

Influence of Wall Position on Flow Characteristics of an Impinging Jet

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ABSTRACT

The study intends physical insight into heterogeneous phenomena of efflux from a small opening impinging on a surface. The work aims at understanding the role of wall location and orientation on flow characteristics of an impinging jet. Experiments were performed on an existing cascade tunnel with flow ejected at a velocity of 37 m/s from a small opening of (30 cm × 9 cm) and corresponding flow features were analyzed. Results show that outside the core region, the flow experiences a monotonic reduction with increase in distance along streamline and radial direction. The orientation of wall is more efficient in bringing substantial change when placed closer to the exit (low velocity losses). The wall orientation primarily governs the chances of strong flow deflection or back flow losses. Wall placed far away from exit results in diminishing returns with a critical value beyond which the flow characteristics become insensitive of wall orientation.

Keywords - Efflux, shear interaction, vortices, wall jets, wall orientation, wall location.

I. INTRODUCTION

The study of jet efflux from a small opening is a phenomenon of practical and functional significance for space research activities. The subject involves mass and heat transfer and is widely characterized as: Free and Wall Jet. This classification is based on presence of a surface (i.e. wall) against the jet expelled. While in free jet configuration, jets exit a nozzle or tube into a stationary or moving fluid (same or different), wall jet refers to a stream of fluid blown normally or tangentially along a wall (subjected to position of wall). The free and wall jets are broadly encountered in nature and cover wide range of applications. Examples include aircraft gas turbine engines, liquid and solid rocket motors, boundary-layer separation control over a wing, film cooling on turbine blades, etc. In the wall jets, an efflux of liquid or gaseous when released against surface large amounts of mass and thermal energy transfers between the surface and the fluid takes place. Figure 1(a) shows the schematic of a free jet issued from a small opening. In free jet mode as the fluid moves downstream, it interacts with the surrounding fluid and its speed drops. Consequently, the efflux of jet rifts into two distinct regions viz., a region near the centerline where fluid interacts less with the surrounding medium and maintains nearly its initial speed some distance downstream.

This region in which the speed is nearly that of the exit is termed as the potential core or the core region (see fig. 1(a) & (b)). The length of core region in jets under different conditions is a prominent factor.

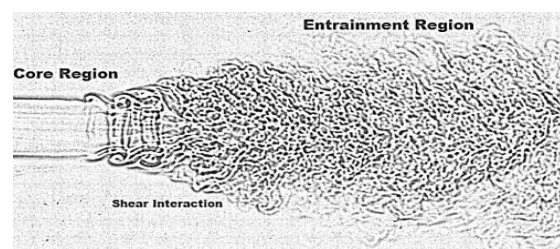
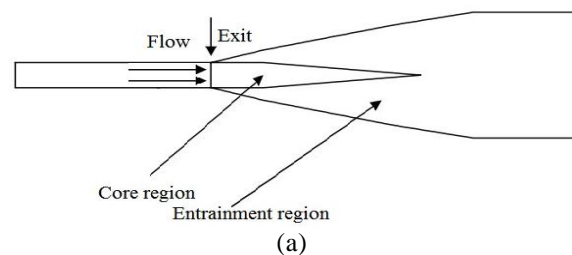


Figure 1: (a) Schematic of a free jet (b) Pictorial view of a free jet.

Next is region outside the core where fluid comprehensively interacts with the surrounding fluid. This region is known as the entrainment region and it is identified by drastic change in flow characteristics (see Fig. 1(b)). The presence of a surface in front of a jet is very likely to alter the flow characteristics. This surface when placed at different locations and orientations will have significant implications.

Following the classical work of Glauert (1956) highlighting the flow due to a jet spreading out over a plane surface. In the last five decades research works have contributed significantly to the advancement in understanding of the free jets. The contributions have been reported in several reviews like Gardon and Akfirat (1966), Kercher and Tabakoff (1970), Sparrow and Alhomoud (1984), Gau and Chung (1991), Gori and Bossi (2000). The works provide an excellent review on the developments up to the end of the century.

In the last decade appreciable advancements have occurred. Roy and Patel (2003) studied the dominant fluid-thermal characteristics of a pair of rectangular air jets impinging on an inclined surface. Heat transfer modes and flow characteristics were studied with eight different Reynolds numbers ranging from 500 to 20000. Aldabbagha and Mohamadb (2009) carried out a three-dimensional numerical study to determine the flow and heat transfer characteristics of impinging laminar array of square jets on a moving surface. They stated that a rather complex flow field with horseshoe vortices formed around the first column of jets due to the cross flow created by the moving surface. The velocity ratio of the moving plate increases the cross flow as a result a ground vortex cannot form in front of the second and third column jets compared with the case of fix surface.

