FLOW VISUALIZATION STUDIES ON SUBMERGED FREE AND IMPINGING JETS.

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Abstract

A submerged water jet is made to impinge on a plate kept at a fixed distance from the nozzle exit. Flow patterns are investigated to study the influence of inlet conditions for free and impinging jets. A smooth circular pipe of l/d ratio of 80 is chosen as a nozzle for the present study. Experiments are done for four different inlet conditions as follows

- *Free jet with nozzle exit aligned with the test tank inlet (Free jet-orifice configuration)*
- *Free jet with nozzle exit protruding in the test tank for l/d = 13.7. (Free jet-Nozzle configuration)*
- *Impinging jet with z/d (ratio between plate and nozzle exit to the nozzle diameter) of 6 and 12.*

Reynolds number is varied and the resulting flow patterns are recorded by a digital camera. Laminar length is measured and the nature of flow (laminar or turbulent) is characterized from digital images. As the Reynolds number is increased till 2000 the flow continued to be laminar and laminar length is seen to be increased. For 2000 < Re < 2500 the flow is fully laminar for both the impinging jet configurations whereas it is semi-turbulent for the free jet configurations. The laminar length started to decrease till it became negligible to turbulent regimes at Re > 2800. The transitional Reynolds number for free jets is found to be around 2200 whereas for impinging jets it is around 2600. The laminar length of free jet in free jet-nozzle configuration is found to be less than the length for the free-orifice configuration for all Reynolds numbers.

Nomenclature

a - Laminar length (*mm*)

d - Diameter of the nozzle (*mm*)

l - Length of the nozzle (*mm*)

Re - Reynolds Number ($\rho Vd/\mu$)

z - Distance between plate and nozzle (*mm*)

v - Velocity of the fluid (*m/s*)

ρ - Density of fluid (kg/m^3)

μ - Viscosity of fluid (*Pa s*)

Introduction

A fair amount of research is reported on the flow patterns of free jets. Reynolds [1] reported for a jet diameter of 0.32 *mm* discharging axially into a cylindrical vessel of 30 *cm* in diameter and 120 *cm* long. Laminar lengths (the length of the jet before its breakdown in the medium) of the jet are measured for different volume flow rates whose corresponding Reynolds numbers are lower than 500. Several modes of breakdown of the jet are classified into 1) Tiny puffs of dye near the nozzle 2) Axisymmetric condensations well away from the nozzle 3) Sinuous waveforms of long wavelength far from the nozzle 4) Peddle breakdown and the formation of foot shaped disturbances and 5) Confused breakdown which is observed at highest flow rates. The position of breakdown of simple jets with changing volume flow rates is also presented.

Experiments on submerged jets in short cylindrical flow vessels are carried out by McNaughton and Sinclair [2]. They have varied the inlet diameters from 0.625 to 2.5 *cm*. while test tank diameters are varied between 7.5 *cm* and 60 *cm* with length to diameter ratios of 1, 2 and 3 with $100 < Re < 28000$. Types of jets for various ranges of Reynolds numbers are investigated. Laminar lengths are measured and the dimensionless quantity a/d is presented as a function of Reynolds number. An empirical relation relating a/d, Re and the vessel dimensions is presented.

Literature review suggests that there is no information on the influence of nozzle inlet conditions on the transitional Reynolds number and laminar length for free jets and impinging jets. Hence, the present study focuses on the effect of two nozzle configurations on laminar length and transitional Reynolds number for free and impinging jets. Two configurations for free jets are, nozzle exit flushing with the test tank inlet and nozzle protruding into the tank with l/d = 13.7. Two configurations for impinging jets are, nozzle placed at a distance of z/d = 6 and 12 from the impinging plate. Reynolds numbers covered in the present study are ranging from 800 to 3500.

Experimental Set-up and Procedure

Figure 1 shows the schematic of the experimental setup needed for carrying out the flow visualization experiments. A cubical vessel of 50 × 50 × 50 cm^3 dimensions is prepared and a plate of dimensions (30 *cm* × 30 *cm*) is fixed in it. The plate is made opaque from behind to observe the patterns clearly. The test tank is covered with white sheets and illuminated with a 60W bulb from above.

