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VISUALIZATION OF FLUID FLOW IN A TUBE

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Abstract- *There are many ways to visualize the fluid flow and numerous sophisticated equipment has been used for flow visualization. The purpose of this work is to design and construct an experimental equipment to visualize the laminar and turbulent flow as well as to measure water flow rate. Dye was injected in the developed flow of water and still pictures were taken to visualize the flow and a slight modified design which took into account the basic laws of fluid to construct the equipment. The apparatus is a valuable resource in the fluid flow visualization as it includes the simplest way for water flow visualization and helpful to the students to clear the concept about laminar and turbulent flow.*

Keywords: Laminar flow, Turbulent flow, Flow regime, Flow visualization

1. INTRODUCTION

Fluid flows which are entirely bounded by a surface are called internal flows. Thus, it incorporates flows through pipes, pump, ducts, nozzles, valves, diffusers, and fittings. These flows could be either laminar or turbulent. Osborne Reynolds was the person studying the conditions under which fluid flow in pipes transitioned from laminar flow to turbulent flow and described the transition from laminar to turbulent flow. In his classic studies in the 19th century, Reynolds developed a device to observe various flow regimes [1]. Laminar flow is characterized by smooth streamlines and highly ordered movement of fluid particles. The particles of fluid in a layer remain in that layer and move smoothly. These layers can be curved if the fluid layers pass around any bend or object. Velocity fluctuations and highly disordered movement of fluid particles characterize turbulent flow and there are random local motions of fluid particles [2]. Developed flow plays an important role in laminar and turbulent flow visualization. A flow is considered fully developed flow if the velocity profile does not change with streamwise direction [3]. The boundary layer continues to develop from the pipe inlet owing to viscosity and finally at a point it becomes developed flow and the hydrodynamic inlet length is generally defined as the distance from the pipe inlet to the developed flow[4]. In entrance length the flow is called developing flow. There is no mass and momentum transfer between two streamlines for laminar flow, which is the fundamental difference between laminar and turbulent flow. If a fluid particle is tracked in laminar flow, the fluid particle remains forever at the same streamline and it never jumps onto another streamline because if it jumps to another streamline, it is no longer laminar behavior but a turbulent behavior. In addition, where it is flatter in turbulent flow, the velocity distribution curve in laminar flow is parabolic [5]. In his classic dye visualization, Reynolds was the first to suggest a criterion for differentiating laminar and turbulent flows and the Reynolds number is the ratio of internal force to viscous force and also suggested the lower critical Reynolds number is 210 [6]. However, the critical Reynolds number varies and relies on the degree to which the flow is disturbed by surface roughness, pipe vibrations and fluctuations in the flow [7]. The aim of this study was to visualize laminar or turbulent flow in a tube, to design and construct a simple equipment for this purpose, to determine Reynolds number, to show the relationship between Reynolds number and visual observation of flow regimes. This experimental set up is a valuable set up for fluid mechanics laboratory and the students could be able to learn about laminar and turbulent flow by this study.

2. EQUIPMENT DESIGN AND DEVELOPMENT

Design process involved demands and requirements for useful product. Some considerations were regarded in this phase when going to prepare the proposed equipment shown in Fig. 1.

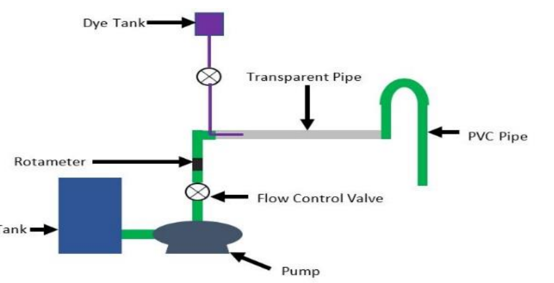


Fig. 1: Schematic diagram of the experimental setup

2.1 EQUIPMENT

(A) Water tank

It was necessary to install a water tank so that a definite source of liquid supply could be established through a transparent pipe. A plastic water container shown in Fig. 2(a) has been equipped for this purpose. The water tank's capability was 85 liters.

