ME 326 Fluid Mechanics Sessional

Level – 3 Term - 2

Department of Mechanical Engineering

Bangladesh University of Engineering and Technology (BUET)

Dhaka-1000, Bangladesh

Credit Hour: 0.75 Cr. Hr.
Contact Hour: 1.5 Hrs.

ME 326 Fluid Mechanics Sessional

Name of the Experiments

Exp. 1	(a) Study of flow meters and Minor Losses (b) Study of Pipe Friction
Exp. 2	(a) Study of flow over a circular cylinder (b) Study of dynamic pressure and velocity measurement by pitot tube
Exp. 3	(a) Study of flow through a converging-diverging (CD) nozzle (b) Study of flow induced noise
Exp. 4	Study of flow through a circular pipe

ME 326 Fluid Mechanics Sessional

Experiment No. 1

(a) Study of flow meters and minor losses

(b) Study of Pipe friction

Experiment Outcomes

The objective of this experiment is to investigate the viscous friction in a pipe flow and to study the flow regimes. Students will also study different types of flow meters and understand the minor losses in a fluid flow. On completion of the experiment, the students should be able to

1. Distinguish between laminar and turbulent flows
2. Determine the friction factors using the Moody diagram
3. Estimate the head loss in a pipe flow
4. Understand the principle of flow measurement in a pipe flow
5. Calibrate flow meters such as orifice meter and Venturi meter
6. Determine the *K* factor for sudden contraction and expansion

Friction factors

In fluid dynamics, head is a concept that relates the energy in an incompressible fluid to the height of an equivalent static column of that fluid. In case of flow over or through a solid surface (for example: pipe flow), head loss is obvious. This is due to the viscous action (friction) in between the fluid and solid surfaces. The viscosity of fluid (μ) is responsible for head loss. This loss is known as *major loss*. Although the head loss represents a loss of energy, it does not represent a loss of total energy of the fluid. *The total energy of the fluid is conserved*. The part of energy which is lost is utilized by the flow to overcome the skin friction drag. In a fully developed laminar pipe flow, the head loss is given by:

$$h_f = \frac{32\mu LV}{\rho g D^2} = \left(\frac{64\mu}{\rho VD}\right)\frac{L}{D}\cdot\frac{V^2}{2g} = f\,\frac{L}{D}\cdot\frac{V^2}{2g} \qquad [1]$$

where, h_f = the head loss (m), f = Darcy friction factor, L = the pipe length (m), D = the hydraulic diameter of the pipe (m), g = the constant for gravitational acceleration (m/s^2) and V = the mean flow velocity (m/s). In this equation, f is the ***Darcy-Weishbach friction factor*** (or commonly known as "*friction factor*") which is given by:

$$f = \frac{64\mu}{\rho VD} = \frac{64}{Re}$$

where, Re is the Reynolds number giving the ratio of inertia force to viscous force in a flow and frequently defined by:

$$Re = \frac{\rho VD}{\mu}$$

where, ρ = density of fluid (kg/m^3) and μ is the molecular (laminar) viscosity of fluid (Pa.s)

The nature of the flow (laminar/turbulent) can be characterized based on the "Reynolds number, Re".

As a general criterion, for flow through smooth pipes,

Re < 2300; flow is laminar
Re > 4000; flow is turbulent

The streamlines of the flow field are well-behaved in laminar flows. However, this well-behavior is no longer exist in turbulent flow. The fundamental difference between laminar and turbulent flow lies in the chaotic, random behavior of the various flow properties such as components of velocity, the pressure, the shear stress, the temperature, and any other variable that has a field description.
Equation [1] may also be rearranged as

$$h_f = \frac{32\mu LV}{\rho g D^2} = 2\left(\frac{16\mu}{\rho VD}\right)\frac{L}{D}.\frac{V^2}{g} = 2f_f\frac{L}{D}.\frac{V^2}{g} \qquad [2]$$

In equation [2], f_f is the **Fanning friction factor** given by

$$f_f = \frac{16\mu}{\rho VD} = \frac{16}{Re} = \frac{1}{4}f$$

For both Darcy-Weisbach (f) and Fanning friction factors ((f_f)) are either read from **Moody diagram** or calculated using various correlations such as **Colebrook equation**.

Principles of flow measurement:
There are many types of flow meters: turbine-type flow meter, rotameter, orifice meter, and venturi meter, etc. In turbine flow meters, a rotor is placed in a flow. The rpm of the rotor varies with flow rate and by measuring the rpm, the flow rate is determined. Rotameters are suitable for measuring flow rate through a vertical pipe. The location of the float in a rotameter depends onthe flow rate. Thus the flow rate is determined by measuring the vertical displacement of the float. The orifice meter and Venturi meter are known as pressure based flow meters (*obstruction type*). These meters reduce the flow area and creates pressure differential which depends on flow rate. Thus flow rate is determined by measuring the pressure drop.

Minor loss:
Minor losses in a pipe flow come from the change in flow area and (or) direction by different types of fittings. Pipe fittings are always required to complete a hydraulic piping system; for example - sudden contraction, sudden expansion, valves, reducers, bends, elbows, crosses, T- joints, etc. Some of them are shown in figure below:

Minor losses are different from the major losses because these come from the viscous (friction) action between the fluid and the pipe wall. If the pipe is long and the number of pipe fittings is small, the minor loss is small compared to the major loss and may, therefore, be neglected. Even though they are termed "minor", the losses can be greater than the major losses. For example, when a valve is almost closed, the loss can be almost infinite or in a short pipe with large number of fittings, the minor loss may dominate over the major loss.

Minor losses are directly related to the velocity head in a flow, meaning that the higher the velocity head the greater the losses will be. Unit for minor loss is feet or meters of a fluid column. For any fittings, the minor losses (h_L) are related to the velocity head ($V^2/2g$) by introducing loss coefficients, K as shown below:

$$h_L = K\frac{V^2}{2g}$$

About the experiment

A venturi meter, an orifice meter and a rotameter are arranged in series in the test bench. A compressor is used to flow air through the flow measuring devices. The flow rate is controlled by a gate valve located at the discharge side of the compressor. Pressure drops in orifice meter as well as in the Venturi meter are measured by water manometers and the theoretical flow rates are calculated from these pressure drops. The orifice meter and venturi meter are calibrated comparing the measured flow rate (theoretical) with the actual flow rate measured by the pre-calibrated rotameter.

The same test rig contains arrangement for measurement of pressure drop across a reducer (sudden contraction) as well as across an enlarger (sudden expansion). Head losses across these fittings are calculated from the measured pressure drops. The velocity head is calculated from the flow rate and flow area. The K factors of these fittings are determined from the measured head losses and velocity heads.

EXPERIMENT 1(a)
Study of flow through an orifice meter and a venturi meter

OBJECTIVES

The objectives of the experiment are to

1. understand the working principle of orifice meter and venturi meter
2. calculate the mean C_d for orifice meter and venturi meter
3. verify the relation between flow rate and pressure drop in orifice meter and venturi meter by plotting the flow rate against manometer reading (pressure drop) in log-log graph paper.