There is a provision for inserting a nozzle in the test tank. A provision for draining the water is made at the bottom of the tank. A nozzle of diameter 7.3 *mm* and a length of 620 *mm* is used. A pipe is connected to the source and a needle valve is placed in between to control the volume flow rate. A provision for inserting a tracer solution is made by piercing a syringe into the pipe at a distance of l/d = 140 upstream to the tank. To facilitate the formation of a homogeneous mixture of water and dye, a flow development tube of 10 *m* is provided. An outlet is provided on the other side of the tank to measure the volume flow rate. The volume flow rate is measured by using a 'catch and time' technique and thus the Reynolds number is calculated.

Before each run, the tank is completely filled with water and the nozzle is adjusted for the desired inlet condition. Sufficient time (15 minutes) is allowed for the system to reach steady state. The steady state flow is measured every in 5 minutes time interval for 5 times and the average volume flow rate is taken for the calculation of Reynolds number. Without disturbing the system, 0.4 *ml* of tracer solution (methylene blue dye) is slowly introduced in the flow. The flow pattern is captured by a video camera (Nikon coolpix 1600 4Megapixel 32-104 mm optical zoom). It is observed that the laminar and semi-turbulent jets have laminar portion where the streamlines are parallel and non-eddying. This is known as the laminar length. Laminar length is measured from the images taken from the video camera. A pre-determined benchmark is taken whose actual distance from the nozzle exit is known. The corresponding distance in the image is measured and the ratio is taken. This ratio is then applied to the observed laminar length in the image to calculate the actual laminar length. This laminar length (a) is found to be useful characterizing parameter for the configurations investigated in the present study.

The measurements of laminar lengths are made for different configurations as depicted in Fig. 2.

Configurations covered for impinging jets are nozzle placed at a distance of z/d = 6 and 12 from the impinging plate (Fig. 2a and 2b respectively). Configurations covered for the free jet experiments are, nozzle exit aligned to the test tank inlet (Fig. 2c) and nozzle protruding in the tank by a distance of l/d = 13.7 (Fig. 2d). The free jet-orifice configuration is studied to compare the results of present study with those of McNaughton and Sinclair [2].

Results and discussion

Experiments are performed for all the configurations depicted in Fig. 2. Laminar lengths and transitional Reynolds numbers are measured for impinging jet (Figs. 2a and 2b) and free jet configurations (Figs. 2c and 2d). These readings are taken at constant volume flow rate. The volume flow rate is then varied to get three readings for $1000 < Re < 2000$, three for $2000 < Re < 2500$ and three for $Re > 2800$. Following are the observations for free and impinging jet flow patterns according to increasing Reynolds numbers.

Impinging Jet configurations

Figure 3a shows the variation of laminar length with Reynolds number for free jet configurations (for z/d = 6 and 12). For $Re < 2500$, the flow is completely laminar for both the configurations (for z/d = 6 and 12). For these configurations, parallel sided non-eddying streamlines are observed throughout the distance between the nozzle and the plate. Hence, the measured laminar length (a) is equal to the distance between the plate and the nozzle exit. Laminar length for z/d = 12 is greater than that for z/d = 6 for all Reynolds numbers below 2500.

Figures 6a and 6b show the flow patterns for flows with Reynolds numbers higher than 2500. It is observed from these figures that for Reynolds numbers above 2500, there is a transition in the flow characteristics for both the configurations, z/d = 6 and 12. The flow becomes completely turbulent above a Reynolds number of 2700. These figures show the turbulent flow patterns for the impinging jet configurations. Fig. 3a shows the reduction in the laminar lengths of impinging jets for $Re > 2500$. At higher Reynolds numbers the laminar length (a) is observed to be fairly constant. It is thus inferred that for impinging jets the transition from laminar to turbulent flow occurs at Reynolds number close to 2600

Free Jet Configurations

The free jet behavior is observed to be different than that of impinging jet. Figure 3b shows the variation of laminar length with Reynolds number for free jet configurations. Figures 4c and 4d show the images of flow patterns in the laminar regime. It is observed that for Reynolds number less than 2000 the flow is laminar for both the configurations (free jet-nozzle and free jet-orifice configuration). The laminar length (a) increases as Reynolds number is increased. Additionally it is observed that the laminar length for the free jet-orifice configuration is always less than that for the free jet-nozzle configuration. This may be attributed to the change in flow patterns due to different inlet conditions.

