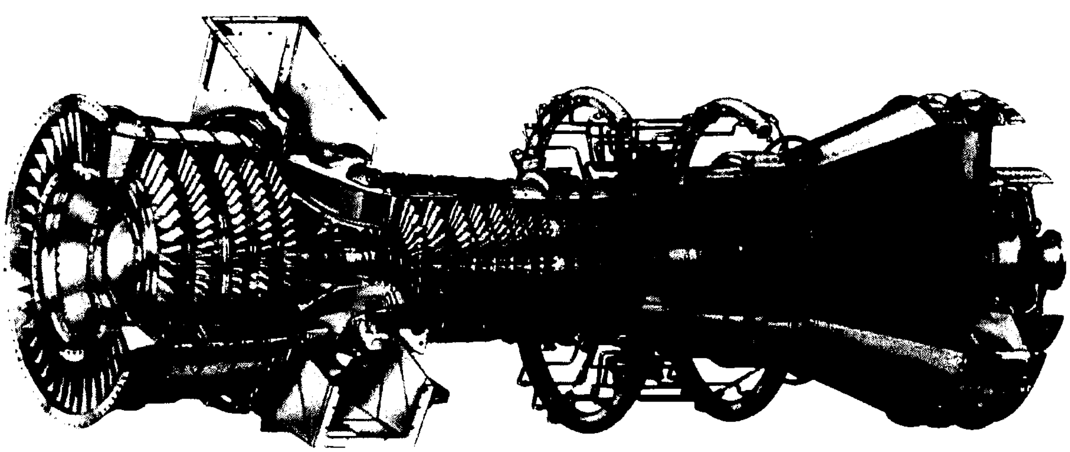
Ryerson University
Department of Mechanical and Industrial Engineering

MEC511 Thermodynamics & Fluid Mechanics

LABORATORY MANUAL



Prepared by: Dr. D. Naylor
Dr. J. Friedman

Updated by: Prof. R. S. Budny
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No Return No Exchange

MEC 511 – Thermodynamics and Fluid Mechanics Laboratory
Department of Mechanical and Industrial Engineering

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Cover: The cover illustration is a General Electric LM6000 Stationary Gas Turbine that delivers 43 MW of electrical power at 42% thermal efficiency. Reproduced with the kind permission of S & S Energy Products, Houston, Texas.

MEASUREMENT OF DYNAMIC VISCOSITY

1.0 OBJECTIVE

The objective of this lab is to determine the dynamic viscosity of engine oil by measuring the terminal velocity of small spheres falling through the oil.

2.0 THEORY

Viscosity is a property that describes the "fluidity" of a fluid i.e., how readily the fluid flows. More specifically, viscosity is associated with the resistance to the sliding motion of one fluid layer over another. This resistance takes the form of a shear stress within the fluid. For most common fluids, the shear stress (τ) is linearly related to the velocity gradient within the fluid as follows:

$$\tau = \mu \frac{\partial u}{\partial y} \tag{1}$$

In Eq.(1), μ is a proportionality constant, called the *dynamic viscosity* (or absolute viscosity). Fluids that obey Eq.(1) are called *Newtonian fluids*.

The method used in this experiment to determine the viscosity of a fluid is to measure the rate at which a sphere of known size and density falls through the fluid under the influence of gravity. A force balance on a sphere falling through a quiescent viscous fluid is shown in Figure 1. It will be assumed that the sphere has been falling for long enough for the sphere to have stopped accelerating. When the sphere has reached a steady velocity (called the *terminal velocity*) the sum of the forces on the sphere will be zero:

$$\Sigma F = ma = 0 \qquad F_D + F_B - W_S = 0 \tag{2}$$

It can be seen from Eq.(2) that at terminal velocity, the weight of the sphere (W_S) is exactly balanced by the upward drag force (F_D) and the upward buoyancy force (F_B).

For very slow motion G.G. Stokes (1851) has shown that the drag force on a sphere moving at constant velocity through a still fluid is:

$$F_D = 3\pi\mu U D \tag{3}$$

where D is the diameter of the sphere, U is the steady velocity of the sphere and μ is the dynamic viscosity of the fluid.

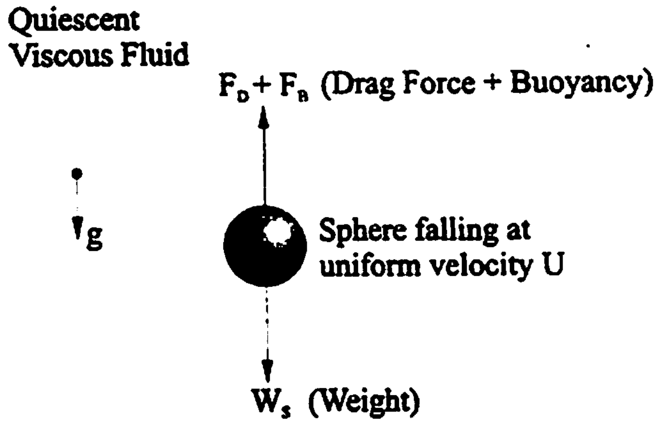


Figure 1: Force balance on a sphere falling through a viscous fluid.

From Archimedes Principle, the upward buoyancy force on the sphere is equal to the weight of fluid it displaces:

$$F_B = \rho_f g V = \rho_f g \frac{\pi D^3}{6} \tag{4}$$

where ρ_f is the density of the fluid. In Eq. (4), it is noted that the volume of a sphere is $V = \pi D^3/6$. The weight (W_S) of the sphere can be expressed as:

$$W_s = mg = \rho_s V g = \rho_s \frac{\pi D^3}{6} g \tag{5}$$

where ρ_S is the density of the sphere. Substituting Eq.s (3), (4), and (5) into Eq.(2), and solving for μ gives:

$$\mu = \frac{D^2 g(\rho_s - \rho_f)}{18U} \tag{6}$$

Using Eq.(6), the dynamic viscosity of the fluid can be determined by measuring the fluid density and terminal velocity, diameter and density of the sphere.