In recently, Azam et al., (2013) studied pressure distributions and oil flow on the plate to figure out the flow structures for the rectangular nozzles by comparing three-dimensional calculations to the experiments. They investigated at three different aspect ratio under-expanded impinging jet issued from rectangular nozzle. The results stated that the flow is separated on the impinging plate from center point toward outside and that the flow on the plate avoids the high-pressure areas. San and Chen (2014) explored the effects of jet-to-jet spacing and jet height on heat transfer characteristics of an impinging jet array. Tiwari et al., (2014) carried out experiments to investigate the effect of wall location on flow characteristics of an impinging jet and the core region. The work showed that increase in centerline wall location enhances the velocity losses. Wall location near to exit causes strong deflection of flow resulting formation of vortices with prominent chances of back flow. Furthermore, for a fixed wall location, increase in radial distance enhances the velocity losses, but it results in diminishing returns beyond a critical value. Although much has been done but complexity of the problem has prevented a complete understanding due to interaction between flow, heat and mass transfer.

Therefore, a systematic study is needed to understand mechanisms controlling the behavior of jets and their flow characteristics.

In the light of above-mentioned works, the work primarily focuses on flow characteristics of an impinging jet against varying wall location and orientation. This aspect of jets is yet to be comprehensively explored. Hence, a systematic study is needed to understand mechanisms controlling the behavior of jets when impinging on a wall placed at different locations and orientations besides the one open to atmosphere or without any wall. The interest in this class of problems is specifically driven by the need to have better understanding of fluid and thermal characteristics of jets. To address the above mentioned issue, the present work

1. Experimentally explores the effects of surface location and orientation on flow characteristics of an impinging jet.
2. Analyzes the role of key controlling parameters.

II. EXPERIMENTAL SETUP AND SOLUTION METHODOLOGY

A simple apparatus (Fig. 2(a)) was adapted for this study. The apparatus consisted of a) cascade tunnel (Fig. 2(b) base made of mild steel b) a Pitot tube (Fig. 2(a)) and c) Micro Manometer (Fig. 2(c)). The cascade tunnel issues a free air jet using a centrifugal blower with a velocity of 37 m/s. The efflux is from a small rectangular opening (dimensions 30 cm × 9 cm (Fig. 2(d)) into the air in a quiescent room. The flow characteristics are determined by establishing the pressure balance between dynamic pressure and the hydrostatic pressure.



(a)



(b)



(c)

Figure 2: Pictorial view of (a) complete experimental setup (b) side view of cascade tunnel (c) micro manometer.

The dynamic pressure is measured using Pitot tube (exposed directly to the flow and stagnates it at surface measuring total pressure, the static holes are at the center and side of the tube measuring static pressure and the dynamic pressure is difference of the two pressures). The micro manometer calculates the hydrostatic pressure due to change in elevation of the fluid used (here distilled water) owing to different dynamic pressures under different conditions. The micro manometer exhibits an accuracy level of 0.001 cm height of the fluid and can measure the differential pressure up till the range of 300 mm of the used fluid. The dynamic pressure is equated to the hydrostatic pressure and the flow velocity (kinetic energy) is measured. It is important to note that all the readings were taken systematically in proper time interval and all the reading taken here represent the repeatability of results obtained. The wall used in the study is a rectangular cardboard surface with dimensions of 180 cm × 120 cm × 1 cm. The flow is turbulent and the effect was noted in fluctuations in the reading, so for every reading taken here the average repeated value with was accounted. The flow velocity is obtained by equating the dynamic head to pressure head obtained by the liquid height change as:

$$\frac{1}{2} \rho_a V^2 = \rho_l g (h_1 - h_0) \quad (1)$$

From equation (1), the flow velocity “V” is determined as:

$$V = \sqrt{2 \frac{\rho_l}{\rho_a} g (h_1 - h_0)} \quad (2)$$

Where

- ρ_a Density of air (Kg/m³)
- ρ_l Density of water (Kg/m³)
- V Flow velocity (m/s)
- g Gravitational acceleration (m/s²)
- h_0 Reading corresponding to zero differential pressure
- $h_1 - h_0$ Liquid head corresponding to the dynamic head
- W_{\square} Wall orientation
- D Equivalent diameter of a circular exit (1D = 18.54 cm)

It is important to note that the density of liquid (here distilled water) depends on the place of use of the manometer (the atmospheric pressure and temperature at the time and place of use). While, the density of air can be calculated using the state relations for air for corresponding pressure and temperature.