As Reynolds number in increased beyond 2000 there is a gradual transition seen in the flow pattern for both the configurations. Figures 5c and 5d show the transitional flow patterns for free jet configurations. It is observed that after a particular jet length eddies are formed in front of laminar region. The entrained fluid re circulates in the direction contrary to the flow of the jet. This is considered to be semi-turbulent regime of flow. From Fig. 3b it is observed that the laminar length, after reaching a maximum value, decreases as Reynolds number increases. At maximum a/d, the flow is observed to have complete laminar nature. The regime for $2000 < Re < 2500$ is called as the transition regime and it is expected that the transition Reynolds number to lie around 2200 in contrast to impinging jets where it is around 2600.

Figures 6c and 6d show the flow patterns for free jet configurations when the Reynolds number is above 2500. It is seen from these figures that the flow is completely turbulent for Reynolds numbers greater than 2500. At higher Reynolds number the laminar length is reduced as the Reynolds number is increased and it becomes equal to the laminar length of impinging jet.

In the present study, the work of McNaughton and Sinclair [2] is also compared with the results obtained with the free jet-orifice configuration. Figure 3c depicts the comparison between the laminar lengths obtained in the present work with those obtained by McNaughton and Sinclair [2]. As observed in Figure 3c, in [2] transition is seen at Re = 1000 whereas in present work it is supposed to be at around Re = 2200. The difference is attributed to the different a/d ratio and different boundary conditions due to the test tank dimensions. In [2] the ratio of test tank diameter to the nozzle diameter is 6 whereas in this work it is 80, which is much greater than the former. Thus it can be inferred that McNaughton and Sinclair's [2] setup is a confined jet whereas this setup might be considered as an unconfined jet. Thus differences in the values of two experiments were observed.

Conclusions

The flow patterns are studied for different configurations namely, impinging jet configurations with z/d = 6 and 12, free jet-nozzle configuration and free jet-orifice configuration. These patterns are examined for different volume flow rates with Reynolds number ranging from 1000 to 3500. Following results may be drawn from the present study.

- For Re < 2000, the flow is observed to be laminar for all the configurations of free and impinging jets. The laminar length (a) for impinging jets is equal to the distance between the impinging plate and the nozzle exit. In contrast, the laminar length for free jet configurations is observed to gradually increase as Reynolds number is increased due to the change in inlet conditions.

- Till Reynolds number of 2500 the laminar nature of the flow persists for impinging jet configurations. As the Reynolds number is gradually increased beyond 2500, there is a transition seen in the flow patterns of impinging jets from laminar to turbulent with reduction in laminar length. At higher Reynolds numbers (Re > 2700) the flow changes to turbulent. It is expected that the transition occurs at Reynolds number around 2600.

- In contrast to the impinging jet configurations, the transition of laminar flow to turbulent in free jets occurs at Re = 2200. The change in transitional Reynolds number is attributed to the change in boundary conditions for impinging jets as compared to free jets. In turbulent regime the laminar lengths are observed to be same for all configurations.

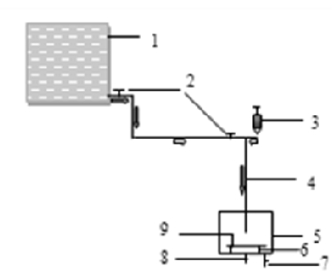
- As the transition Reynolds number obtained by McNaughton and Sinclair [2] is in the range of 1000. In contrast, as in present work the transition is obtained at Re = 2200 This is attributed to the difference in the test tank dimensions, and the diameter of the orifice

References

1) Reynolds A.J., 1962, Observations of liquid into liquid jet, Cavendish Laboratory, Cambridge.

2) McNaughton K.J., Sinclair C.G., 1966, Submerged jets in short cylindrical flow, Journal of Fluid Mech., Vol 25, part 2, pp 367-375.

Fig. 1 Schematic for experimental setup for conducting flow visualization experiments

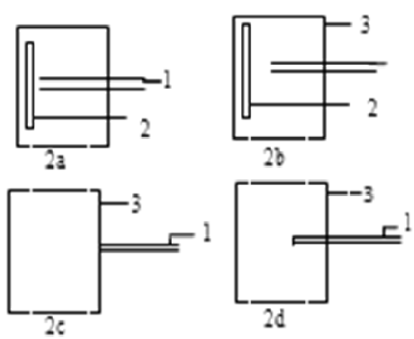


1) Water tank 2) Needle valves 3) Syringe for die injection 4) Flow development pipe

5) Cubical transparent box 6) Spacers 7) Drain 8) Outlet for flow measurement 9) Fixed plate

Fig. 2 Various configurations covered in the present study

2a z/d = 6, 2b z/d = 12, 2c orifice configuration, 2d submerged nozzle configuration