EXPERIMENTAL SET UP

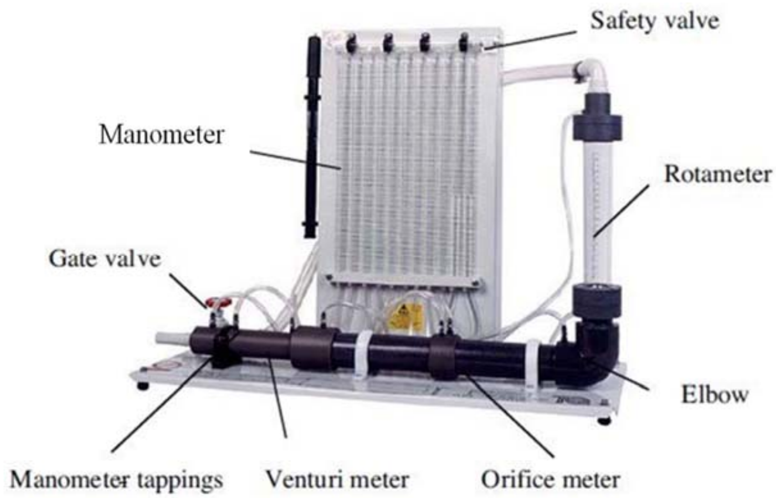


Figure 2.1: A typical test bench for flow measurement device

NECESSARY EQUATIONS

Theoretical flow rate for orifice meter, $Q_T = k_1\sqrt{H_m} = A_o\sqrt{\dfrac{2g\left(\dfrac{\gamma_m}{\gamma}-1\right)}{1-C_C\left(\dfrac{D_o}{D_1}\right)^4}}\sqrt{H_m}$

Theoretical flow rate for venturi meter, $Q_T = k_1\sqrt{H_m} = A_2\sqrt{\dfrac{2g\left(\dfrac{\gamma_m}{\gamma}-1\right)}{1-\left(\dfrac{D_2}{D_1}\right)^4}}\sqrt{H_m}$

Actual flow rate, $Q_a = kH^n$

Coefficient of Discharge, $C_d = \dfrac{Q_a}{Q_T}$

DATA COLLECTION

Given data:

Pipe diameter, D_1 =

Orifice diameter, D_o =

Venturimeter throat diameter, D_2 =

Room temperature, T_r =

Rotameter absolute pressure, p_R = 1000 mm Aq G

Rotameter absolute temperature, T_R = 303 K

Experimental Data:

Specific weight of mercury =

Specific weight of water =

Specific weight of air =

Table 1: Manometer and Rotameter readings

No of Obs.	Air temp, inside the pipe, T_a (ºC)	Manometer reading									Flow rate from rotameter, Q_R (m^3/min)
		flow pressure in the pipe (Hg manometer)			across the orifice (water manometer)			across the venturi (water manometer)			
		Left column (mm)	Right column (mm)	Net deflection $H_{m,Hg}$ (mm of Hg)	Left column (mm)	Right column (mm)	Net deflection $H_{m,O}$ (mm of water)	Left column (mm)	Right column (mm)	Net deflection $H_{m,V}$ (mm of water)	
1											
2											
3											
4											
5											

CALCULATION AND RESULT

Table 2: Calculation of C_d for Orifice meter

No of Obs.	p_a (Pa)	T_a (K)	k_1	Manometric deflection, $H_{m.O}$ (m)	Theoretical flowrate, Q_T (m^3/s)	Actual flowrate, Q_a (m^3/s)	$C_d = \frac{Q_a}{Q_T}$	Mean C_d	From graph	
									n	C_d
1										
2										
3										
4										
5										

Sample calculation for orifice meter:

Observation no:

1. Flow pressure, $p_a = \rho_{Hg} g H_{m,Hg} + p_{atm} =$

2. $k_1 = A_o \sqrt{\dfrac{2g\left(\dfrac{\gamma_m}{\gamma} - 1\right)}{1 - C_C\left(\dfrac{D_o}{D_1}\right)^4}} =$

(assume Cc = 1.0)

3. Theoretical flow rate, $Q_T = k_1 \sqrt{H_{m,O}} =$

4. Actual flow rate, $Q_a = \dfrac{Q_R \times p_R}{60 \times T_R} \times \dfrac{T_a}{P_a} \times 0.8 =$

   where 0.8 is correction factor and p_R = 1000 mm AqG +p_{atm}

5. Coefficient of discharge, $C_d = \dfrac{Q_a}{Q_T} =$

Table 3: Calculation of C_d for Venturi meter

No of Obs.	p_a (Pa)	T_a (K)	k_1	Manometric deflection, $H_{m,V}$ (m)	Theoretical flowrate, Q_T (m³/s)	Actual flowrate, Q_a (m³/s)	$C_d = \frac{Q_a}{Q_T}$	Mean C_d	From graph	
									n	C_d
1										
2										
3										
4										
5										

Sample calculation for Venturi meter:

Observation no:

1. Flow pressure, $p_a = \rho_{Hg} g H_{m,Hg} + p_{atm} =$

2. $k_1 = A_2 \sqrt{\dfrac{2g\left(\dfrac{\gamma_m}{\gamma} - 1\right)}{1 - \left(\dfrac{D_2}{D_1}\right)^4}} =$

3. Theoretical flow rate, $Q_T = k_1 \sqrt{H_{m,V}} =$

4. Actual flow rate, $Q_a = \dfrac{Q_R \times p_R}{60 \times T_R} \times \dfrac{T_a}{P_a} \times 0.8 =$

where 0.8 is correction factor and p_R = 1000 mm AqG +p_{atm}

5. Coefficient of discharge, $C_d = \dfrac{Q_a}{Q_T} =$

GRAPHICAL PRESENTATION OF RESULTS

(i). **Relation between flow rate and pressure drop across a flow meter:**

Draw the Q_a vs H_m curve in log-log graph paper for both orifice meter and venturi meter

Results:

Value of C_d for orifice meter =

Value of C_d for venturi meter =

DISCUSSION

EXPERIMENT 1(a)
Study of minor losses

OBJECTIVES

The objectives of this experiment are

1. to measure the minor loss in a sudden contraction and a sudden expansion fittings
2. to determine the loss coefficients or *K* factors for the sudden contraction and the sudden expansion

EXPERIMENTAL SET UP

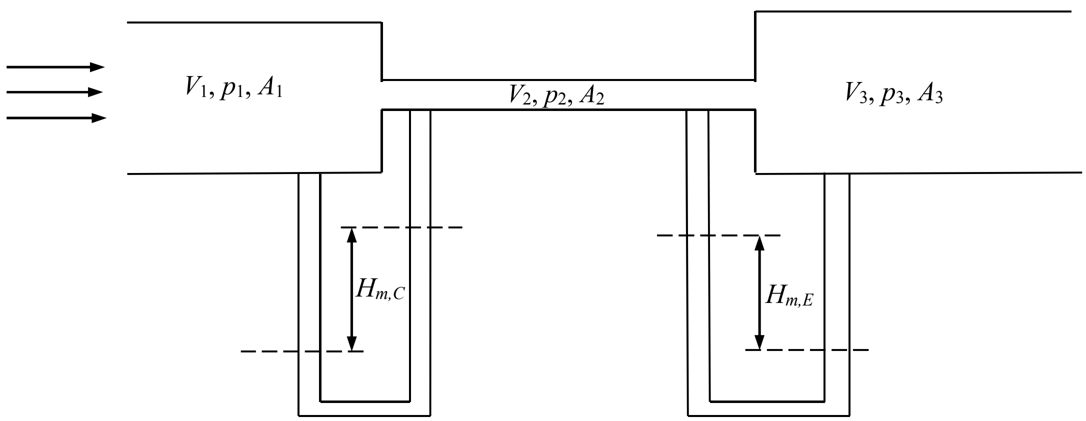


Figure 2.2: Sudden contraction and sudden expansion

Experimental data:

Pipe diameter at inlet,	$D_1 = D_3 =$
Pipe diameter at contraction,	$D_2 =$
Room temperature,	$T_r =$
Absolute pressure at Rotameter,	$p_R =$ 1000 mm Aq G
Absolute temperature at Rotameter,	$T_R =$ 303 K

Table 4: Manometer and Rotameter readings for the pipe fittings

No of Obs.	Air temp, inside the pipe, T_a (ºC)	Manometer reading									Flow rate from rotameter, Q_R (m^3/min)
		flow pressure in the pipe (Hg manometer)			across the contraction (water manometer)			across the expansion (water manometer)			
		Left column (mm)	Right column (mm)	Net deflection $H_{m,Hg}$ (mm of Hg)	Left column (mm)	Right column (mm)	Net deflection $H_{m,C}$ (mm of water)	Left column (mm)	Right column (mm)	Net deflection $H_{m,E}$ (mm of water)	
1											
2											
3											
4											
5											

CALCULATION AND RESULT

Table 5: Determination of K factors for sudden contraction and sudden expansion

No of Obs.	p_a (Pa)	T_a (K)	ρ_a (Kg/m^3)	Actual flowrate, Q_a (m^3/s)	$V_1^2/2g$ (m of water)	$V_2^2/2g$ (m of water)	$V_3^2/2g$ (m of water)	$h_{L,\text{contraction}}$	$h_{L,\text{expansion}}$	***K*** factor	
										Contraction	Expansion
1											
2											
3											
4											
5											

Sample calculation:
Observation No.