As mentioned above, Eq.(6) is accurate only for slow motion. Experiments have shown that Eq.(6) gives accurate results provided the following condition is met:

$$\frac{\rho_f U D}{\mu} < 1 \tag{7}$$

This dimensionless ratio of parameters is called the *Reynolds number*. If this condition is met, the flow pattern about the sphere will be as illustrated in Figure 2. In this figure, lines of dye have been injected into the fluid to show the flow pattern. Note that for the slow motion depicted in Figure 2, there are no eddies or recirculating flow behind the sphere.

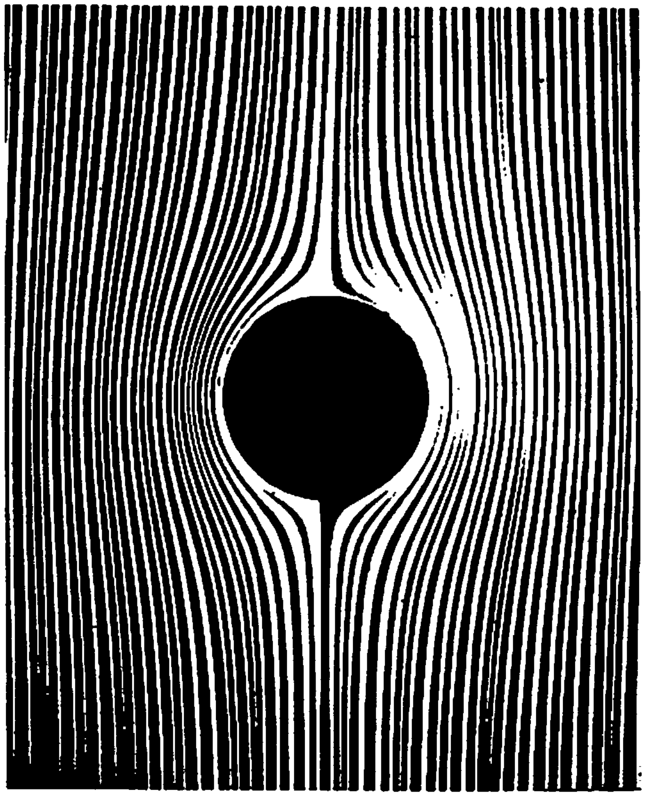


Figure 2: Photograph of very slow flow ("Stokes flow") over a sphere.

3.0 APPARATUS

The apparatus for this experiment is as follows:

- tall graduated cylinder, filled with oil
- three spheres of various sizes
- hydrometer for measuring the specific gravity of the oil
- stop watch and metre stick to measure the steady velocity of the sphere
- weigh scale to determine the mass of each sphere
- micrometer to determine the diameter of each sphere
- thermometer to measure the oil temperature

4.0 PROCEDURE

1. At the start of the test, measure the temperature of the oil with a thermometer.
2. Determine the specific gravity of the oil using the hydrometer.
3. There are three sizes of spheres to be used for this experiment. For each size of sphere, measure the *steady* velocity of the sphere in the oil using a stop watch.
4. To check the reproducibility of your results, repeat the measurement for the largest sphere.

5.0 CALCULATIONS

1. From Eq.(6), calculate the dynamic viscosity of the oil using the data for each sphere. Also, for each sphere check that the "slow flow" criterion (given by Eq. (7)), is met.

2. Compare your results with the properties of engine oil given in property tables. When making this comparison, be sure to account for the variation of viscosity with temperature.

Present your raw experimental data and calculated results in properly labelled tables.

6.0 DISCUSSION

Points to consider in the discussion of your results:

- Did the data for each sphere yield the same dynamic viscosity? If not, why?

- Which size of sphere likely gave the most accurate result? Why?

- How does your viscosity measurement compare with value in property tables? Give possible reasons for any differences observed.

THE VENTURI FLOW METER

1.0 OBJECTIVE

The objective of this lab is to study incompressible flow through a Venturi flow meter. Using Bernoulli's equation, the theoretical volume flow rate will be calculate from pressure measurements and an estimate of the Venturi discharge coefficient will be made.

2.0 INTRODUCTION

Venturi flow meters are widely used in industry to measure volume flow rates in pipes. As shown in Figure 1, a Venturi flow meter measures the flow rate using the Bernoulli Principle. The diameter of the pipe (D_1) is gradually decreased to a minimum at the throat of the meter (D_2). The decrease in flow area causes an increase in velocity that is accompanied with a decrease in pressure. The differential pressure (P_1-P_2), measured from taps located around the circumference of the pipe, can be used to determine the volume flow rate Q.

Venturi flow meters are designed to have low head losses i.e., low pressure drop across the meter. The flow area is gradually expanded downstream of the throat to convert the high kinetic energy back to pressure energy. So, most of the head loss in a well-designed Venturi meter is caused by the viscous shear stress on the walls of the meter, rather than by turbulent mixing.

