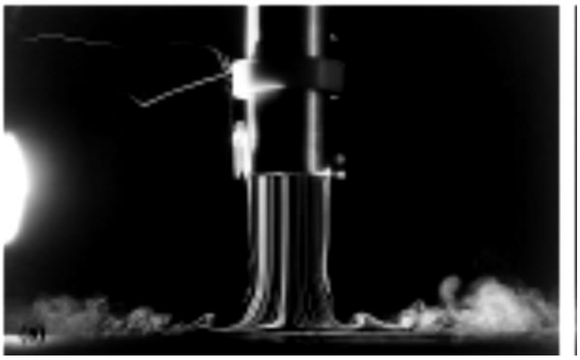
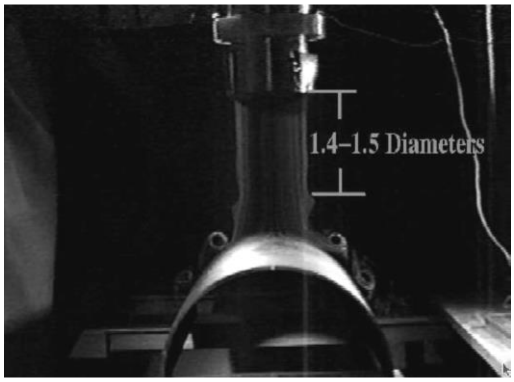


Fig.6 Round jet over convex surface 90^o orientation [22]

Same oscillation type behavior of round jet issuing from a straight tube and impinging on a convex surface of high relative curvature of d/D= 0.18-0.38, at z/d=1-4, tube diameter(d) 47.2, 72.6 and 98.6 mm is observed by Fleisher et al [24]. They investigated the effect of (Re), (z), and (d/D) on vortex initiation (Xi), vortex separation from surface (ϴs) and vortex break up (Xb). They found increasing (Re) decreases (Xi), indicating faster movement of vortices. Effect of (z) is not straight forward, Maximum (Xi) occur if nozzle to surface spacing is near to potential core length, decreasing or increasing from this value, decrease vortex initiation distance (Xi) (fig 7).

The variation with (d/D) shows Xi increases till d/D = 0.28 then decreases. Vortex period(ι) doubled with (d/D) 0.18 to 0.28 and 10 times from 0.18 to 0.38 for same Re and z/d. Increasing (Re) has no clear trend on ϴs, but with decreasing (z/d) it decreases slightly or remains constant at high z/d, vortices dissipate prior to striking the surface and no separation is observed. Increasing d/D result in larger (ϴs) i.e. vortices stayed on the surface longer for high curvature.



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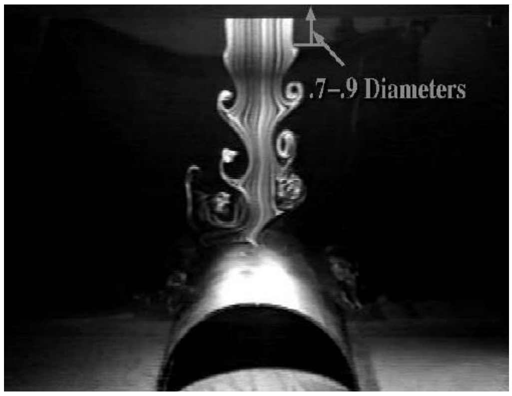

b

Fig 7 Vortex initiation location for a). z/d = 3, b). z/d = 4 [24]

For large z/d, the vortices break up as they reach the end of potential core of the jet prior to impingement due to vortex merging. For small z/d the vortices break up rapidly after separation from the surface (fig 8). If vortex breaks up before impingement i.e. for large z/d increasing Re decreases Xi and Xb, decrease in vortex initiation distance seems to carry over to vortex break up. If vortex break up after impingement, increasing Re slightly increases angle at which break up occur. With decreasing z/d, vortices breakup at smaller distance from nozzle prior to impingement and at smaller angle from impingement point. Since decreasing z/d reduces Ɵs i.e vortices are separating as well breaking up sooner. Increasing d/D, vortex break up location prior to impingement and vortex break up angle after impingement both increase, as with increasing d/D, Ɵs increases i.e. vortices remains with surface longer, only breakup after separation occur.