1. Flow pressure, $p_a = \rho_{Hg} g H_{m,Hg} + p_{atm} =$

2. Density of air at T_a, $\rho_a =$

3. Actual flow rate, $Q_a = \dfrac{Q_R \times p_R}{60 \times T_R} \times \dfrac{T_a}{P_a} \times 0.8 =$

   where 0.8 is correction factor and p_R = 1000 mm AqG $+p_{atm}$

4. Velocity at section 1, $V_1 = \dfrac{Q_a}{\frac{\pi}{4} D_1^2} =$

   Velocity head at section 1 = $V_1^2/2g$ =

5. Velocity at section 2, $V_2 = \dfrac{Q_a}{\frac{\pi}{4} D_2^2} =$

   Velocity head at section 2 = $V_2^2/2g$ =

6. Velocity at section 3, $V_3 = \dfrac{Q_a}{\frac{\pi}{4} D_3^2} =$

   Velocity head at section 3 = $V_3^2/2g$ =

7. Head loss due to sudden contraction, $h_{L,contraction} = H_{m,C}\left(\dfrac{\rho_w}{\rho_a} - 1\right) + \dfrac{V_1^2 - V_2^2}{2g} =$

8. Head loss due to sudden expansion, $h_{L,\text{expansion}} = H_{m,E}\left(\dfrac{\rho_w}{\rho_a} - 1\right) + \dfrac{V_2^2 - V_3^2}{2g} =$

9. *K* factor for contraction =
   K factor for expansion =

GRAPHICAL PRESENTATION OF RESULTS

(i) **Determination of *K* factor from graph:**
Plot on a log-log paper head loss against velocity head for both sudden contraction and sudden expansion. Determine the *K* factors from the slopes of the curves.

(ii) Compare the *K* factors calculated in Table 5 with those obtained from the graphs.

DISCUSSION

EXPERIMENT 1(b)
Study of pipe friction

OBJECTIVES

The objectives of the experiment are to

i. Measure head loss in a pipe flow at various Reynolds number, Re
ii. Find Darcy-Weisbach friction factor and Fanning friction factor from Moody diagrams and estimate the corresponding head loss
iii. Calculate the hydraulic gradient (f/L)

EXPERIMENTAL SET UP

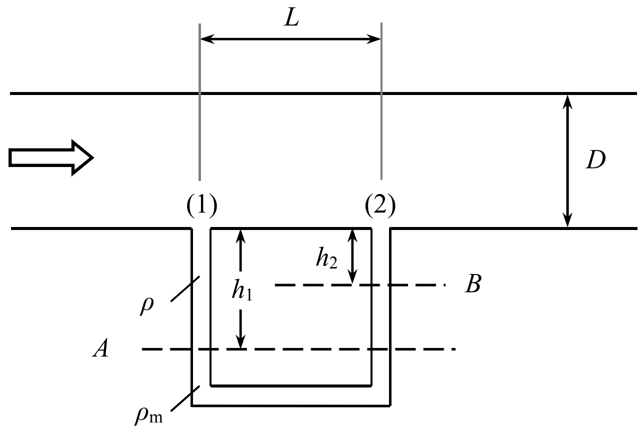


Figure 1.1: Experimental setup for study of pipe friction

DATA COLLECTION

Given data:

Length of the pipe, L =
Diameter of the pipe, D =
Room Temperature, T =
Sp. weight of the flowing fluid, γ =
Sp. weight of the manometric fluid, γ_m =
Density of the flowing fluid, ρ =
Viscosity of the flowing fluid, μ =

Experimental Data:

Table 1. Data for determination of head loss

No. of Obs.	Mass of Water Collected (kg)	Time of Collection (s)	Mass flow rate, (kg/s)	Manometer reading for head loss			Measured head loss, h_f (m of H_2O)
				Left Column (m)	Right Column (m)	Net deflection, h (m)	
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							

Table 2. Data for variation estimating head loss using Moody diagrams

No. of Obs.	Volume flow rate, Q (m^3/s)	Mean velocity, V (m/s)	Reynolds Number, Re	Friction factor from Moody diagram		Estimated head loss, h_f (m of H_2O)	Hydraulic gradient h_f/L
				Darcy	Fanning		
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							

Sample calculations:

Observation no.:

1. Measured head loss, $h_f = h\left(\frac{\gamma_m}{\gamma} - 1\right) =$

2. Reynolds number, $\mathrm{Re} = \frac{\rho V D}{\mu} =$

   Darcy friction factor, $f =$

   Fanning friction factor, $f_f =$

3. Estimated head loss using Darcy friction factor, $h_f = f\frac{L}{D}\frac{V^2}{2g} =$

4. Estimated head loss using Fanning friction factor, $h_f = 2f_f\frac{L}{D}\frac{V^2}{g} =$

5. Hydraulic gradient, $i = h_f/L =$

GRAPHICAL PRESENTATION OF RESULTS

i) Plot experimentally determined head loss against estimated head loss.

ii) Plot hydraulic gradient (h_f/L) versus velocity (V) in a log-log graph and hence find the value of exponent n to velocity V.