(B) Pump Selection and Installation

When pump selection is considered necessary for any service, it is required to determine and identify the types of liquids, the total dynamic head and, in most cases, the temperature and liquid viscosity. Such complications, however, are unnecessary in this case as it is to handle water at ambient temperature. The pump capacity was estimated by using Eqns. (1)-(3) and moody chart,

$$\left(H_p + \frac{p}{\gamma} + \frac{v^2}{2g} + z\right)_1 = \left(\frac{p}{\gamma} + \frac{v^2}{2g} + z + H_f\right)_2 \quad (1)$$

$$H_f = \frac{fLv^2}{2gD} \quad (2)$$

$$P = \gamma\, Q\, H_p \quad (3)$$

Subscripts 1 and 2 denote water in the tank at the suction pipe level and tube exit respectively. The pump power estimated in this model was 0.000724 HP which is considerably small and unavailable in local market where $(Z_1 - Z_2) = 0.425$ m, $Q = 1.17 \times 10^{-4}$ m^3/s and $f = 0.03$. To serve the purpose the pump was chosen with the minimum pumping capacity available in market. The pump purchased was a centrifugal pump of 0.5 HP shown in Fig. 2(b).

(C) Rotameter

A tube type rotameter equipped in this experimental setup shown in Fig. 2(c) and the measure range of this rotameter is 1-7 LPM.

(D) Pipe

Transparent acrylic pipe shown in Fig. 2(d) was used in this experiment. The diameter of the pipe is 0.01905 m. The entry length for laminar flow was 115×0.01905=2.19 m and for turbulent flow it is 10×0.01905=0.1905 m. The concept of entrance length was neglected here to keep the pipe length short. The length of the pipe was 2 m. The injector was placed at the length of 0.245 m from the pipe inlet. The glass tube was not selected due to the complexity of the thread cutting process. One side of the transparent pipe has been directly connected to the PVC pipe and the other side of the pipe has been connected to U shaped PVC pipe. PVC pipe was also used in this experiment due to different reasons. The diameter of the PVC pipe was also 0.01905 meter. U shaped PVC pipe shown in Fig. 2(e) was used to eliminate the problem of backflow. Besides, in order to full flow of the pipe with water at low flow rate U shaped pipe plays a vital role.

(E) Gate valve

A flow control valve regulates the flow of a fluid. The gate valve used in this experiment shown in Fig. 2(f). One side of the gate valve is connected to the pump and the other side of the gate valve is connected to rotameter.

(F) Dye Reservoir and Dye

An ordinary infusion set has been used as a dye reservoir shown in Fig. 2(g). There is a control valve to control the flow of dye. There is also an injector in the infusion set. Potassium permanganate solution was used as a dye.

Fig. 2: Experimental equipment

2.2 FABRICATION OF EXPERIMENTAL SETUP

All the equipment has been assembled to get a complete setup. The photographic view of the experimental setup shown in Fig. 3.

Fig. 3: Photographic view of the experimental setup

The water tank was connected to a 0.5 HP centrifugal pump. The suction pipe of pump was connected to the water tank and the delivery pipe was directly connected to the gate valve. The other side of the gate valve was connected to one end of the tube type rotameter, and the other end of the rotameter was connected to a small PVC pipe through which the dye tube entered into the transparent pipe. This small PVC pipe can be replaced easily so that the injector can be put into the transparent pipe in exact place. The injector has been placed at the distance of 0.2667 meter from the fittings by trial and error. Another end of the transparent pipe was directly connected to a U-shaped pipe. Various fittings were used in pipe systems to connect straight sections of pipe, adapt to different sizes or shapes and for other purposes. 90 degrees elbow, nipple, bushing, union were used.