III. RESULTS

A parametric experimental study was carried out to study the flow characteristics of a jet issued from a small opening and impinging on a wall placed normal at different locations and orientations. The effect was investigated by placing the wall placed at three different locations viz. far away from exit (18D & 15D), at an intermediate distance (10D) and at locations very close to exit (2D and 5D) and further varying orientation of wall in capacity of horizontal, vertical, 30°, 45°, 60° against the efflux. Here, ‘D’ normalizes the streamline distance and all the readings were taken in folds of ‘D’. It must be noted that ‘D’ represents the equivalent diameter of a circular exit when compared to the exit of cascade tunnel (rectangular). First, the results obtained from the experimental setup were validated with the benchmark subject of flow characteristics of a free jet.

Figure 3 shows the variation of normalized centerline velocity as a function of normalized streamline distance for a free jet. The exit velocities at different locations are normalized by maximum velocity (here, 37 m/s) and the streamline distance is normalized by the equivalent circular diameter ‘D’. Results show that the flow characteristics exhibit a monotonically reducing behavior with increment in streamline distance.

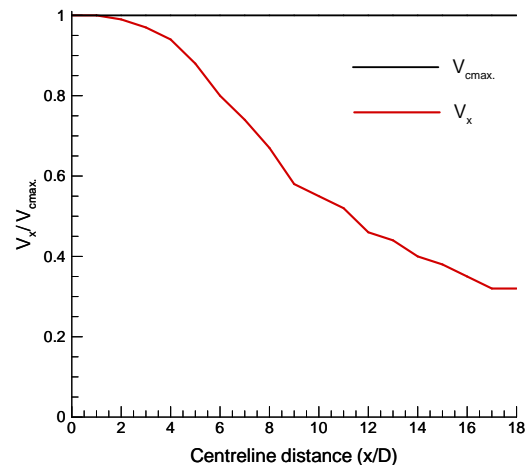


Figure 3: Variation of normalized centerline velocity as a function of normalized streamline distance for a free jet.

Looking at the plot one can note that as the jet exits the tunnel, there is drastic loss of flow velocity (kinetic energy) with increase in streamline distance. The core region is seen to extend till 3 units. Alongside the axial variation of a free jet, the variation of flow velocity in radial direction at various orientations (at differential of 5 mm) is investigated.

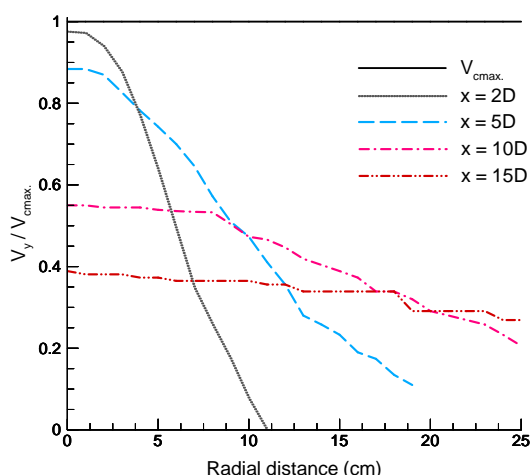


Figure 4: Variation of normalized radial velocity as a function of radial distance for a free jet.

Figure 4 shows the variation of normalized velocity with distance in radial direction at axial locations of 2D, 5D, 10D and 18D respectively. Interestingly, a trend similar to variation in axial direction is observed in radial direction as well. As expected, the flow velocity reduces with increase in radial distance subjected to width of core region (here noted as 3 cm). Looking at the profiles it was noticed that, when the reading is taken very close to exit (here 2D), the flow lies in core region and with increase in distance suddenly comes out of it and velocity falls drastically.