Merging of vortices causes the central jet to move just slightly to the left or right of impinging point, the next vortex merging occur on the opposite side, pushing the jet in other direction, continuous happening causes oscillation of jet around impinging point. Vortex merging occurs at high (D) and high (z/d), indicating vortices doesn't move fast enough to prevent them from being entrained in fluid flow. At low z/d merging not occur due to high fluid velocity of jet resulting vortices moves fast enough to impact the surface prior to merging.

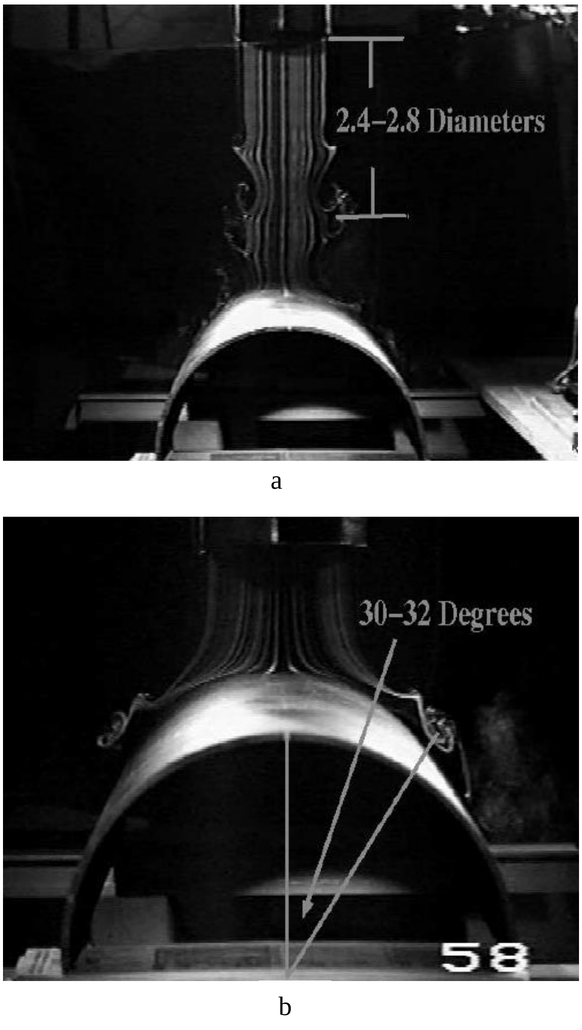

Fig 8 Vortex breakup location for a). z/d = 3, b). z/d = 1 [24]

V. CONCLUSIONS

Flow images for free jet shows vortex structure formed wherever flow instabilities occur and vortex size increases as it moves downstream. Location and behavior of these vortex structures affected up to great extent by the type of impingement surface, however vortex nature remains more or less same. On the convex surfaces centrifugal force stabilizes the flow thus no large 3D vortices called "Taylor-Görtler" are observed but on concave surface due to instabilities causes by centrifugal force such vortices are observed. These counter rotating vortices increase the momentum and energy exchange in the flow, which can enhance the heat transfer along the wall.

At high z/d radial oscillation of stagnation point is seen, which reduces on decrease in (z/d) but oscillation in axial direction appears. With increasing curvature flow spends more time over convex surface result in enhanced heat transfer, transition of flow from laminar to turbulent occur at low curvature result in earlier vortex separation and hence low heat transfer. High Re reduces vortex initiation distance indicating faster movement of vortices but effect of increasing jet diameter is more prominent due to significant mixing with ambient air results in earlier termination of potential core. Jet becomes wide and fully turbulent before reaching to surface. Curvature effect is prominent for high Re and at stagnation region, away from stagnation in wall jet region effect of curvature vanishes. At the small (z/d) the flow is deflected away from the front surface of the cylinder and lacks energy to reattach on the backside, thus ineffective cooling flow at backside. At large (z/d) the cylinder is located beyond the free jet potential core and the jet center line velocity is reduced by entrainment effect; the approaching free jet momentum on the surface is degraded to a level where the high turbulence cannot compensate for reduced impingement velocity.

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