2.3 EXPERIMENTAL PROCEDURE

The tank was filled with water and leave the tank for a while so that the water could come to rest in the tank. The temperature of the water was recorded to determine the density and dynamic viscosity of water. The dye reservoir was filled with potassium permanganate solution. Then, the pump was switched on to flow water through the transparent pipe. Now however, the flow control valve was adjusted to flow water through the transparent pipe at a low flow rate by opening the valve partly and the volume flow rate was recorded from rotameter. The inlet valve of the dye injector was fully opened and potassium permanganate solution was let to flow through the transparent pipe. Observe the dye filament appearance was observed in the transparent pipe and the type of flow acquired for the specific discharge was recorded. Still picture of the appearance of the dye filament was taken. The above process was repeated for various discharge rates by opening in tiny increments the flow control valve. The rotameter was calibrated and find the actual flow rate was found from it. Finally, the Reynolds number at actual flow rate was calculated and the visual observation of the flow regimes were compared with the calculated Reynolds number.

3. EXPERIMENT AND RESULT

Before data taking the rotameter was calibrated. The rotameter was calibrated by conventional method. The rotameter was adjusted to the lowest setting representing 1 l/min. The drawn flow quantity was measured using a stop watch at 10 seconds. These steps were repeated at different rotameter settings. Finally, actual flow rates were calculated from the equation provided. A linear equation was obtained after plotting the Actual Reading vs Rotameter flow rate as shown in Fig. 4.

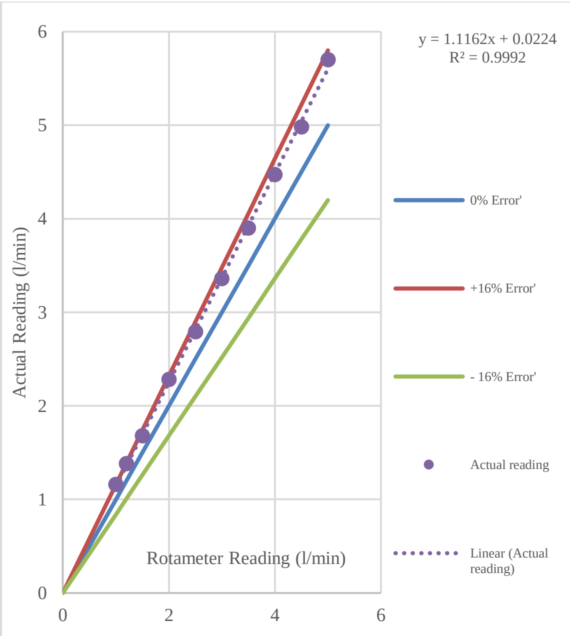


Fig. 4: Rotameter Reading vs Actual Reading

For this set of data, the equation is, y = 1.1162x + 0.0224 and R^2 = 0.9992, x denotes the rotameter reading(l/min) and y denotes the actual reading, Q((l/min). R^2 value close to one means the consideration of a higher linear relationship between two variables. Finally, the actual volume flow rates were calculated from this equation. The root mean square value of error between the actual volume flow rate calculated from this equation and the actual volume flow rate is 0.039786 which is considerably small. 0% error line indicates that there is no error between rotameter reading and actual reading at different flow rates. +16 % error line indicates that actual flow rate is 16% higher than rotameter reading at different flow rate and -16% indicates that the actual flow. rate is 16% lower than rotameter reading. In this experimental setup the highest percentage error between the rotameter volume flow rate and the actual volume flow rate is 16 %.

Temperature recorded = 34 degree Celsius, ρ =994.4 kg/m^3, µ = 0.0007337 Pa. s, D = 0.01905 m, A = 2.85023×10^{-4} m^2. Finally, Reynolds number was calculated using Eq. (4), Eq. (5), Eq. (6) and Eq. (7).

$$Q\ (l/min) = 1.1162x + 0.0224 \quad (4)$$

$$Q\ (m^3/s) = Q\ (l/min) \times \left(\frac{10^{-3}}{60}\right) \quad (5)$$

$$v = \frac{Q\ (m3/s)}{A} \quad (6)$$

$$Re = \frac{\rho v D}{\mu} \quad (7)$$

Table 1, Table 2, Table 3 shows the relationship between Reynolds number and flow regime and compares the theoretical regime and visual observation of flow regime. The still pictures were taken by 12-megapixel mobile camera.