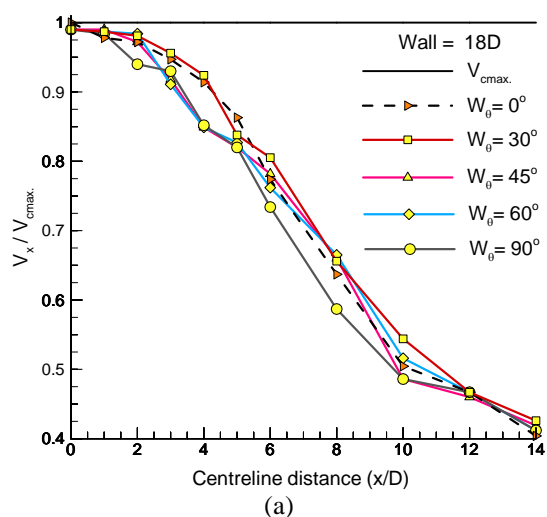
When the same trend was introspected at 5D, the maximum velocity (here at centerline) was found lower than at 2D. However a sudden drop in radial velocity was noted beyond some distance as the flow moves out of core region. While, at an intermediate distance of 10D, the flow is already out of core regime and is in entrainment region thus an overall sudden drop in flow velocity is seen. Furthermore, as the distance in radial direction increases, unlike wall placed closer to exit, here flow velocity reports a gradual drop.

Similarly, at location far away from exit (here 18D), the trend of maximum velocity being lower with axial distance is followed alongside the gradual drop in flow velocity with increase in radial distance. The reason for above mentioned changes in axial and radial direction can be attributed to the shear interaction with surroundings leading to strong energy conversions. The length and width of core region dictates the velocity loss at different positions. Since from the results obtained it is evident that the experimental setup predicts correct results as preceding theories substantiates, the study was extended to investigate the effect of presence of a

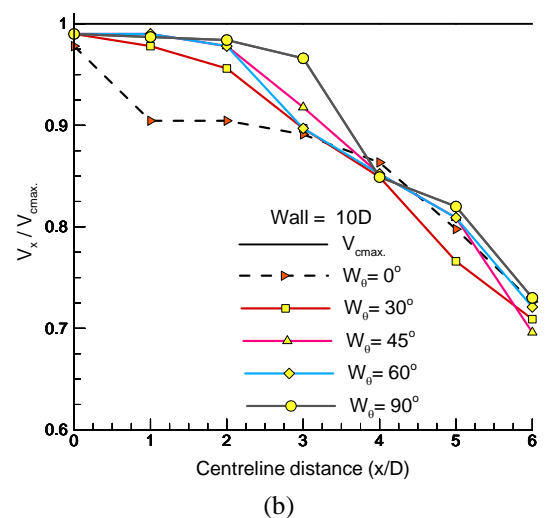
wall at different axial locations and orientations on flow characteristics.

First the wall was placed in centerline against the flow at three different locations viz., very near to exit (5D), at an intermediate distance (10D), at a location far away from the exit (18D) in capacity of horizontal, vertical, 30°, 60°, 90° orientations respectively.

Figure 5 shows variation of normalized centerline velocity as a function of wall location and orientation in comparison to maximum velocity. One can note that, when the wall is located far from exit (see Fig. 5(a)) with increment in orientation the velocity reduces. The centerline velocity at 18D is seen lower than maximum indicating the loss of kinetic energy.



(a)



(b)

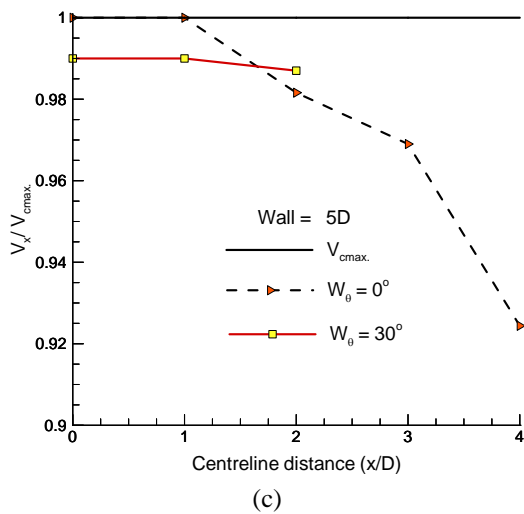


Figure 5: Variation of normalized centerline velocity as a function of wall orientation for wall located at (a) 18D (b) 10D (c) 5D.

