57:020 Mechanics of Fluids and Transfer Processes

Exercise Notes for the Pipe Flow TM

Measurement of Flow Rate, Velocity Profile and Friction Factor in Pipe Flows

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1. Purpose

The purpose of this investigation is to provide students with *hands-on* experience using a pipe stand test facility and modern measurement systems including pressure transducers, pitot probes, and computerized data acquisition with Labview software, to measure flow rate, velocity profiles, and friction factors in smooth and rough pipes, determining measurement uncertainties, and comparing results with benchmark data. Additionally, this laboratory will provide an introduction to PIV analysis, using an ePIV system with a step-up model.

2. Experimental Design

2.1 Part 1: Pipe Flow

The experiments are conducted in an instructional airflow pipe facility (Figure 1). The air is blown into a large reservoir located at the upstream end of the system. Pressure builds up in the reservoir, forcing the air to flow through any of the three horizontal pipes. Pressure taps are located on each pipe, at intervals of 1.524m, for static pressure measurements. Characteristics for each of the pipes are provided in Appendix A. At the downstream end of the system, the air is directed downward and back, through any of three pipes of varying diameters fitted with Venturi meters (Figure 2). The top three valves control flow through the experimental pipes, while the bottom three valves control the Venturi meter to be used. The Venturi meter with 5.08cm diameter is used to measure the total flow rate, while the other two are kept closed. Six gate valves are used for directing the flow. The top and bottom 5.08cm pipes are used for measurements, while the middle one is kept closed during the experiment. Velocity measurements in the top and bottom pipes are obtained using pitot probe (Figure 3).