DISCUSSION

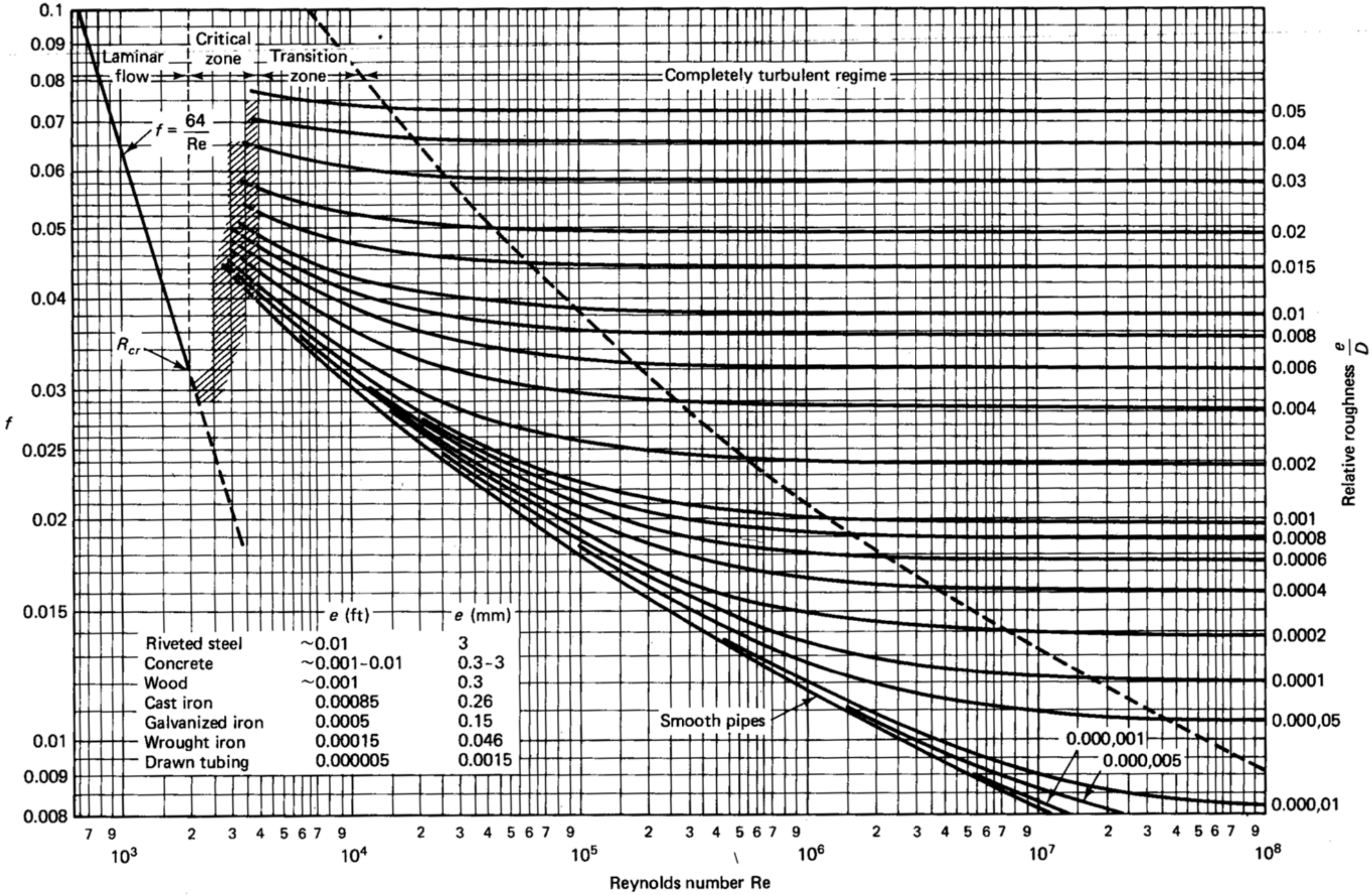
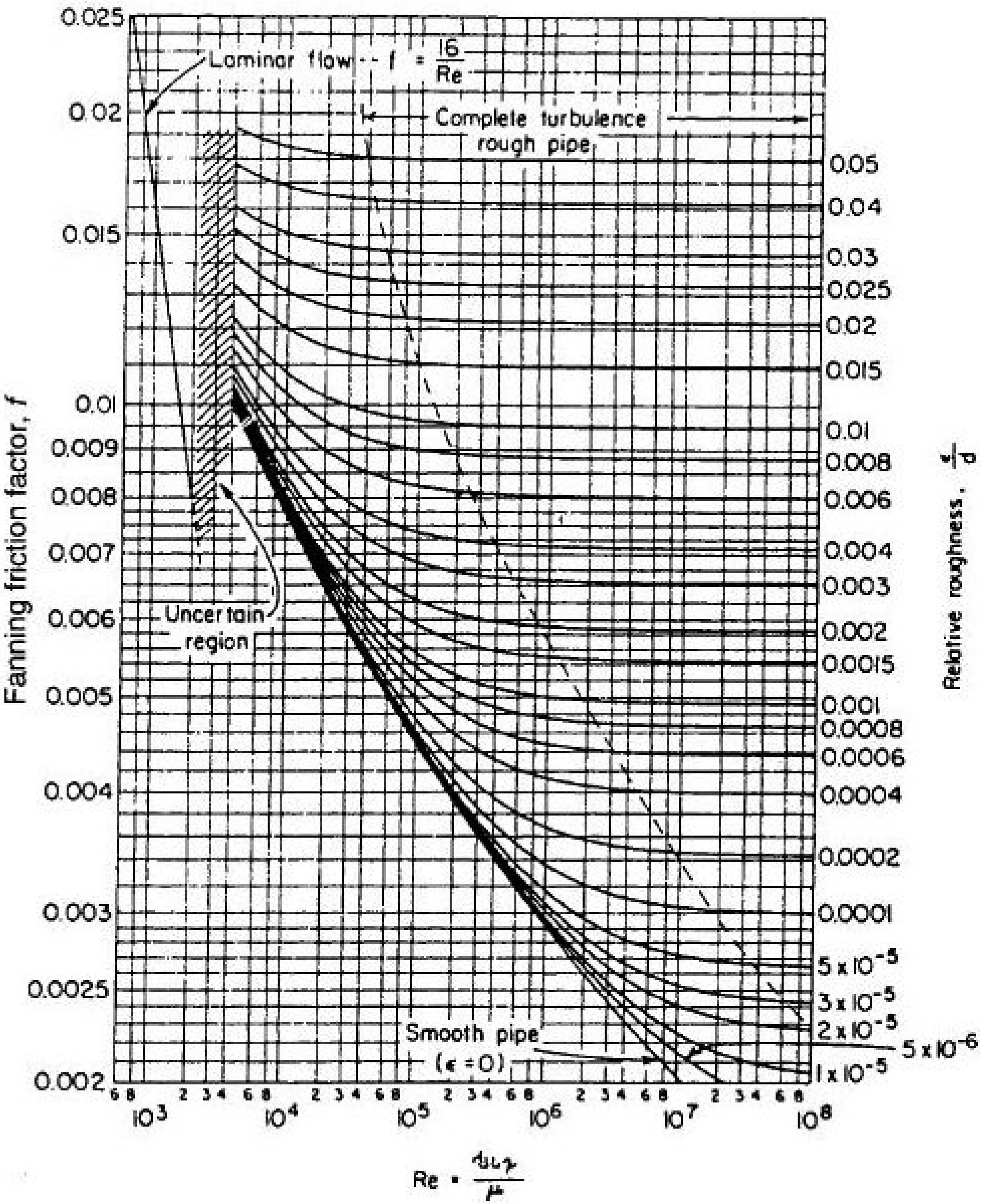


Figure 7.13 Moody diagram. (From L. F. Moody, *Trans. ASME*, Vol. 66, 1944.)


Laminar flow $f = \frac{16}{Re}$
Complete turbulence rough pipe
Uncertain region
Smooth pipe ($\epsilon = 0$)
Fanning friction factor, f
Relative roughness, $\frac{\epsilon}{d}$
$Re = \frac{d u \rho}{\mu}$
0.025
0.02
0.015
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.0025
0.002
0.05
0.04
0.03
0.025
0.02
0.015
0.01
0.008
0.006
0.004
0.003
0.002
0.0015
0.001
0.0008
0.0006
0.0004
0.0002
0.0001
5×10^{-5}
3×10^{-5}
2×10^{-5}
5×10^{-6}
1×10^{-5}
10^3
10^4
10^5
10^6
10^7
10^8

ME 326 Fluid Mechanics Sessional

Experiment No. 2

(a) Study of flow over a circular cylinder

(b) Study of dynamic pressure and velocity measurement by pitot tube

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Experiment Outcomes

The objective of this experiment is to show how pressure and velocity varies on the surface of a circular cylinder when air flows over it. The students will also learn the principle of dynamic pressure measurement using a pitot tube. On completion of the experiment, the students should be able to

(i) Visualize the pressure distribution around a cylinder placed in air stream
(ii) the concept of stagnation point
(iii) the concept of drag coefficient and drag force
(iv) understand the principle of dynamic pressure and velocity measurement in a fluid flow.

Flow over a circular cylinder

This experiment involves the study of flow past a circular cylinder in a uniform stream. The flow pattern and the drag on a cylinder are functions of the Reynolds number, $\text{Re} = \rho U_\infty D / \mu$ based on the cylinder diameter D and the undisturbed free-stream velocity, U_∞. Reynolds number represents the ratio of inertia to viscous forces in the flow. At the leading edge of the cylinder, a stagnation point is formed where the oncoming flow is brought to rest. The pressure here is equal to the stagnation pressure and the pressure coefficient, $C_p = (p - p_\infty)/\left(1/2\,\rho_\infty U_\infty^2\right)$ is, therefore, equal to unity. To either side of the stagnation point the flow accelerates around the forward surface of the cylinder producing a drop in the static pressure.

Immediately adjacent to the cylinder surface a thin boundary layer is formed. The boundary layer is a region where the velocity drops rapidly to zero to satisfy the no-slip condition at the cylinder surface. The direct effects of viscosity are felt only within the boundary layer. The flow separates from the cylinder surface at some point known as separation point. However, in potential flow theory, the flow is considered as inviscid, irrotational and incompressible and there is no separation of flow.

If Re is less than about 4×10^5, the boundary layer remains laminar from the stagnation point at the front of the cylinder to the point where it separates. The resulting flow pattern is associated with a high drag on the cylinder C_d being about 1.2. The laminar boundary layer separates just upstream of the maximum thickness. Downstream of the separation, the flow quickly becomes turbulent and a broad wake is formed. The wake as a whole is unstable and rolls up into vortices that are shed antisymmetrically at regular intervals from the cylinder. This type of wake is called a **von Kármán vortex street**.