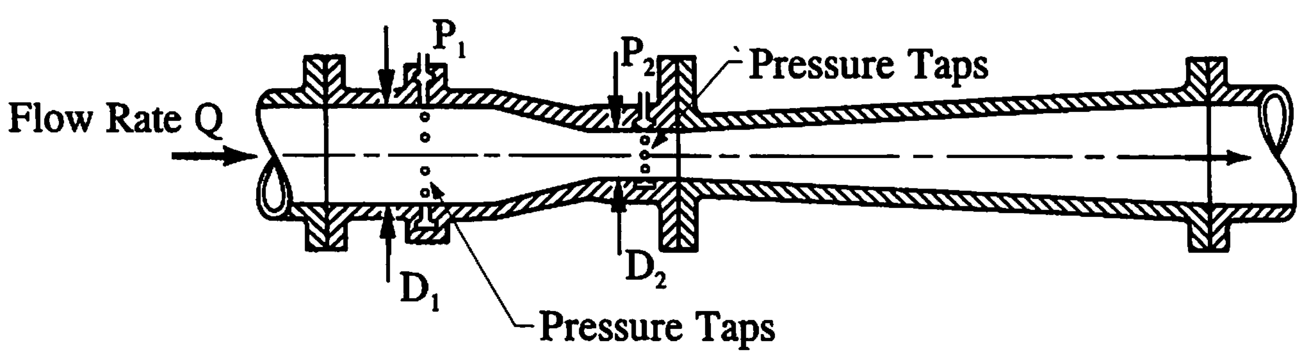


Figure 1: A Typical Venturi Flow Meter

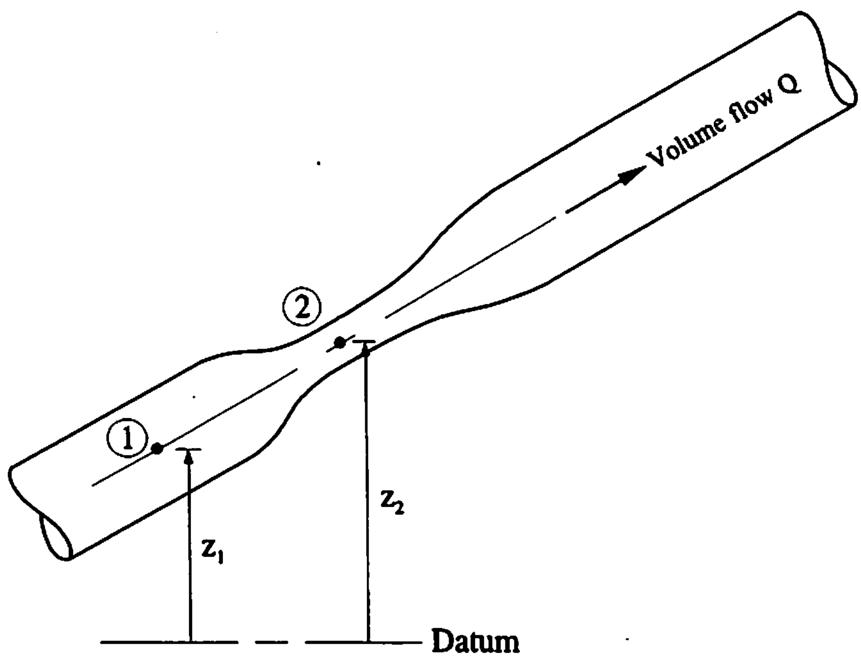


Figure 2: Sketch of a Venturi Flow Meter.

3.0 THEORY

A sketch of a Venturi flow meter is shown in Figure 2. It is desired to relate the volume flow rate Q to the pressures at the upstream location (P_1) and at the throat (P_2). Applying Bernoulli's equation (without losses) from location 1 to location 2 gives:

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + z_2 \qquad (1)$$

Note that the elevations z_1 and z_2 have been expressed relative to a datum. V_1 and V_2 are the average velocities across the sections 1 and 2, respectively. Applying the continuity equation for incompressible flow:

$$V_1 A_1 = V_2 A_2 \qquad (2)$$

where A_1 and A_2 are the pipe cross sectional areas at sections 1 and 2. Equations (1) and (2) may be solved for velocity V_2:

$$V_2 = \sqrt{\frac{2g[(P_1 - P_2)/\gamma + (z_1 - z_2)]}{(1 - (A_2/A_1)^2)}} \qquad (3)$$

V_2 is the theoretical velocity at the throat of the Venturi that is predicted by Bernoulli's equation. Experiments have shown that the actual velocity will usually be slightly lower than predicted by Equation (3). In practice, the actual velocity V_{2a} is obtained as follows:

$$V_{2a} = C_v V_2 = C_v \sqrt{\frac{2g[(P_1 - P_2)/\gamma + (z_1 - z_2)]}{(1 - (A_2/A_1)^2)}} \tag{4}$$

where C_v is the *discharge coefficient*. (For Venturi meters C_v is sometimes called a *velocity coefficient*.) Figure 3 shows the typical variation of discharge coefficient with Reynold number. The shaded area in Figure 3 illustrates the range of values that are typical for Venturi flow meters. It can be shown that meters with the same geometric shape, but of different size, will have the same velocity coefficient, provided the Reynolds numbers are the same. Note that the Reynolds number is based on the velocity (V_1) and diameter (D_1) at location 1.

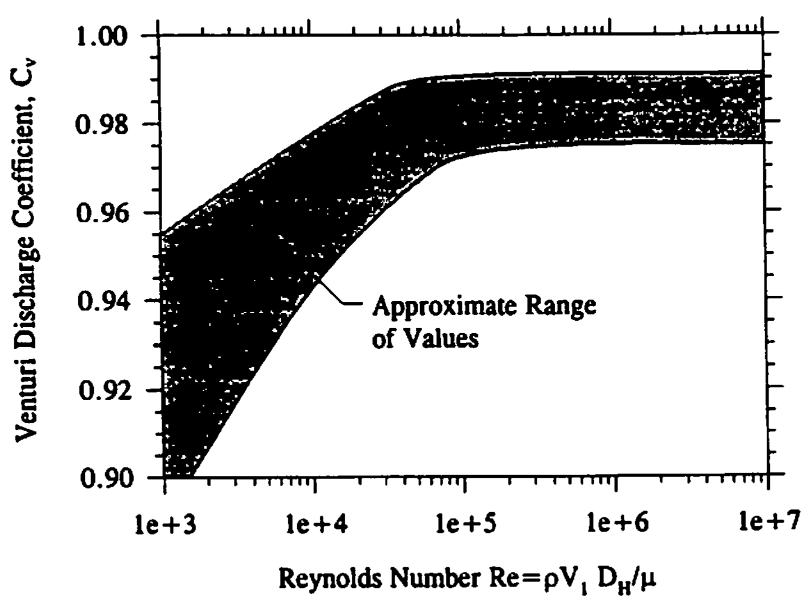


Figure 3: Approximate Range of Discharge Coefficients (C_v) for Venturi Flow Meters.

For the wall mounted Venturi flow meter in the lab, the flow cross section is not round. If this apparatus is used, the Reynolds number should be based on the *hydraulic diameter* (D_H) at location 1. Hydraulic diameter is defined as:

$$D_H = \frac{4A_1}{P_{wet}} \tag{5}$$

where P_{wet} is the wetted perimeter of the rectangular pipe and A_1 is the cross sectional area of the rectangular pipe at section 1.