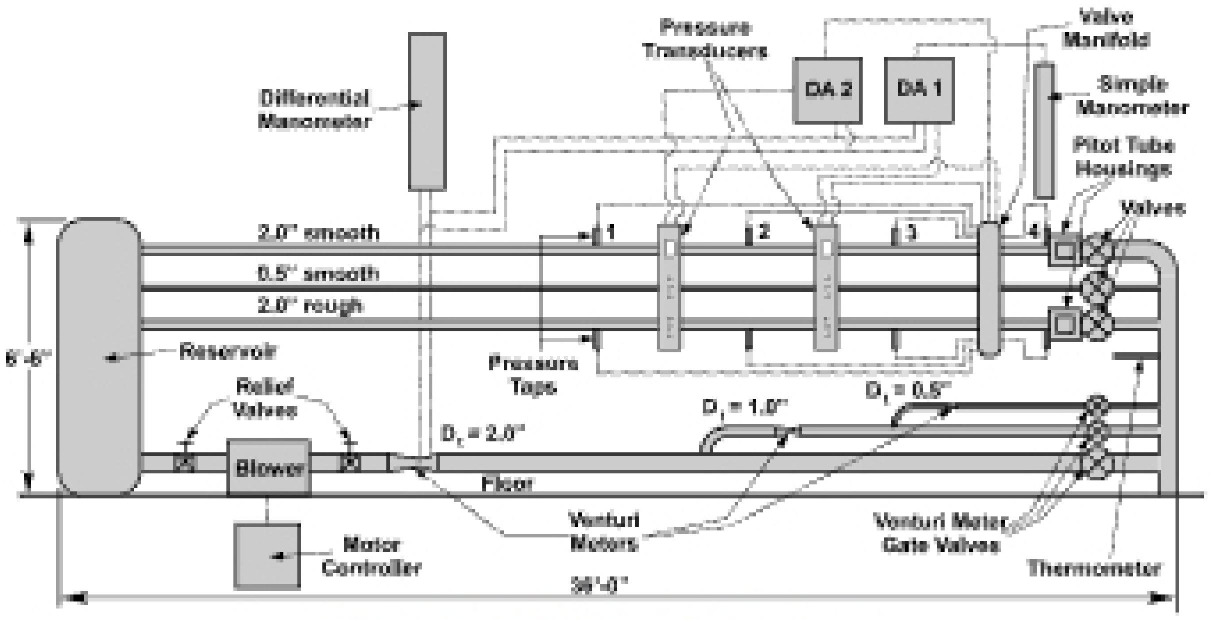

Figure1. Airflow pipe system

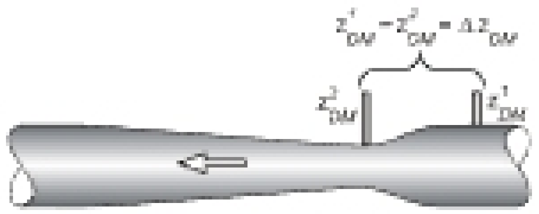

Figure 2. Venturimeter

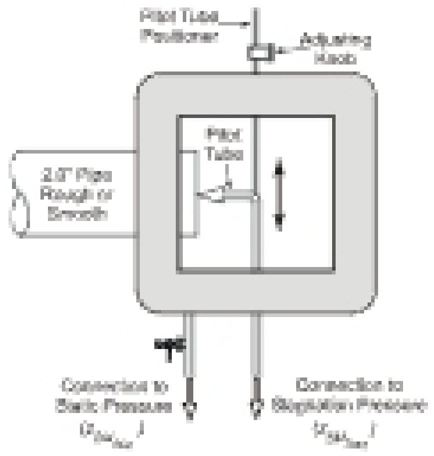

Figure 3. Pitot-probe

Pressures are acquired either manually, using simple and differential manometers for data acquisition, or automatically, with the manometers connected to an automated Data Acquisition (DA) system that converts pressure to voltages using pressure transducers. Data acquisition is controlled and interfaced by Labview software, described in Appendix B. The schematic of the two alternative measurement systems is provided in Figure 4.

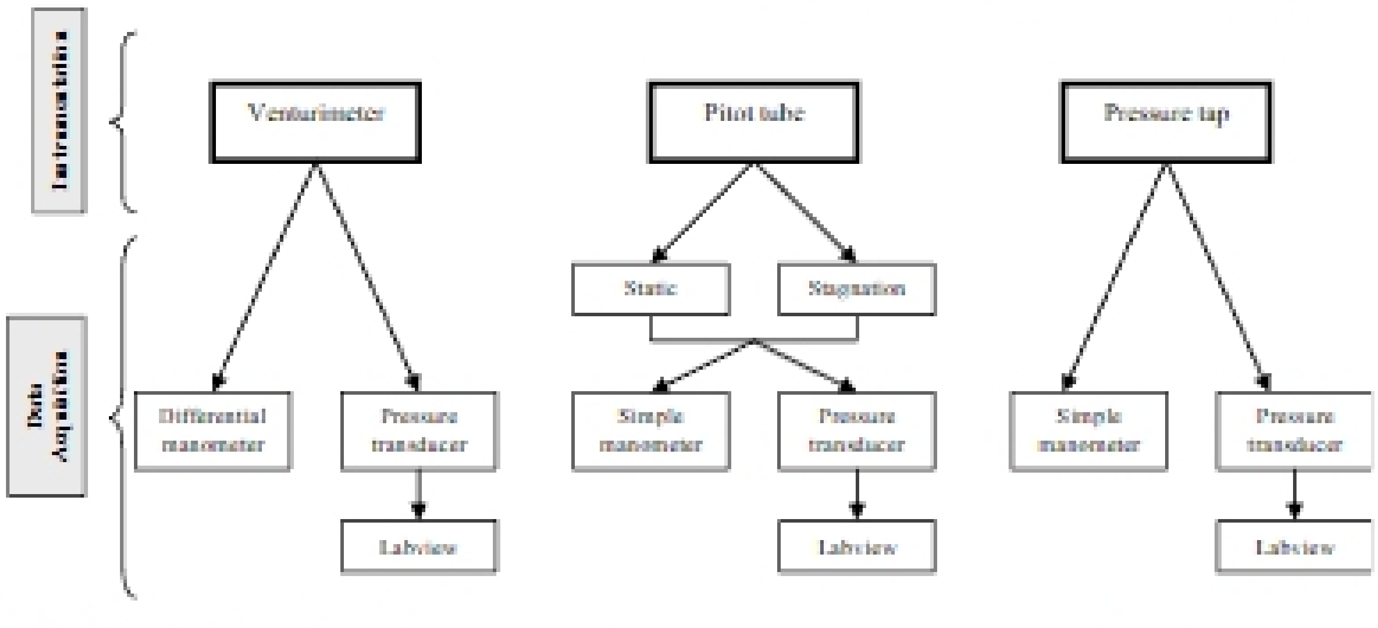

Figure4. Manual and automated measurement systems used in the experiment

All pressure taps on the pipes, Venturi meters, and pitot probes have 0.635cm diameter quick coupler connections that can be hooked up to the pressure transducers.