At Reynolds numbers greater than 4×10^5, the boundary layer on the forward face of the cylinder undergoes transition and becomes turbulent. The resulting flow pattern is associated with a much lower drag, C_d being about 0.3. The precipitous drop in C_d that occurs as a result of transition to

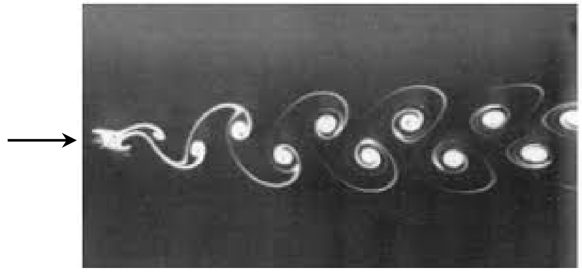


Fig. 3.1 von Karman vortex street behind a circular cylinder at Re = 300

turbulence is usually referred to as the ***drag crisis***. The turbulent boundary layer generated is much less susceptible to adverse pressure gradients. It remains attached to the cylinder surface well past its maximum thickness. As a result the wake is much narrower, the imbalance of pressure forces on the cylinder surface is much smaller and the pressure drag is greatly reduced.

To study this case, a circular cylinder of diameter of 2 inch has been installed inside a low-speed wind tunnel. The cylinder consists of a small hole mounted with a pitot tube (P_5). This pitot tube measures the pressure on the cylinder surface. The cylinder can be rotated at angular steps of 10º. The pressure readings on the cylinder surface are recorded by rotating the cylinder.

Pitot tube and pitot static tube

A Pitot tube is an instrument used to measure fluid flow velocity. It is widely used to determine the airspeed of an aircraft, water speed of a boat, and to measure liquid, air and gas velocities in industrial applications. The pitot tube is used to measure the local velocity at a given point in the flow stream and not the average velocity in the pipe or conduit.

A basic pitot tube consists of a tube pointing directly into the fluid flow. As this tube contains fluid, the moving fluid is brought to rest as there is no outlet to allow flow to continue. This pressure is the stagnation pressure of the fluid, also known as the total pressure or (particularly in aviation) the pitot pressure.

A pitot-static tube combines the features of a pitot tube and a static port by using two concentric tubes. The inner tube with opening at the tip gives stagnation or total pressure. The outer tube with pressure taps on its side wall gives the static pressure. The output of a pitot static tube is the difference between the two and is called the dynamic pressure, $\Delta p = \frac{1}{2}\rho U^2$. So, the flow velocity is given by, $U = \sqrt{\frac{2\Delta p}{\rho}}$.

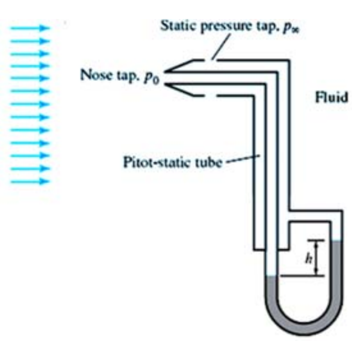


Figure 3.2: Pitot static tube

EXPERIMENT 2(a)

Study of flow over a circular cylinder

OBJECTIVES

The objectives of the experiment are to

i. study the flow over a circular cylinder
ii. find the pressure distribution over the cylinder surface
iii. calculate the pressure coefficient, C_p and drag coefficient, C_d

EXPERIMENTAL SET UP/ APPARATUS

(i) Wind tunnel
(ii) Circular cylinder
(iii) Inclined manometer
(iv) Pitot tube

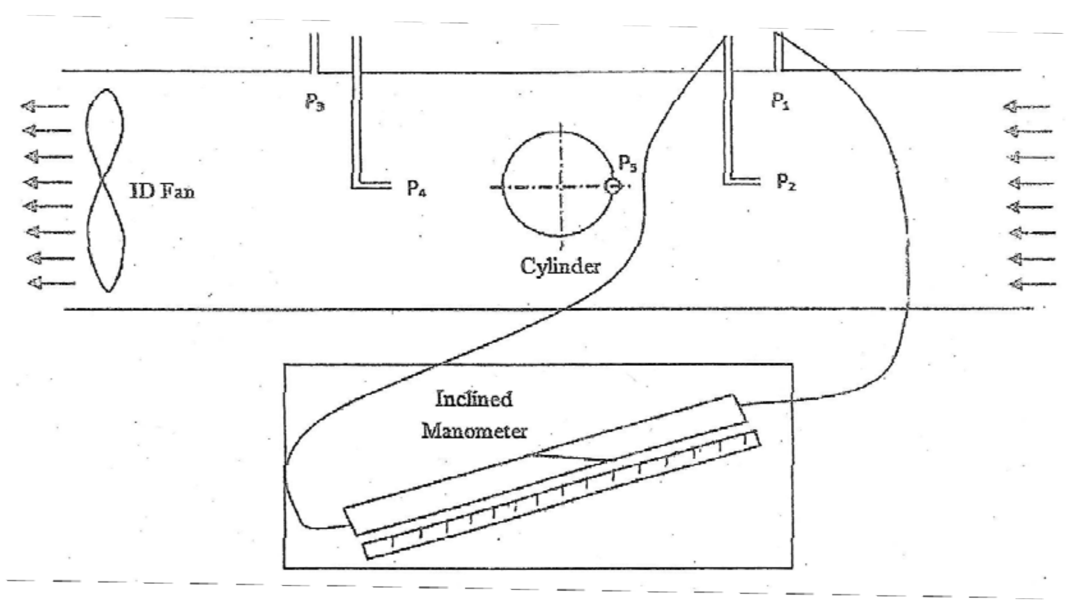


Figure 3.3: Experimental set up

DATA COLLECTION

Given data:

Diameter of the cylinder, D = 2 inch = 50.8 mm

Room Temperature (T_{room}) =

Density of air, ρ_{air} =

Density of water, ρ_{water} =

Initial reading of manometer (H) =

Free stream dynamic pressure head, ($h_2 - h_1$) =

Experimental Data and calculation:

Table 1. Table for calculation of coefficient of pressure, C_p

No. of obs.	Position, θ (deg)	Manometer reading, M	$h_5 - h_1 = M - H$	Experimental C_p	Theoretical $C_p = 1 - 4\sin^2\theta$	Experimental $C_p \cos\theta$
1	0				1	
2	10				0.88	
3	20				0.54	
4	30				0	
5	40				-0.65	
6	50				-1.35	
7	60				-2	
8	70				-2.53	
9	80				-2.88	
10	90				-3	
11	100				-2.88	
12	110				-2.53	
13	120				-2	
14	130				-1.35	
15	140				-0.65	
16	150				0	
17	160				0.54	
18	170				0.88	
19	180				1	
20	190				0.88	
21	200				0.54	
22	210				0	
23	220				-0.65	
24	230				-1.35	
25	240				-2	
26	250				-2.53	
27	260				-2.88	
28	270				-3	
29	280				-2.88	
30	290				-2.53	
31	300				-2	
32	310				-1.35	
33	320				-0.65	
34	330				0	
35	340				0.54	
36	350				0.88	
37	360				1	

Sample calculation:

Observation no.:

1. Angular position: θ (deg) =

2. Manometer reading: M =

3. $h_5 - h_1 = M - H$ =

4. Experimental coefficient of pressure, $C_p = \dfrac{h_5 - h_1}{h_2 - h_1} =$

5. Theoretical (potential theory) coefficient of pressure, $C_p = 1 - 4\sin^2\theta =$

6. Experimental, $C_d = \frac{1}{2} \times$ (Area under the $C_p \cos\theta$ vs. θ_{rad} curve)

7. Theoretical $c_d = \frac{1}{2} \times \int_0^{2\pi} c_p \cos\theta \, d\theta = \frac{1}{2} \times \int_0^{2\pi} (1 - 4\sin^2\theta) \cos\theta \, d\theta =$

GRAPHICAL PRESENTATION OF RESULTS

(i) Plot theoretical and experimental pressure coefficient C_p against the angular position θ

(ii) Plot $C_p \cos\theta$ against θ_{rad} and calculate the drag coefficient C_d from the plot.