4.0 PROCEDURE

1. Adjust the flow through the Venturi to give the maximum difference between the manometer readings at the upstream location and at the Venturi throat.

2. Record all the manometer readings.

3. Measure the actual volume flow rate (Q_a) of the water. Make at least two measurements and average the results.

4. Adjust the flow until the difference between upstream manometer reading and the throat manometer reading is one half of the full flow value.

5. Repeat steps 2 and 3 for this lower flow rate.

5.0 CALCULATIONS

1. Verify the derivation of equation (3). Include the algebraic details in the Appendix of your report.

For each flow rate calculate the following:

2. Using the height of fluid in the first manometer (at the Venturi inlet) and manometer reading at the throat, calculate the theoretical velocity at the throat (V_2) and the theoretical volume flow rate (Q).

3. Calculate the Reynolds number at the location of the first manometer, i.e, at Section 1, the inlet to the Venturi meter.

4. Using the theoretical volume flow rate (Q) and the actual measured volume flow rate (Q_a), calculate the Venturi discharge coefficient, C_v. Compare your results with the expected range of values given in Figure 3.

5. Calculate the actual fluid velocity at the location of each manometer using the actual volume flow rate, i.e., using $V=Q_a/A$.

6. Using the fluid height in the first manometer (at the Venturi inlet) as a reference, and the actual fluid velocities calculated in step 5 (above), calculate the theoretical height of the remaining manometers from Bernoulli's equation. Plot the actual and theoretical manometer height variation along the length of the Venturi.

Present your raw experimental data and calculated results in properly labelled tables and graphs.

6.0 DISCUSSION

Points to consider in the discussion of your results:

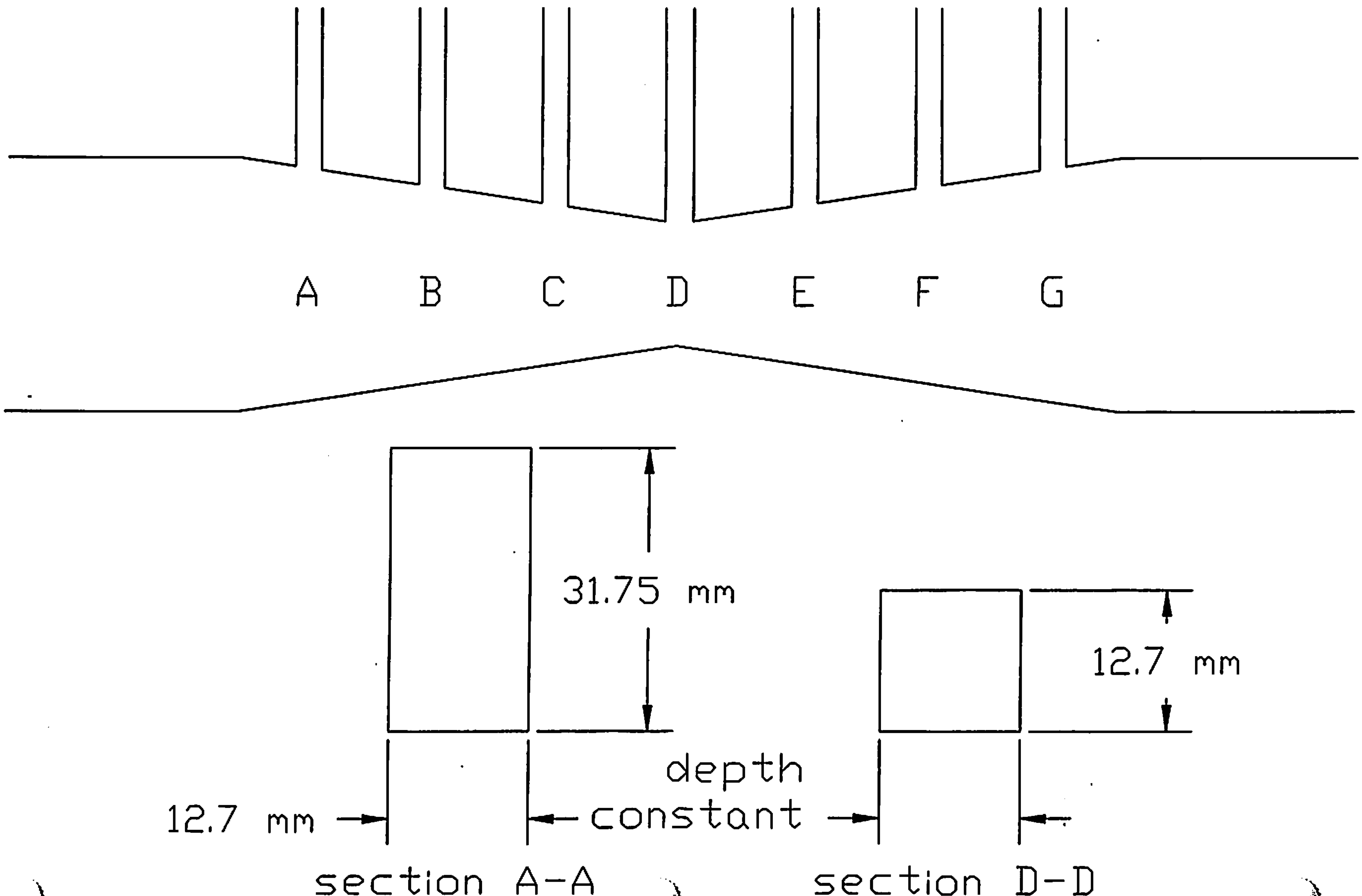
• Why is the actual fluid velocity different from than the theoretical velocity predicted by Bernoulli's equation?

• Is the discharge coefficient within the expected range? If not, discuss possible reasons for the discrepancy.

• According to your results, where are the head losses the greatest in the Venturi flow meter?

VF-3

Channel Dimensions (Wall-Mounted Apparatus Only)



REYNOLDS APPARATUS AND PIPE FRICTION

1.0 OBJECTIVE

The objective of this lab is to study flow in pipes. The qualitative difference between laminar and turbulent flows will be examined, as well as the pressure loss as fluid flows in the pipe.