2.1.1 Data reduction (DR) equations

In fully developed, axisymmetric pipe flow, the axial velocity $u = u(r)$, at a radial distance r from the pipe centerline, is independent of the direction in which r is measured (Figure 5). However, the shape of the velocity profile is different for laminar and turbulent flows.

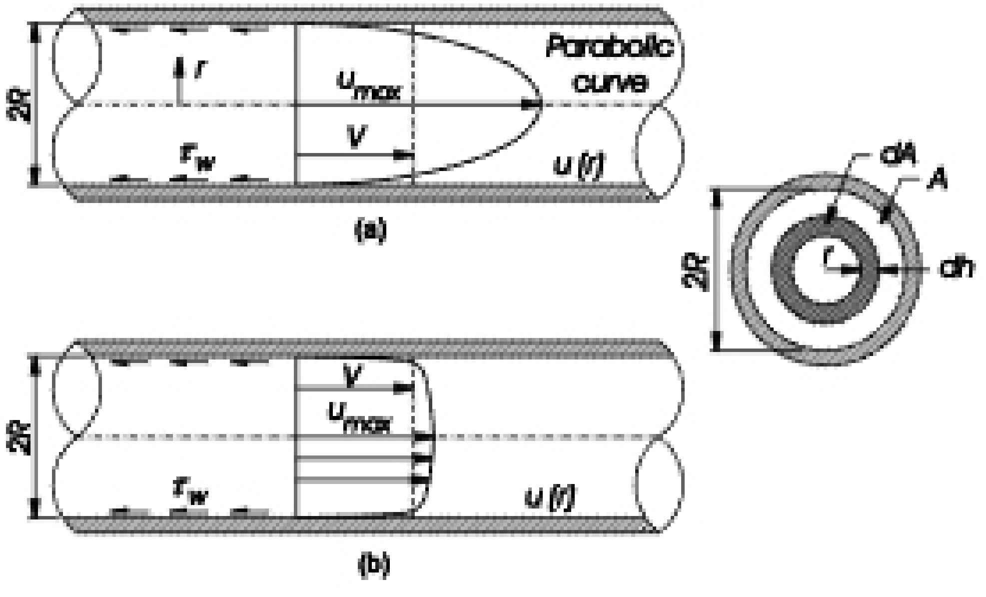

Figure 5. Velocity distributions for fully developed pipe flow: a) laminar flow; b) turbulent flow

Laminar and turbulent flow regimes are distinguished by the flow Reynolds number, defined as

$$\mathrm{Re} = \frac{VD}{\nu} = \frac{4Q}{\pi D \nu} \qquad (1)$$

Where, V is the average pipe velocity, D is the pipe diameter, Q is the pipe flow rate, and ν is the kinematic viscosity of the fluid. For fully developed laminar flow (Re < 2000), an analytical solution for the differential equations of the fluid flow (Navier-Stokes and continuity) can be obtained. For turbulent pipe flows (Re > 2000), there is no exact solution, hence semi-empirical laws for velocity distribution are used instead.

The pipe head loss due to friction is obtained from the Darcy-Weisbach equation:

$$h_f = f \frac{L}{D} \frac{V^2}{2g} \qquad (2)$$

where, f is the (Darcy) friction factor, L is the length of the pipe over which the loss occurs, h_f is the head loss due to viscous effects, and g is the gravitational acceleration. The Moody diagram provides the friction factor for pipe flows with smooth and rough walls in laminar and turbulent regimes. The friction factor depends on the Reynolds number and the relative roughness k/D of the pipe (for large enough Re, the friction factor is solely dependent on the relative roughness).