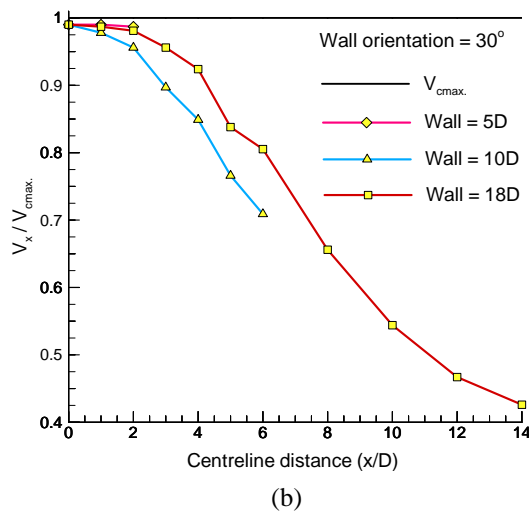
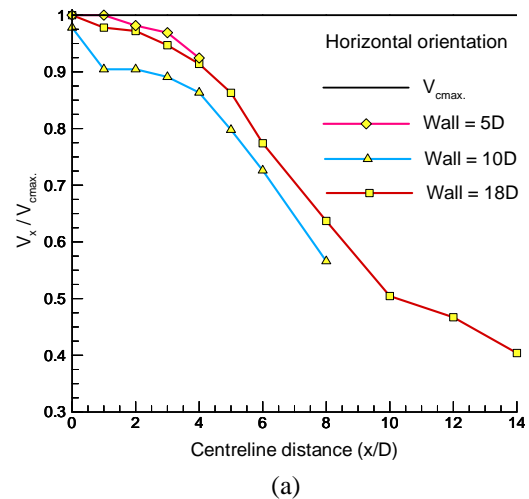
This loss of flow velocity is more when the wall is placed in vertical orientation however when kept horizontal or closer (here till 30°) the effect more or less is same.

This dictates that up to a fixed wall orientation the effect of shear interaction is within a closer range but as wall orientation changes beyond to vertical, it behaves as a case of free jet and significant losses are noted. Increased wall orientation increases the induced loss in flow velocity. Interestingly, at certain centerline distance the velocity profiles converges to corroborate the loss. For present case, till centerline distance of 3 units, the flow velocity loss is lower for all profiles indicating the presence of core region. Following the core region, further increment results sharp drop in velocity profiles. In this work, we refer to the point up-till which the core region exist in streamline direction as “VRM-PPT point” (Here 3 units= ~ 55 cm). A trend almost similar to far located wall (18D) is noted at a location of 10D. Beyond “VRM-PPT point” sharp drop in flow velocities is noted. The flow profiles are seen merging at centerline distance of 4 units. However, in this case when wall is placed parallel or is in vertical orientation to the flow the loss is lower than wall orientation in the range of (0-30°). For wall located at 10D the applicability of the flow can be more when wall is close to or vertically oriented. For the case when wall is located closer to exit (5D), the study was extended only for two orientations viz., horizontal and 30°.

Expectedly, the centerline velocity is more and the flow is mainly confined in the core region. A crossover in flow velocity profiles is noted at a streamline distance of 1.5 cm. Here, the results

strongly pronounce that when wall is located far away and orientated in range of horizontal, the tangential component of flow velocity can be effectively used for engineering applications. However, when placed closer flow gets deflected, there are strong chances of flow getting back so safety needs to be ensured especially in cases such as liquid and solid rocket motors where exhaust comes out at very high velocity. This engineering aspect can be widely used in applications ranging from heating, cooling to engineering where preceding designs are not sufficient. To understand the results in Figure 5, we next explore the effect of varying wall location for fixed orientations on centerline velocity.

Figure 6 shows variation of normalized centerline velocity as a function of streamline distance for varying wall location and fixed orientation.