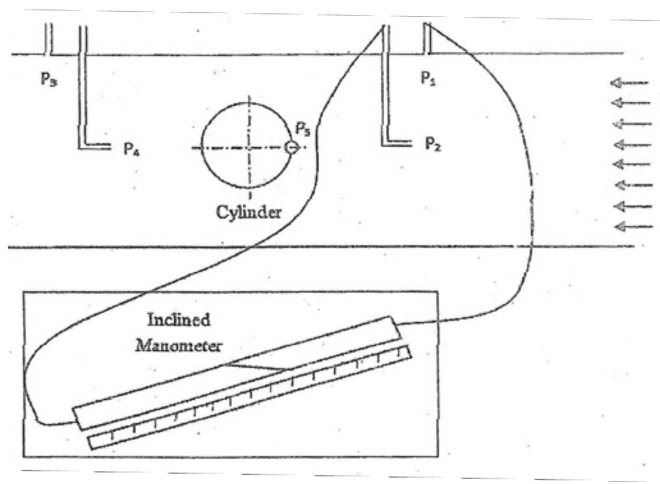
DISCUSSION

EXPERIMENT 2(b)
Study of dynamic pressure and velocity measurement by pitot tube

OBJECTIVES
The objectives of this experiment are

i. to study the construction and different connections of a pitot tube
ii. to measure the velocity at different locations in a wind tunnel
iii. to draw the inlet velocity profile in a wind tunnel

EXPERIMENTAL SETUP



DATA SHEET
Room temp =
Density of air, ρ_{air} =
Density of water, ρ_{water} =

Table 2. Table for determination of velocity profile

No. of Obs.	Position of pitot tube, (inch)	Manometer reading, $h_2 - h_1$	Velocity, v (m/s)	Average velocity, V (m/s)
1	0 (Surface)			
2	0.4			
3	0.8			
4	1.2			
5	1.6			
6	2			
7	2.4			
8	2.8			
9	3.2			
10	3.6			
11	4			
12	4.4			
13	4.8			
14	5.2			
15	5.6			
16	6 (Center)			

Sample Calculation
Observation no.:

Free stream dynamic pressure, $\frac{1}{2}\times\rho_{air}\times v^2=(h_2-h_1)\times g\times\rho_{water}$

So, velocity, $v=\sqrt{\frac{2\times(h_2-h_1)\times g\times\rho_{water}}{\rho_{air}}}\quad=$

GRAPHICAL PRESENTATION OF RESULTS

Plot velocity vectors at different measurement locations and draw the velocity profile.

DISCUSSION

ME 326 Fluid Mechanics Sessional

Experiment No. 3

(a) Study of flow through a converging-diverging (CD) nozzle

(b) Study of flow induced noise

Experiment Outcomes

The objective of this experiment is to make students familiar with the behavior of flow through a Converging-Diverging (CD) nozzle. On completion of the experiment, the students should be able to understand the

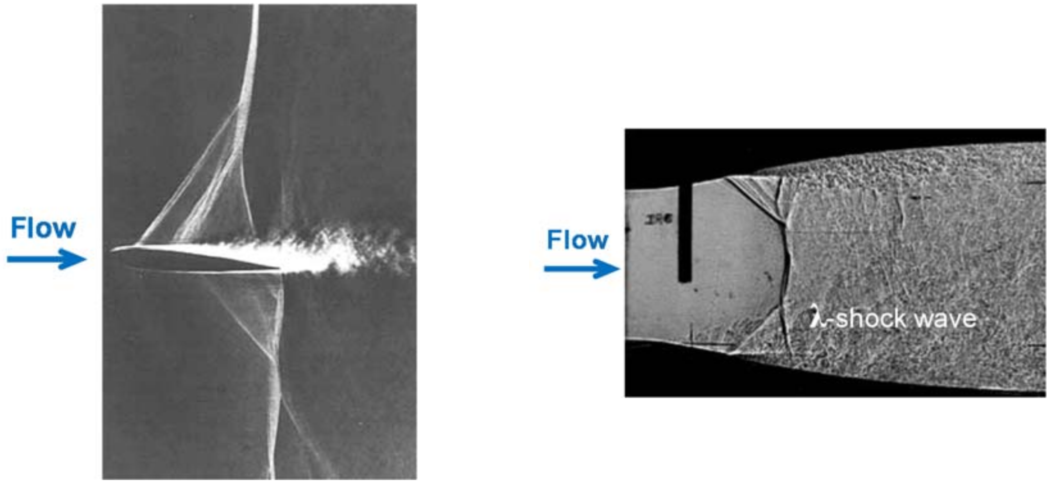
- nature of compressible flow through a CD nozzle and the condition of choked flow.
- level of the noise generated by air issuing from a pressurized reservoir.

Basic information on compressible flow

For low speed flows, density may be assumed constant, without significant loss of accuracy. At very high speeds, however, compressibility effects become important, and in fact dominate the flow field. The most important parameter in compressible flows is **Mach number**, $\boldsymbol{M = V/a}$, where '*V*' is the flow velocity and '*a*' is the speed of sound at local thermodynamic conditions. The speed of sound is calculated as $a = \sqrt{kRT}$ for an ideal gas where *k* is the ratio of specific heats (1.4 for air), *R* is the gas constant (287 J/KgK for air), and *T* is the local temperature (K)]. At $M = 1.0$, the flow is called **sonic**, meaning that the flow velocity equals the speed of sound. The flow fields are classified based on Mach number as follows:

$M < 0.3$:	***Incompressible flow*** and compressibility effects are negligible.
$0.3 < M < 0.8$:	***Subsonic flow***, where compressibility effects are important but no appearance of shock waves
$0.8 < M < 1.2$:	***Transonic flow***, where shock waves first appear in the flow field, dividing the subsonic and supersonic flows.
$1.2 < M < 3.0$:	***Supersonic flow***, where shock waves are present but there are no subsonic regions
$M > 3.0$:	***Hypersonic flow***, where shock waves and other physical changes (surface chemistry, plasma dynamics) are especially very strong.

The commercial civil aircrafts (Boeing 787 Dreamliner, Boeing 777, Airbus A380, etc.) are flying in transonic regime; while the military fighters (F-22, MIG-29, Sukhoi Su-57, etc.) are operating at supersonic velocities. On the other hand, an example of hypersonic flow is encountered when the space shuttle re-enters the earth's atmosphere and descends to earth.



(a) Shock waves around an airfoil (b) Shock waves inside a CD nozzle

Fig. 4.1 Schlieren images for high speed flows with formation of shock waves

About the experiment

In this experiment, high pressure air from a reservoir tank is passed through a converging diverging (CD) nozzle to generate subsonic as well as supersonic flow at various exit pressures. The pressure distribution along the axis of the CD nozzle and mass flow rate are measured. **Choked flow condition** and **shock wave** phenomena are analyzed.

In the second part of the experiment, high pressure air is released from the reservoir to the ambient and subsequently **jet noise** is induced. Sound pressure level (SPL) in dBA is measured at various reservoir pressures. Sound pressure level in dBA indicates the intensity of sound pressure with respect to the sound pressure at the hearing threshold. High level of sound pressure, if unwanted, is called noise and is damaging to human ear. Prolonged exposure to high level of noise can cause permanent deafness.

EXPERIMENT 3(a)
Study of flow through a converging-diverging (CD) nozzle

OBJECTIVES

The objectives of the experiment are to study

1. the flow through a converging-diverging (CD) nozzle
2. the effect of delivery (back) pressure on pressure distribution along the nozzle axis
3. the effect of delivery (back) pressure on mass flow rate from the CD nozzle
4. the phenomena of choked flow and shock waves.