Nozzle 2) Impinging plate 3) Test section

Fig. 3 Graphical representation of flow characteristics

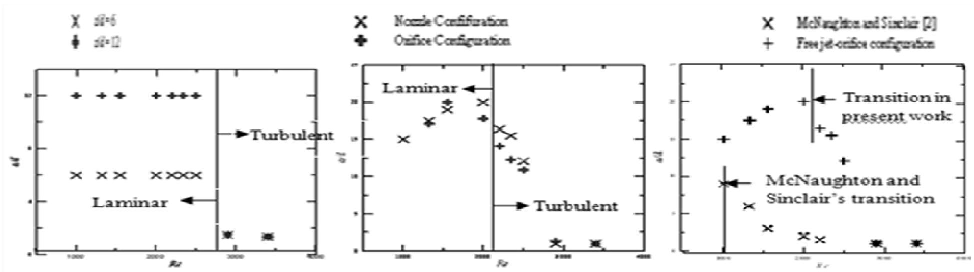


Fig. 3a Fig. 3b Fig. 3c

Fig. 3a Variation of laminar length with Reynolds number for impinging jet configurations
Fig. 3b Variation of laminar length with Reynolds number for free jet configurations
Fig. 3c Comparison of laminar lengths of free jet-orifice configuration with McNaughton and Sinclair's [2] results

Fig. 4 Comparison of flow patterns for 1000 < *Re* < 2000

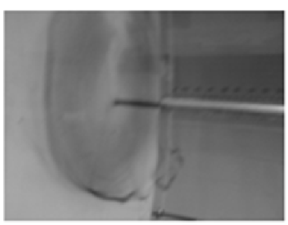
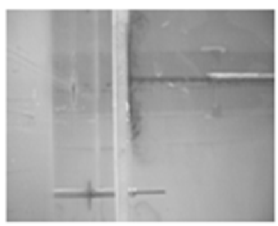
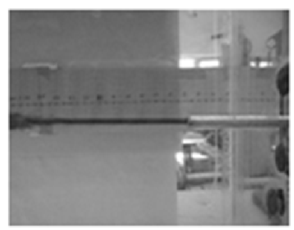
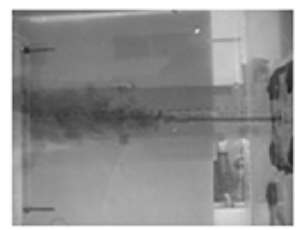





Fig. 4a *z/d* = 6 **Fig. 4b *z/d* = 12** **Fig. 4c Nozzle submerged** **Fig. 4d Orifice Config.**

Fig. 5 Comparison of flow patterns for 2000 < *Re* < 2500

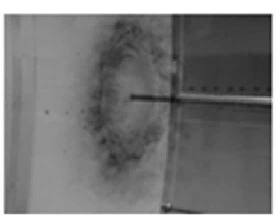
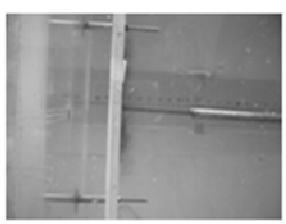



Fig. 5a *z/d*=6 **Fig. 5b *z/d*=12** **Fig. 5c Nozzle submerged** **Fig. 5d Orifice Config.**

Fig. 6 Comparison of flow patterns for Reynolds numbers ranging above 2500

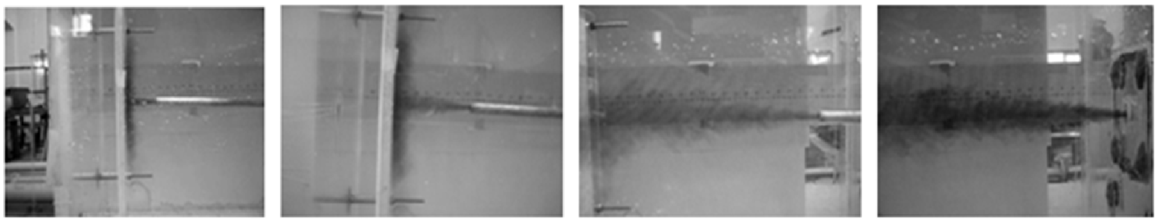


Fig. 6a z/d**=6** **Fig. 6b** z/d**=12** **Fig. 6c Nozzle submerged** **Fig. 6d Orifice Configuration**