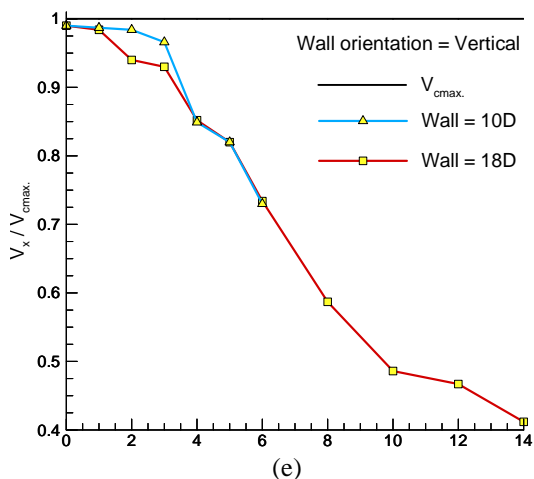
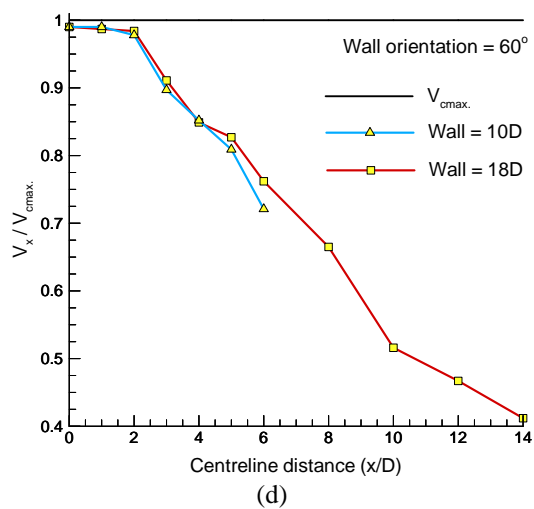
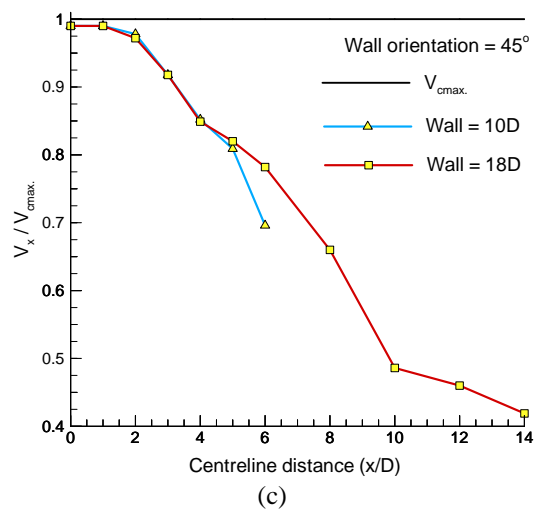
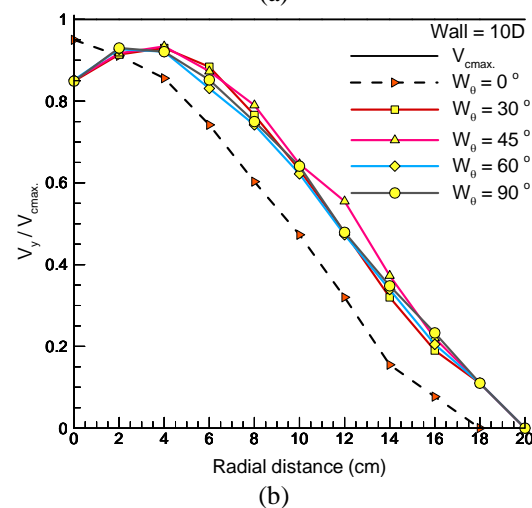
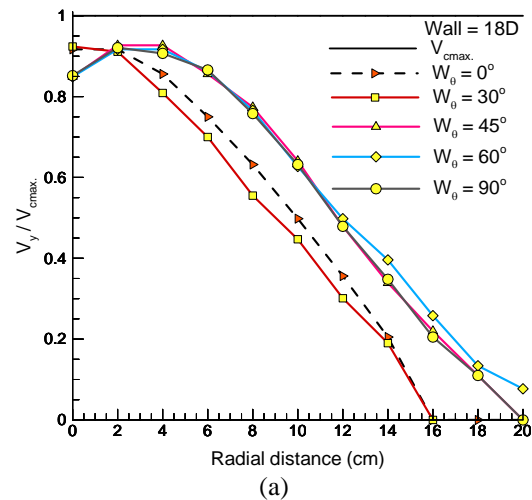


Figure 6: Variation of normalized centerline velocity as a function of wall location at different orientations
 (a) Horizontal (b) 30° (c) 45° (d) 60° (e) Vertical

loss in flow velocity increases. One can note that the wall placed closer to exit have more centerline velocity than the one placed far away. However, beyond “VRM-PPT point” all profiles fall drastically. When placed closer, the losses are low but when wall is placed far away the losses increases significantly. It is interesting to note that the flow velocity profiles for wall locations of 10D and 18D are close to each other and that loss of velocity at 18D is significantly lesser than at 10D till wall orientation is 30° . However, beyond orientation of 45° the profiles are seen to merge with each other. All profiles are seen to merge at centerline distance of 14 Units. For vertical orientation of wall, the loss in flow velocity is less for 10D as compared to 18D.