EXPERIMENTAL SET UP

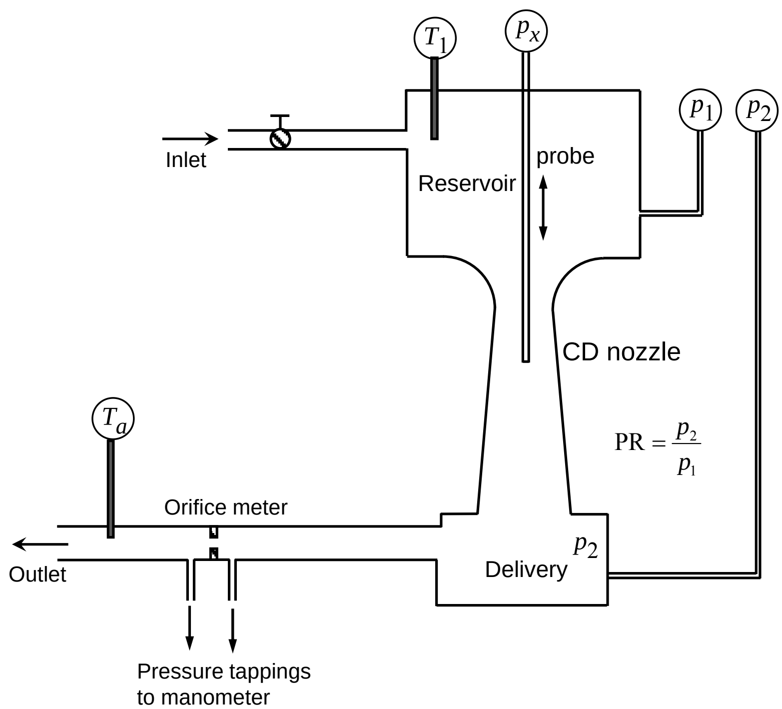


Fig 4.2.: Experimental set up for studying the flow through a converging-diverging nozzle.

DATA COLLECTION

Given data:

For nozzle, throat diameter, $d_t = 0.1893$ inch = 4.808 mm

Nozzle exit diameter, d_e =

Nozzle Expansion ratio, $\varepsilon = \frac{d_e^2}{d_t^2} =$

Pressure probe diameter, $d_p = 0.133$ inch = 3.378 mm

Experimental Data:

Inlet pressure, p_1 (psig) = 80 Temperature of reservoir, T_1 (K) =

Table 1. Data for variation of local pressure (p_x) along the axis of the nozzle

Numeric probe position, x	Delivery pressure p_2 (psig)						
	70	60	50	40	30	20	10
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
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26							
27							
28							
29							
30							

CALCULATION AND RESULT

p_1= 80 psig = kPa (abs); Throat area, A_t (m^2) =

Table 2. Flow rate through the nozzle at different pressure ratio

back pressure p_2		Inlet Pressure p_1 (kPa abs)	Pressure Ratio PR= p_2/p_1	Throat pressure, p_t (kPa abs)	p_t/p_1	Air vel. at throat, V_t (m/s)	Air temp. at throat T_t (K)	Air density at throat, ρ_t (kg/m^3)	Mass flow rate, $\dot{m}$ (kg/s)	Max. mass flow rate, $\dot{m}_{\max}$ (kg/s)	$\frac{\dot{m}}{\dot{m}_{\max}}$
psig	kPa abs.										
70											
60											
50											
40											
30											
20											
10											

Sample calculation

Observation no:

1. Velocity of air at throat of the nozzle, $V_t = \sqrt{\frac{2k}{k-1}RT_1\left[1-\left(\frac{p_t}{p_1}\right)^{\frac{k-1}{k}}\right]}$

   where, k = ratio of specific heats = 1.4 for air and R = gas constant = 287 J/kgK for air. Subscript 1 indicates inlet/reservoir properties and t throat properties.

2. Temperature of air at the throat of the nozzle, $T_t = \left(\frac{p_t}{p_1}\right)^{\frac{k-1}{k}} T_1 =$

3. Density of air at the throat of the nozzle, $\rho_t = \frac{p_t}{RT_t} =$

4. Area at the throat of the nozzle, $A_t = \frac{\pi}{4}\left(d_t^2 - d_p^2\right) =$

5. Mass flow rate of air at throat, $\dot{m} = \rho_t A_t V_t$ =

6. Maximum flow rate, $\dot{m}_{\max}$ =

7. Mass flow ratio, $\dfrac{\dot{m}}{\dot{m}_{\max}}$ =

GRAPHICAL PRESENTATION OF RESULTS

i) **Axial pressure distribution**: local pressure p_x vs. axial position (x) for different pressure ratio, (p_2/p_1)

ii) **Effect of pressure ratio on mass flow rate**: Mass flow ratio $\dfrac{\dot{m}}{\dot{m}_{\max}}$ vs pressure ratio, (p_2/p_1)

DISCUSSION

EXPERIMENT 3(b)
Study of flow induced noise

OBJECTIVES
To study the sound pressure level (noise level) during the issue of high pressure air from a reservoir

APPARATUS
1. Compressor with air reservoir
2. Sound Level Meter
3. Pressure gauge
4. Personal safety equipment (PSE) to protect ears from exposure to high level of noise

Figure 4.3: A typical air compressor with reservoir.

DATA SHEET
Distance of the sound meter from the sound or noise source =

Observation No.	Air pressure in the reservoir (bar)	Sound Pressure Level (dBA)
1		
2		
3		
4		
5		

DISCUSSION

Experiment No. 4
Study of Flow through a Circular Pipe

EXPERIMENT OUTCOMES

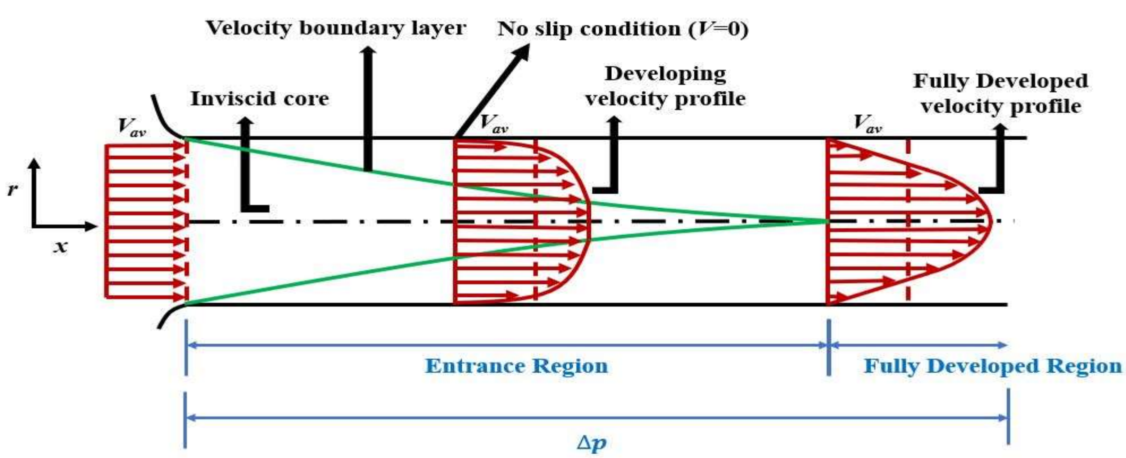
The objective of this experiment is to demonstrate the velocity variation at throat and different radii of a circular pipe when air flows through that pipe. On completion of the experiment, the students should be able to

- Understand physical description of internal flow and the velocity boundary layer.
- Visualize the velocity distribution around a circular pipe due to the fluid flow.
- The concept of laminar and turbulent flow in a circular pipe.

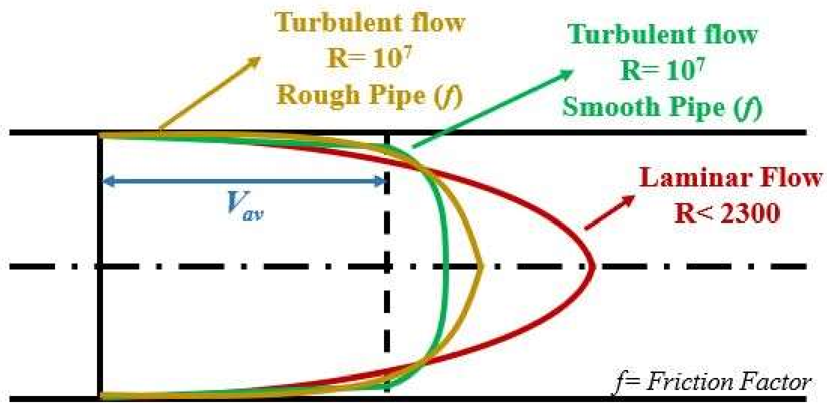
FLOW THROUGH A CIRCULAR PIPE

Concept of Velocity Boundary layer

For an internal flow as such the current study, when a fluid enters a circular pipe at a uniform velocity, the fluid particles at the boundary of the pipe come to a complete rest because of the no-slip condition. As a result, the fluid particles in the adjacent layers slow down gradually due to friction. To keep the mass flow rate through the pipe constant, the velocity of the fluid at the midsection of the pipe increases to make up for the velocity reduction. Thus, a velocity gradient develops along the pipe. The region of the flow in which the effects of the viscous shearing forces caused by fluid viscosity are felt is called the velocity boundary layer. The hypothetical boundary surface divides the flow in a pipe into two regions: the boundary layer region, in which the viscous effects and the velocity changes are significant, and the inviscid (core) flow region, in which the frictional effects are negligible and the velocity remains essentially constant in the radial direction. The region from the pipe inlet to the point at which the boundary layer merges at the centerline is called the hydrodynamic entrance region.