2.0 INTRODUCTION AND THEORY

Fluid flowing steadily in tubes or pipes has been observed to flow either smoothly, with uniform velocity variation across the pipe and no temporal velocity variation, or irregularly, with random velocity fluctuations superimposed on a steady mean velocity field. The smooth flow is called "laminar flow" and the irregular flow is termed "turbulent flow". A typical pipe flow will assume one of these two flow characteristics (sometimes it may fluctuate between each) depending on the system geometry, flow rate, fluid properties and external disturbances. These characteristics were first observed by Osborne Reynolds in 1883 using apparatus similar to that used in this lab; ie glass tubing and dye injection to produce a fine filament of dye in the flowing medium. He discovered that at low velocity, the dye emerged as a thin, unbroken filament which maintained its structure far downstream, indicative of laminar flow. As flow velocity increased, the dye filament began to break up in a random manner, indicative of turbulent flow. The velocity at which turbulent flow became apparent was termed the "upper critical velocity". As the flow velocity in the turbulent flow field was reduced, laminar flow was seen to be restored at a velocity termed the "lower critical velocity", usually significantly less than the upper critical velocity. Further experimentation by Reynolds showed that it was not fluid velocity by itself that determined whether a flow would be laminar or turbulent, but rather a combination of fluid velocity, fluid properties and system geometry. The parameter combining all these factors is now known as the Reynolds number, given by:

$$\mathrm{Re} = \frac{\rho V d}{\mu}$$

where Re is the Reynolds number, ρ is the fluid density, *V* is the flow velocity, *d* is the tube or pipe diameter and μ is the fluid absolute viscosity. It should be noted that Re is **unitless**. Reynolds found that any flow with a Re less than $\mathrm{Re}_{cr,\,lower}$ would be laminar, and any flow with an Re greater than $\mathrm{Re}_{cr,\,upper}$ would be turbulent. Any flow with a Re falling between these critical bounds would be unstable, and could be laminar, turbulent or oscillating between these modes. Figure 1 shows laminar and turbulent instantaneous reaction zones in a flame. Note the smoothness of the laminar region and the irregularity of the turbulent region.

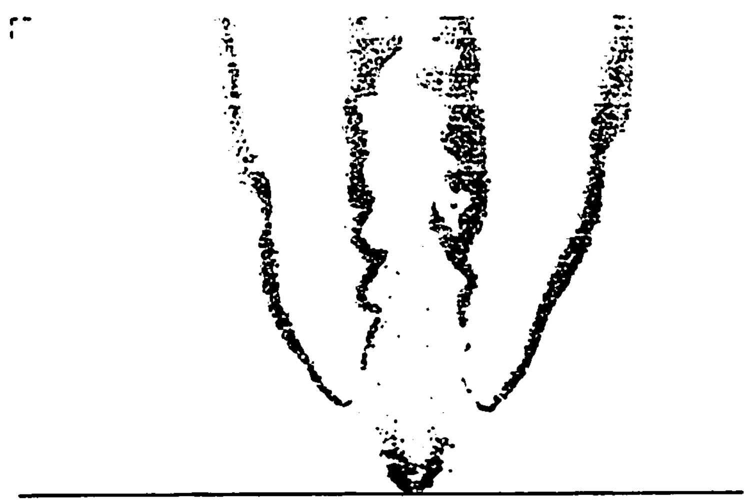


Figure 1: Laminar and turbulent flame fronts in a methanol spray flame

Another important phenomenon in pipe flows is the pressure loss. Pipe flows are generally driven by pressure, and as the flow travels through the pipe, pressure is lost due to viscous friction along the pipe walls. It has been found that, for a given flow configuration, the pressure loss per unit length of pipe is directly proportional to flow rate for laminar flows, and to flow rate squared for turbulent flows.

3.0 PROCEDURE

1. Turn on the apparatus and observe the dye streak at both low (0.02 *l*/s) and high (0.1 *l*/s) steady flow rates. Sketch the appearance of the dye streak for both these cases.

2. Inject a blob of dye at both low and high flow rates. Observe how the blob distorts as it progresses downstream. Sketch the shape of the blob at three successive locations for each flow rate.

3. Set the inclined manometer so that its base is level, its tubes are inclined at 45° and the liquid level in the tubes is around 320mm on the manometer scale (at no flow).

4. Open the downstream valve and take readings of manometer differential pressure and volume flow rate ($\dot{Q}$) at about 10 equal flow increments as measured on the large rotameter. (Keep the small

rotameter closed).

5. Open the small rotameter and close the large one. Incline the manometer to 15° and take manometer differential pressure readings at 10 equal **decrements** of $\dot{Q}$.

6. Plot pressure loss versus flow rate for the two cases above.

NOTE: Pressure loss (in mm water) = (upper manometer reading - lower manumeter reading) x sin(θ) where θ is the manometer inclination.