The reason for this can be attributed to the shear interaction of flow as it starts expanding. The vortices formation when wall is placed at an orientation increases the flow losses.



All the profiles are in comparison to maximum centerline velocity. One can note that, for all fixed orientations as location of wall increases the

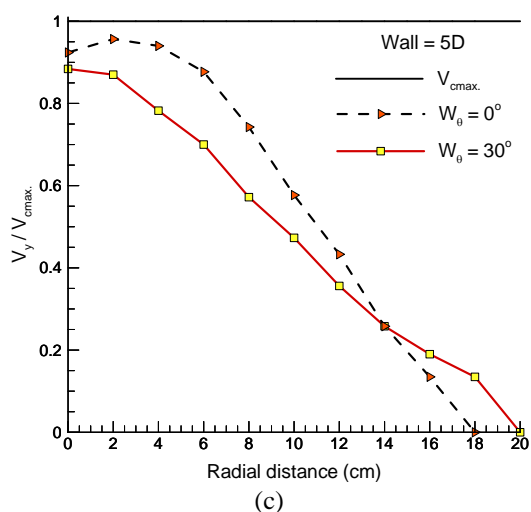


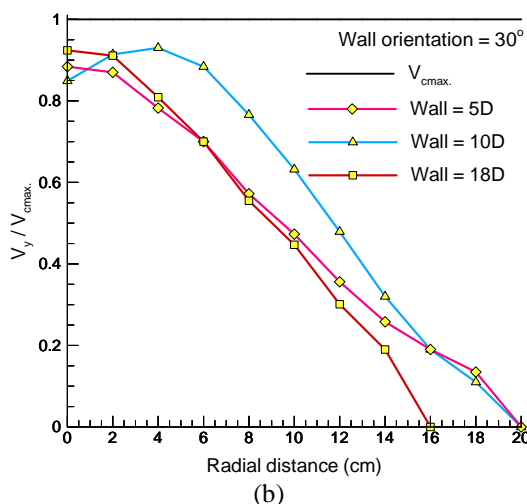
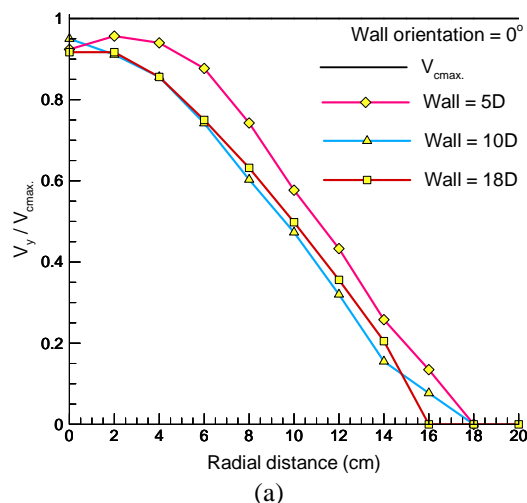
Figure 7: Variation of normalized radial velocity at orientation of 4D as a function of streamline wall orientation (a) 18D (b) 10D (c) 5D.

Next, the effect of wall orientation on radial component of flow velocity is explored. The wall was placed at axial locations of 5D, 10D and 18D. Figure 7 shows variation of normalized radial component of velocity as a function of radial distance for varying wall location and orientations. The effect in radial direction is catapulted to a distance of 20 cm at axial orientation of 4D for all the profiles. Looking at the profiles, one can note that beyond radial distance of 3 cm, the velocity profiles for different wall orientations exhibits drastic drop in kinetic energy similar to the centreline variation. As expected, the rate of reduction in flow velocity is more when wall is placed far away (here 10D and 18D). For all the profiles, a gradual drop till “VRM-PPT” and then sharp drop is noted. It is interesting to note that when wall is placed far away, the loss at a fixed location is more when placed horizontal. However, as the location of wall reduces, the loss due to horizontal orientation is found minimum. Wall locations of 18D and 10D almost follows same trend showing insensitiveness beyond a critical value. Almost similar trend is observed at wall locations of 30° . Beyond a certain orientation (here 30°) the losses are insignificant to the wall orientation as most of the profiles looks similar and follows same trend.