Table 1: Reynolds number and visual observation of flow regime for laminar flow.

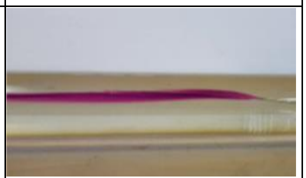
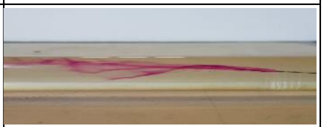
Reynolds number	Theoretical Regime	Visual observation (Direction: ⟵)
1382	Laminar	
1550	Laminar	
1719	Laminar	
1887	Laminar	
2056	Laminar	

Table 2: Reynolds number and visual observation of flow regime for transition flow.

Reynolds number	Theoretical Regime	Visual observation (Direction: ←)
2561	Transition	
3067	Transition	
3404	Transition	

Table 3: Reynolds number and visual observation of flow regime for turbulent flow.

Reynolds number	Theoretical Regime	Visual observation (Direction: ←)
3572	Turbulent	
4752	Turbulent	
5932	Turbulent	
7954	Turbulent	
9302	Turbulent	
10313	Turbulent	
10650	Turbulent	

The experiment found that fluid work should be performed accurately and carefully to achieve a compatible outcome and mitigate the inconsistency. From the data set, it is observed that the flow regime belongs to laminar flow starts with Reynolds number 1382.0 and the flow regime belongs to turbulent flow ends with Reynolds number 10650.5. The lower critical Reynolds number 2056.0 and the upper critical Reynolds number is 3572.7. The critical Reynolds numbers are slightly different from the literature value. The position of the injector is a main reason of this deviation. Not only the position of the injector is a reason but also the quality of the tube used for injection of the dye liquid is a big reason of varying the critical Reynolds number at different set up. Besides, tube connected with injector inside the pipe is also responsible for disturbing the flow which causes the deviation.

4. CONCLUSION

The experimental setup developed in this work provides a simple means to visualize the flow regimes and compare them with theoretical flow regimes. The lower and upper critical Reynolds numbers are approximately 2056 and 3572. This equipment works with the Reynolds number from 1382 to 10650. Actual flow rates can be measured using the empirical equation provided. Volume flow rate measurements have an error of +16% error associated with the rotameter. Experimental setup still faces the problem of water hammer although the problem associated with backflow and fulfillment of water pipe at low flow rate were resolved using U-shaped pipe. The critical Reynolds numbers deviated from the literature value due to the position of the injector, quality of dye tube. Besides the dye tube inside the transparent pipe causes the disturbance. Simple means of visualizing the flow and determining the Reynolds can be developed in the near future using sensors or computer software. Several factors need to be investigated further, however, and some issues still have to be resolved

- Use of an effective tracing system (e.g. tracing dye) where the density and viscosity of the dye are the same as water so that the water flow within the pipe is not affected. Computer software can be used to demonstrate the flow is also an option to a tracing dye.
- Replacing the dye injection system which consists of a needle connected with rubber tube with a L-shaped needle connected with metal tube so that the metal tube can be straight or with an injection syringe with a L-shaped needle.
- Placing the injector at the entrance length.
- Using equipment or method to reduce water hammer.

5. REFERENCES

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8. NOMENCLATURE

Symbol	Meaning	Unit
H_p	Pump head	(m)
p	Pressure	(Pa)
γ	Specific weight	(N/m^3)
υ	Mean velocity	(m/s)
g	Gravitational acceleration	(m/s^2)
Z	Elevation head	(m)
H_f	Friction head	(m)
L	Length of pipe	(m)
D	Diameter of pipe	(m)
F	Friction factor	Dimensionless
Q	Volume flow rate	(m^3/s)
ρ	Density	(kg/m^3)
μ	Dynamic viscosity	(Pa. s)
A	Area of the pipe	(m^2)
Re	Reynolds number	Dimensionless