Velocity distributions in the pipes are measured with Pitot tubes housed in glass-walled boxes (Figure 3). The data reduction equation (DRE) for the measurement of the velocity profiles is obtained by applying Bernoulli's equation for the Pitot tube:

$$u(r) = \left[\frac{2 \cdot g \rho_w}{\rho_a} \cdot \left[z_{SM_{Stag}}(r) - z_{SM_{Stat}} \right] \right]^{1/2} \qquad (3)$$

where $u(r)$ is the velocity at the radial position r, g is the gravitational acceleration, $z_{SM_{Stag}}(r)$ is the stagnation pressure head determined by the Pitot probe located at radial position r, and $z_{SM_{Stat}}$ is the static pressure head in the pipe, equal to that of the ambient pressure inside the glass-walled box. These pressure head readings are given in height of a liquid column (ft of water). The DRE for the friction factor is one of the Darcy Weisbach equation forms (Roberson & Crowe, 1997), given as follows:

$$f = \frac{g \pi^2 D^5}{8LQ^2} \frac{\rho_w}{\rho_a} \left(z_{SMi} - z_{SMj} \right) \qquad (4)$$

where ρ_w, is the density of water, ρ_a is the density of air, L is the pipe length between pressure taps i and j, and $z_{SMi} - z_{SMj}$ is the difference in pressure between pressure taps i and j. The flow rate Q is directly measured using the calibration equations for the Venturi meters (Rouse, 1978):

$$Q = C_d A_t \sqrt{2g \Delta z_{DM} \cdot \frac{\rho_w}{\rho_a}} \qquad (5)$$

where C_d is the discharge coefficient, A_t is the contraction area, and Δz_{DM} is the head drop across the Venturi, measured in height of a liquid column (ft of water) by the differential manometer or the pressure transducer. Appendix A lists Venturi meter characteristics. Alternatively, the flow rate can be determined by integrating the measured velocity distribution over the pipe cross-section, as follows:

$$Q_i = 2\pi \int_0^r u(r) r dr \tag{6}$$

2.2 Part 2: ePIV

EFD Lab 1 investigated the use of ePIV as a method for visualizing streamlines around a circular cylinder. This laboratory will further explore the uses of Particle Image Velocimetry (PIV) to track fluid motion and calculate velocity vectors to describe the flow around a step-up model.

In ePIV analysis, a seeded fluid is illuminated by a laser sheet, and a camera takes rapid photographs of the fluid flow, at a rate of 30 Hz. Four parameters are used to control the camera settings;

- Brightness – This controls the overall brightness of the image. For the best PIV results, brightness should be set to a medium-low value.
- Exposure – This controls how long the camera sensors are exposed per image frame taken. Higher values correspond to shorter exposure times, and lower values correspond to longer exposure times. PIV analysis benefits from high exposure values (short exposure times), to facilitate software tracking of patterns of particles.
- Gain – This controls the sensitivity of the sensors per unit time. Using higher gain will amplify the signal obtained by the sensors, so typically higher gain values are needed for images taken with short exposure times, which would otherwise be very dark. However, increasing the gain has a side effect: using higher gain increases the noise in the image.
- Frames – This specifies how many images the camera will take, for PIV analysis. At least two images are needed to process vectors, and taking more will allow the software to average results and reduce precision error.

After images are captured, they are processed to determine velocity vectors and magnitudes. The software takes a pair of consecutive images and breaks it into many small regions, called interrogation windows. In each interrogation window, the PIV software compares the two images, determines how far the pattern of particles has moved in the amount of time between the two images, and calculates a single velocity vector for that window. This is repeated across the entire measurement area, generating a vector field. With the ePIV system, three PIV parameters can be adjusted.

- Window Size – This sets the size (in pixels) of the interrogation window. Ideally, smaller windows are desired, because they show more flow detail, averaging over a smaller region of the flow. However, if values are too small, fewer particles pass through the interrogation window, which can result in unstable vector computation.
- Shift Size – This determines the distance (in pixels) that the software moves to start a new interrogation window. For example, if a window size of 80 and a shift size of 40 were used, the software would compute a vector in the first 80x80 interrogation window, and then shift 40 pixels, computing a second vector in a new 80x80 window. The two windows would overlap by 50%. A smaller shift size results in more vectors being computed, but the increased overlap means that some of the data reported is repeated between the vectors.
- PIV Pairs – This specifies how many pairs of images are used for PIV calculations. PIV analysis compares any two consecutive images, if 10 images are captured, up to 9 PIV pairs can be specified for computation. Results computed for each individual pair are averaged together, reducing precision error.