The region beyond the entrance region in which the velocity profile is fully developed and remains unchanged is called the hydrodynamically fully developed region. The velocity profile in the fully developed region is parabolic in laminar flow and somewhat flatter (or fuller) in turbulent flow due to eddy motion and more vigorous mixing in the radial direction. However, in fluid flow, it is convenient to work with an average velocity V_{av}, which remains constant in incompressible flow when the cross-sectional area of the pipe remains constant and fluid properties evaluated at some average temperature are also treated as constants.



Criteria:

Fluid flow regime is mainly characterized by the ratio of inertial forces to viscous forces in the fluid. This ratio is called the Reynolds number and is expressed for internal flow in a circular pipe as

$$Re = \frac{intertia\ force}{viscous\ force} = \frac{\rho V_{av} D}{\mu}$$

where V_{av} = average flow velocity (m/s), D = characteristic length of the geometry (diameter in this case, in m), and μ/ρ = kinematic viscosity of the fluid (m^2 /s).

As a general criterion, for flow through smooth pipes,

Re < 2300 signifies the flow to be laminar

Re > 4000 signifies the flow to be turbulent.

At large Reynolds numbers, the inertial forces are large relative to the viscous forces, and thus the viscous forces cannot prevent the random and rapid fluctuations of the fluid. At small or moderate Reynolds numbers, however, the viscous forces are large enough to suppress these fluctuations and to keep the fluid "in line." Thus, the flow is turbulent in the first case and laminar in the second.

ABOUT THE EXPERIMENT

In this experiment, ambient air driven primarily by a pressure difference is passed through a parabolic nozzle to the circular pipe. Velocity of the flowing fluid at the throat of the parabolic nozzle is then calculated from the manometric deflection of the water manometer (For the constant operating speed of 3800 rpm). Further down the circular pipe a pitot traverse is located in a perspex box. Linear distance travelled by the traverser after each full revolution represents the radial location in the circular pipe and a corresponding manometric deflection is obtained from the inclined water manometer connected to the pitot tube. Thus, velocity profile in circular pipe is obtained.

EXPERIMENT 4
Study of flow through a circular pipe

OBJECTIVES

The objectives of the experiment are to

i) To measure the velocity of flowing fluid
- At the throat of the inlet nozzle
- At various radii of the circular pipe.

ii) To find the flow rate of flowing fluid.

iii) To compare the discharge obtained graphically (V vs r^2) with that obtained through the parabolic nozzle.

APPARATUS

Apparatus used in this experiment are:

i) A smooth long pipe
ii) A parabolic nozzle at the inlet of the pipe
iii) A suction fan at the outlet of the pipe
iv) Three (air-water) manometers one at nozzle and other at pitot tube
v) Pitot tube with traverse mechanism
vi) Static pressure tube at various distances

EXPERIMENTAL SET UP

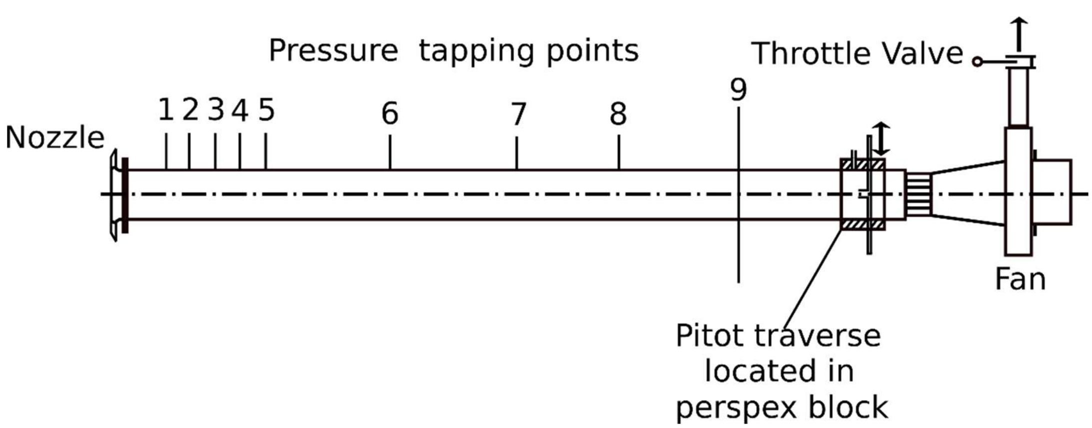


Figure: Experimental set-up of flow through a circular pipe

DATA COLLECTION

Given Data:

Nozzle throat diameter = 2 inch = $5.08 * 10^{-2}$ m

Pipe diameter = 3.1 inch = $7.87 * 10^{-2}$ m

Pitot tube diameter = $1.2 * 10^{-2}$ m

Linear distance travelled by the traverser after one full revolution= 0.1 inch = 2.54 mm

Co-efficient of discharge of the nozzle, C_d = 0.98

Universal gas constant, R = 287 Nm/KgK

Barometric pressure, P (Pa) =

Room temperature, T (K) =

Density of air, ρ_{air} (kg/m^3) =

Viscosity of air, μ_{air} (N.s/m^2) =

Specific weight of water γ_w (N/m^3) =

Experimental Data:

Table 1. Data for Velocity of Flowing Fluid at the Throat of the Parabolic Nozzle (For the constant operating speed of 3800 rpm)

Observation Position	Manometric Deflection, H_w (m of water)	Velocity of Air, V_{th} (m/s)
Throat		

Table 2. Data for Velocity Profile in Circular Pipe (Measuring with pitot tube)

No. of Observations	No. of Revolutions	Radial Location ,r (mm)	r^2 (mm^2)	Manometric Deflection, (m of water)	Velocity of Air (m/s)
1					
2					
3					
4					
5					
6					
7					
8					
9					

10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					
21					
22					
23					
24					
25					
26					
27					
28					
29					

CALCULATIONS AND RESULTS

Sample Calculation:

Observation no.

Manometric deflection, H_w (m of water) =

Throat velocity, $V_{th} = \sqrt{\frac{2\Delta P}{\rho_{air}}} = \sqrt{\frac{2H_w\,\gamma_w}{\rho_{air}}} =$

Nozzle throat cross-sectional area, $A_{th} = \pi\,\frac{(throat\ dia.)^2}{4} =$

Flow rate of nozzle, $Q_{nozzle} = C_d * A_{th} * V_{th}$

$=$

Velocity at a radial location , $V_r = \sqrt{\frac{2H_w \gamma_w}{\rho_{air}}}$ =

Discharge obtained graphically, Q_{graph} = π * area under the curve (V vs r^2)

= (using Trapezoidal rule)

=

Cross sectional area of the pipe, $A_p = \pi \frac{(pipe\ dia.)^2}{4}$ =

Average velocity, $V_{av} = \frac{Q_{nozzle}}{A_p}$ =

Reynolds number, Re= $\frac{\rho D V_{av}}{\mu}$ =

% of error in flow rate = $\left|\frac{Q_{nozzle} - Q_{graph}}{Q_{nozzle}}\right|$ * 100% =

GRAPHICAL PRESENTATION OF RESULTS

i) Plot the velocity profile along the radius of the circular pipe (V vs r).

DISCUSSION