In the last part, the wall locations were kept fixed and orientations were varied and effect on radial component was investigated. Furthermore, to get a holistic understanding, next we fix the wall orientation and analyze the effect of wall location on flow energy. Figure 8 shows variation of normalized radial velocity as a function of radial distance for varying wall location and fixed orientation. All velocity profiles are determined at axial location of 4D. As seen in Fig.7, beyond an orientation of 30° the

significant change in velocity profiles is not noted. Wall when placed at 18D at different orientations shows that, at an orientation of 30° maximum reduction in velocity is noted followed by horizontal. One can also note that wall when placed at 45° , 60° , 90° almost follows similar profiles. The velocity profiles were also compared for vertical and horizontal orientations and it was observed that the loss in velocity with horizontal orientation is less than vertical. Furthermore at a radial distance of 14 cm and above profiles are seen merging.

The velocity profiles for 10D and 18D were found to merge with each other indicating that beyond a certain distance the velocity change is insensitive to wall orientation. At a faraway distance of 13 mm all the velocity profiles are seen converging to a common value indicating a peculiar point of identical velocity loss.



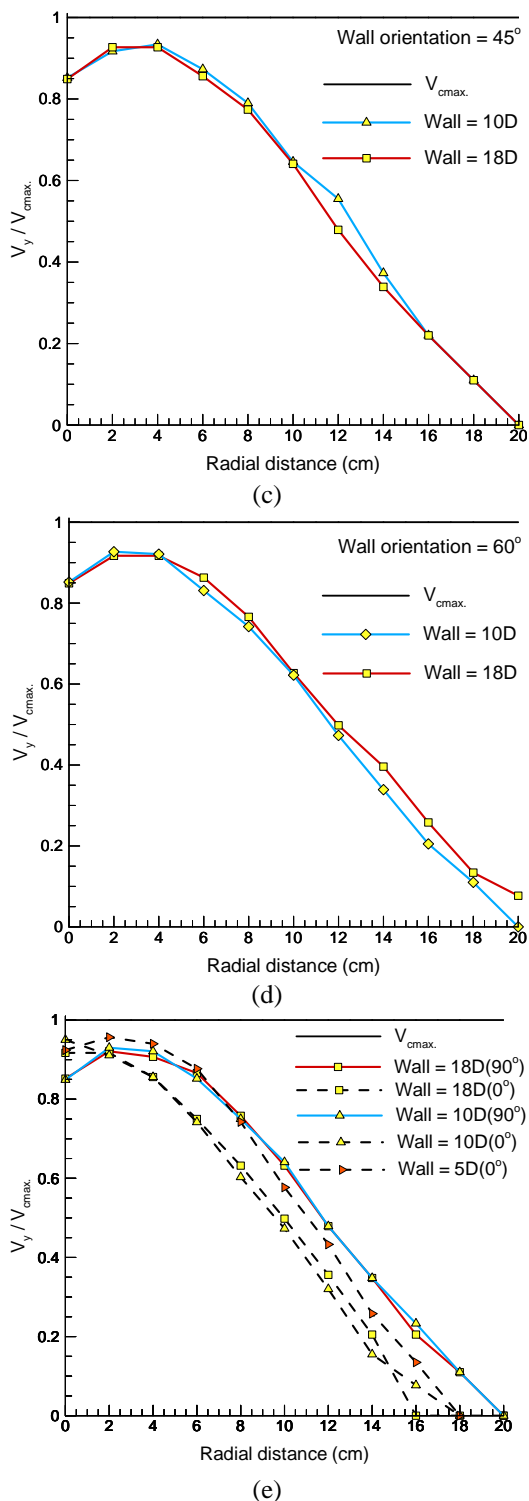


Figure 8: Variation of normalized radial velocity at radial location of 4D as a function of streamline wall location at different orientations (a) Horizontal (b) 30° (c) 45° (d) 60° (e) Vertical

IV. CONCLUSIONS

An experimental exploration was carried out to understand the effects of wall orientation on flow characteristics of a free jet. The results predicted by existing experimental setup were validated with benchmark preceding free jet theory and extended further to note the implications of wall orientation. Based on results obtained following conclusions may be drawn from this study: The increase in wall orientation axially, enhances the velocity losses beyond a critical distance (i.e., core region). The orientation of wall near to exit results in low velocity losses and consequently strong deflection of flow resulting formation of vortices with more chances of back flow. For a fixed wall orientation, increase in radial distance enhances the velocity losses, but it results in diminishing returns beyond a critical value indicating insensitiveness of wall orientation after a certain distance.

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