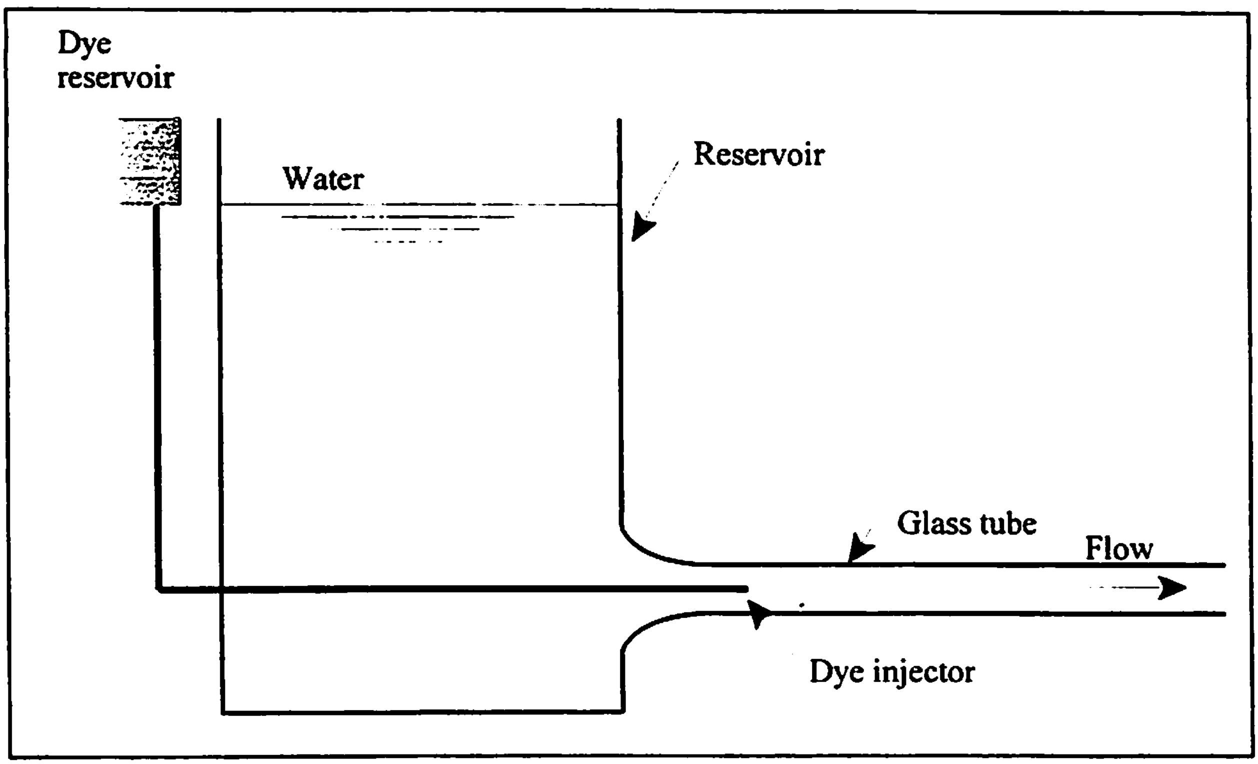


Figure 2: Reynolds apparatus schematic diagram

4.0 DISCUSSION

Points to consider in the discussion of your results:

- In laminar flows, does the dye streak increase in diameter as it flows downstream due to diffusion? How do you expect mixing rates due to diffusion and mixing rates due to turbulence to compare? What are some implications of this?

- According to theory, the pressure loss in pipes is directly proportional to flow rate for laminar flow, but proportional to the square of flow rate for turbulent flows. Does your data bear this out?

- Based on your data, can you estimate the values for $Re_{cr,\ upper}$ and $Re_{cr,\ lower}$?

Temperature-Pressure Relationship

Objective

This experiment investigates the relationship between pressure and temperature for steam undergoing a constant volume process, and provides an opportunity to compare experimental results against reference values.

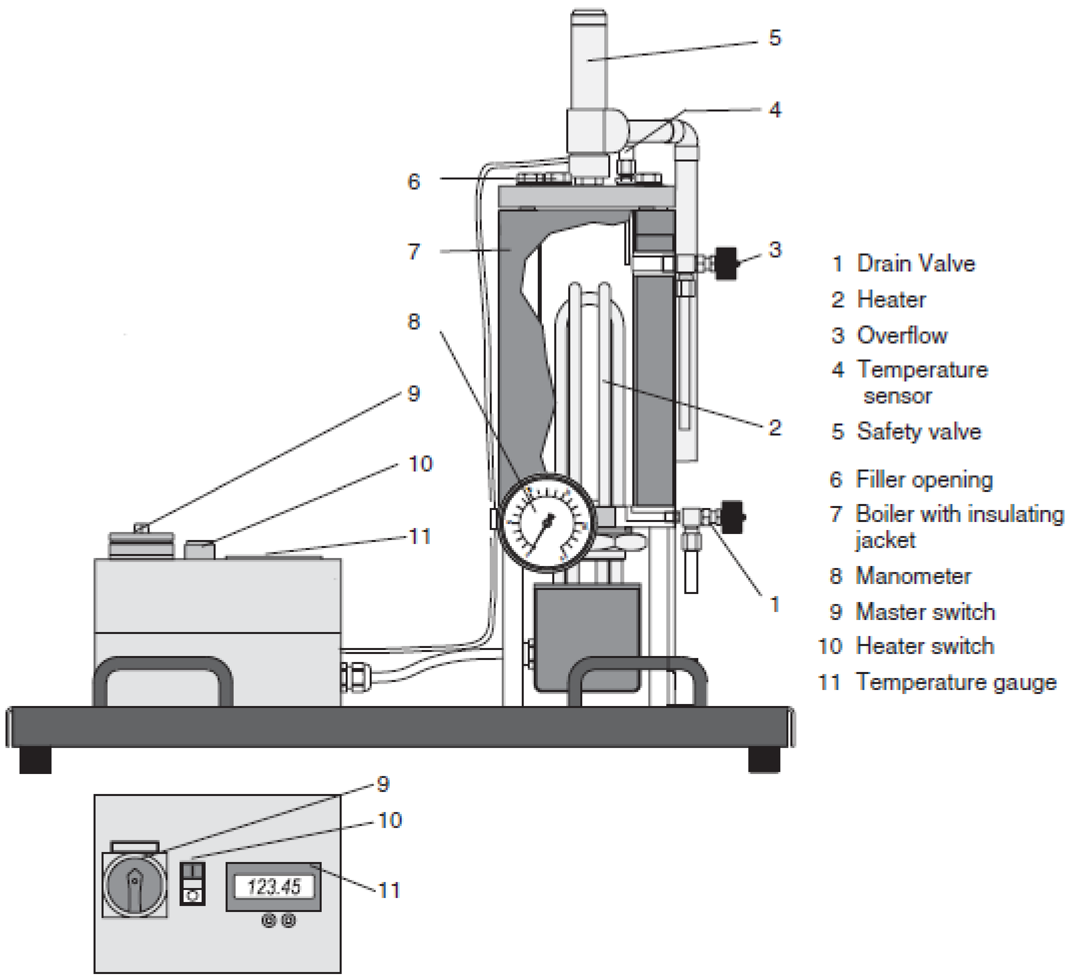


Figure 1 new: WL 204 general view

Apparatus

The experiment WL 204 Steam pressure curve of saturated steam demonstrates the correlation between steam pressure and heating temperature on an enclosed model steam boiler. An insulated steel vessel is filled with a defined quantity of water and sealed pressure-tight. The water is heated by an electric heater and brought to the boil. To record the heating and steam temperature the unit has a temperature sensor element with an electronic evaluation unit and a

Experimental Data

Record your observations here. Make note of the units.

Atmospheric pressure:

Atmospheric temperature:

Pressure, relative [bar]	Pressure, absolute [bar]	Steam temperature [°C]
0,5		
1		
1,5		
2		
2,5		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		

digital display. The steam pressure occurring in the boiler during the experiments is calculated and indicated by a mechanical manometer. A safety valve prevents excess pressure build-up in the boiler. The setup of this bench-top unit permits the saturated steam pressure curve of water to be determined steplessly up to a pressure of 16 bar. The measurement can be compared against the tabulated values from the relevant literature. The experiment is executed as a user-friendly benchtop unit. However, for safety reasons it should only be run under the supervision of trained personnel, as experimenting with hot steam by nature involves a certain risk. It is designed only for educational and training purposes.

Procedure

ATTENTION!

The safety valve may suddenly activate

Loud noise !

Large quantities of hot steam will be emitted !

- Measure the barometric pressure. Correct for local conditions (temperature, ambient pressure).
- Switch on the unit at the master switch (9).
- Switch on the heater at the heater switch (10) and heat up the boiler. The heater control is limited to a temperature of 200°C in order to prevent excess pressure build-up.
- Deaerating the Boiler: Heat up the boiler to 100 °C. Let the water cook approx. 1 min. so that the steam can pass through the open valve (3).
- Log the boiler pressure and temperature values in increments of approximately 0.5 bar (Table 1).
- Compare your own measurements with the values from the literature.
- Shutting Down the Boiler: After the experiment switch off the unit at the master switch. Disconnect the unit from the mains power. Leave the boiler to cool down.

Calculations and Discussion

- For each gauge pressure reading, calculate the absolute pressure and the corresponding pressure-temperature pairs from saturated steam tables (eg. Table A-2 or A-3 in Moran and Shapiro’s *Fundamentals of Engineering Thermodynamics*). Remember: Steam tables are written in absolute pressure!
- Plot your results in tabular form.
- Plot both your absolute pressure versus temperature results and the steam table values, as two separate curves on one plot for comparison. Determine the maximum and average percentage difference between your results and the published steam table values. Provide some plausible reasons for any discrepancies.
- **See next page for sample calculations and steam properties Table A.3.**

Sample Interpolation for Temperature T* Using Observed Pressure p_{abs}

1) Suppose p_{atm} = 1.013 b (i.e., 101.3 kPa) and observations pair (p_{rel}, T) = (1.5 b, 134.5°C).
2) Set $p_{abs} = p_{rel} + p_{atm}$ = 1.5 + 1.013 = 2.513 b. <u>Nearest pressures</u> in Table A.3 are 2.50 & 3.00 b.
3) Read nearest (p, T) pairs: (p_1, T_1) = (2.50 b, 127.4°C) and (p_2, T_2) = (3.00 b, 133.6°C).
4) Calculate ratio $r = (p_{abs} - p_1) / (p_2 - p_1)$ = (2.513 – 2.50) / (3.00 – 2.50) = 0.02600.
5) Interpolate for $T^* = (1 - r)\cdot T_1 + r\cdot T_2$ = (1 - 0.02600)(127.4) + (0.02600)(133.6) = 127.6°C.
6) Error in observed T is E% = 100(T – T*) / T* = 100(134.5 – 127.6) / 127.6 = +5.408%.
7) Repeat steps 2) to 6) for each new (p_{rel}, T) pair. You need to find new pairs (p_1, T_1) & (p_2, T_2).
8) On one graph with two curves, plot p_{abs} on x-axis and T & T* on y-axis.

TABLE A-3 Properties of Saturated Water (Liquid–Vapor): Pressure Table

		Specific Volume m³/kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		
Press. bars	Temp. °C	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	Press. bars
0.04	28.96	1.0040	34.800	121.45	2415.2	121.46	2432.9	2554.4	0.4226	8.4746	0.04
0.06	36.16	1.0064	23.739	151.53	2425.0	151.53	2415.9	2567.4	0.5210	8.3304	0.06
0.08	41.51	1.0084	18.103	173.87	2432.2	173.88	2403.1	2577.0	0.5926	8.2287	0.08
0.10	45.81	1.0102	14.674	191.82	2437.9	191.83	2392.8	2584.7	0.6493	8.1502	0.10
0.20	60.06	1.0172	7.649	251.38	2456.7	251.40	2358.3	2609.7	0.8320	7.9085	0.20
0.30	69.10	1.0223	5.229	289.20	2468.4	289.23	2336.1	2625.3	0.9439	7.7686	0.30
0.40	75.87	1.0265	3.993	317.53	2477.0	317.58	2319.2	2636.8	1.0259	7.6700	0.40
0.50	81.33	1.0300	3.240	340.44	2483.9	340.49	2305.4	2645.9	1.0910	7.5939	0.50
0.60	85.94	1.0331	2.732	359.79	2489.6	359.86	2293.6	2653.5	1.1453	7.5320	0.60
0.70	89.95	1.0360	2.365	376.63	2494.5	376.70	2283.3	2660.0	1.1919	7.4797	0.70
0.80	93.50	1.0380	2.087	391.58	2498.8	391.66	2274.1	2665.8	1.2329	7.4346	0.80
0.90	96.71	1.0410	1.869	405.06	2502.6	405.15	2265.7	2670.9	1.2695	7.3949	0.90
1.00	99.63	1.0432	1.694	417.36	2506.1	417.46	2258.0	2675.5	1.3026	7.3594	1.00
1.50	111.4	1.0528	1.159	466.94	2519.7	467.11	2226.5	2693.6	1.4336	7.2233	1.50
2.00	120.2	1.0605	0.8857	504.49	2529.5	504.70	2201.9	2706.7	1.5301	7.1271	2.00
2.50	127.4	1.0672	0.7187	535.10	2537.2	535.37	2181.5	2716.9	1.6072	7.0527	2.50
3.00	133.6	1.0732	0.6058	561.15	2543.6	561.47	2163.8	2725.3	1.6718	6.9919	3.00
3.50	138.9	1.0786	0.5243	583.95	2546.9	584.33	2148.1	2732.4	1.7275	6.9405	3.50
4.00	143.6	1.0836	0.4625	604.31	2553.6	604.74	2133.8	2738.6	1.7766	6.8959	4.00
4.50	147.9	1.0882	0.4140	622.25	2557.6	623.25	2120.7	2743.9	1.8207	6.8565	4.50
5.00	151.9	1.0926	0.3749	639.68	2561.2	640.23	2108.5	2748.7	1.8607	6.8212	5.00
6.00	158.9	1.1006	0.3157	669.90	2567.4	670.56	2086.3	2756.8	1.9312	6.7600	6.00
7.00	165.0	1.1080	0.2729	696.44	2572.5	697.22	2066.3	2763.5	1.9922	6.7080	7.00
8.00	170.4	1.1148	0.2404	720.22	2576.8	721.11	2048.0	2769.1	2.0462	6.6628	8.00
9.00	175.4	1.1212	0.2150	741.83	2580.5	742.83	2031.1	2773.9	2.0946	6.6226	9.00
10.0	179.9	1.1273	0.1944	761.68	2583.6	762.81	2015.3	2778.1	2.1387	6.5863	10.0
15.0	198.3	1.1539	0.1318	843.16	2594.5	844.84	1947.3	2792.2	2.3150	6.4448	15.0
20.0	212.4	1.1767	0.09963	906.44	2600.3	908.79	1890.7	2799.5	2.4474	6.3409	20.0
25.0	224.0	1.1973	0.07998	959.11	2603.1	962.11	1841.0	2803.1	2.5547	6.2575	25.0
30.0	233.9	1.2165	0.06668	1004.8	2604.1	1008.4	1795.7	2804.2	2.6457	6.1869	30.0
35.0	242.6	1.2347	0.05707	1045.4	2603.7	1049.8	1753.7	2803.4	2.7253	6.1253	35.0
40.0	250.4	1.2522	0.04978	1082.3	2602.3	1087.3	1714.1	2801.4	2.7964	6.0701	40.0
45.0	257.5	1.2692	0.04406	1116.2	2600.1	1121.9	1676.4	2798.3	2.8610	6.0199	45.0
50.0	264.0	1.2859	0.03944	1147.8	2597.1	1154.2	1640.1	2794.3	2.9202	5.9734	50.0
60.0	275.6	1.3187	0.03244	1205.4	2589.7	1213.4	1571.0	2784.3	3.0267	5.8892	60.0
70.0	285.9	1.3513	0.02737	1257.6	2580.5	1267.0	1505.1	2772.1	3.1211	5.8133	70.0
80.0	295.1	1.3842	0.02352	1305.6	2569.8	1316.6	1441.3	2758.0	3.2068	5.7432	80.0
90.0	303.4	1.4178	0.02048	1350.5	2557.8	1363.3	1378.9	2742.1	3.2858	5.6772	90.0
100.	311.1	1.4524	0.01803	1393.0	2544.4	1407.6	1317.1	2724.7	3.3596	5.6141	100.
110.	318.2	1.4886	0.01599	1433.7	2529.8	1450.1	1255.5	2705.6	3.4295	5.5527	110.

STEAM QUALITY MEASUREMENT

1.0 OBJECTIVE

Steam leaving a boiler (not a superheater) generally consists of saturated water vapour with a very small quantity of liquid water mixed in. (This is why steam leaving a kettle is visible. "Dry" steam is invisible.) As the hot steam flows through the system piping, it loses heat to the environment and some of the saturated vapour is converted to liquid water, increasing the liquid content of the steam. The fraction of the steam (by mass) that is saturated vapour is called the steam **quality**. The objective of this lab is to measure the quality of steam drawn from the main building supply line.

2.0 INTRODUCTION AND THEORY

The quality of steam, x, is defined as the mass fraction of saturated water vapour in the steam:

$$x = \frac{m_{vapour}}{m_{liquid} + m_{vapour}} \tag{1}$$

The quality of steam is an important parameter in many applications. Steam turbines can be damaged if the steam quality falls too low, as liquid impingement on turbine blades can cause erosion. Excessively low steam quality can hinder heat exchanger performance and reduce heat transfer rates. It is therefore important to be able to evaluate the quality of steam in many industrial processes. There are many methods available to determine steam quality. The one used in this lab involves three major steps. First, liquid water is mechanically separated and collected. This can be accomplished in a number of ways, including passing the steam vertically up through a large diameter pipe to reduce its velocity, thus allowing large water droplets to collect at the bottom. Another method is to introduce the steam tangentially into a vertical pipe, and allow centrifugal forces to cause liquid droplets to impinge on the pipe walls and then drip down to the pipe bottom. After mechanical separation of larger water droplets, the steam is throttled, or forced through an orifice or valve which reduces the steam pressure at constant enthalpy. The throttled steam is then passed through a condenser, which condenses the steam to saturated liquid and collected. The process is illustrated schematically in Figure 1 and on a p-v diagram in Figure 2. Note that it is necessary to include a mechanical separation stage to ensure that the steam is nearly "dry" prior to throttling in order that the throttled steam emerge in a superheated condition.

The quality of the steam can be determined from the above method by operating a system consisting of a mechanical separator and a condenser at steady state, and collecting the condensate and mechanically-separated liquid water over a known period of time while monitoring pressure and temperature at each stage of the process. A measurement of pressure and temperature at point 3, just downstream of the throttle, allows determination of h_3 from steam tables, since in the superheat region p and T fix the state. Since throttling is a constant enthalpy process, $h_2 = h_3$. Once h_2 is known, x_2 can be determined from:

$$h_2 = (1 - x_2)h_f + x_2 h_g \tag{2}$$

Assuming that all the steam was condensed, the total mass of steam that entered the system during the measuring interval is equal to the mass of condensate plus the mass of liquid mechanically separated. Hence, the quality of the entering steam is given by:

$$x_1 = \frac{x_2 m_{cond}}{m_{cond} + m_{sep}} \tag{3}$$

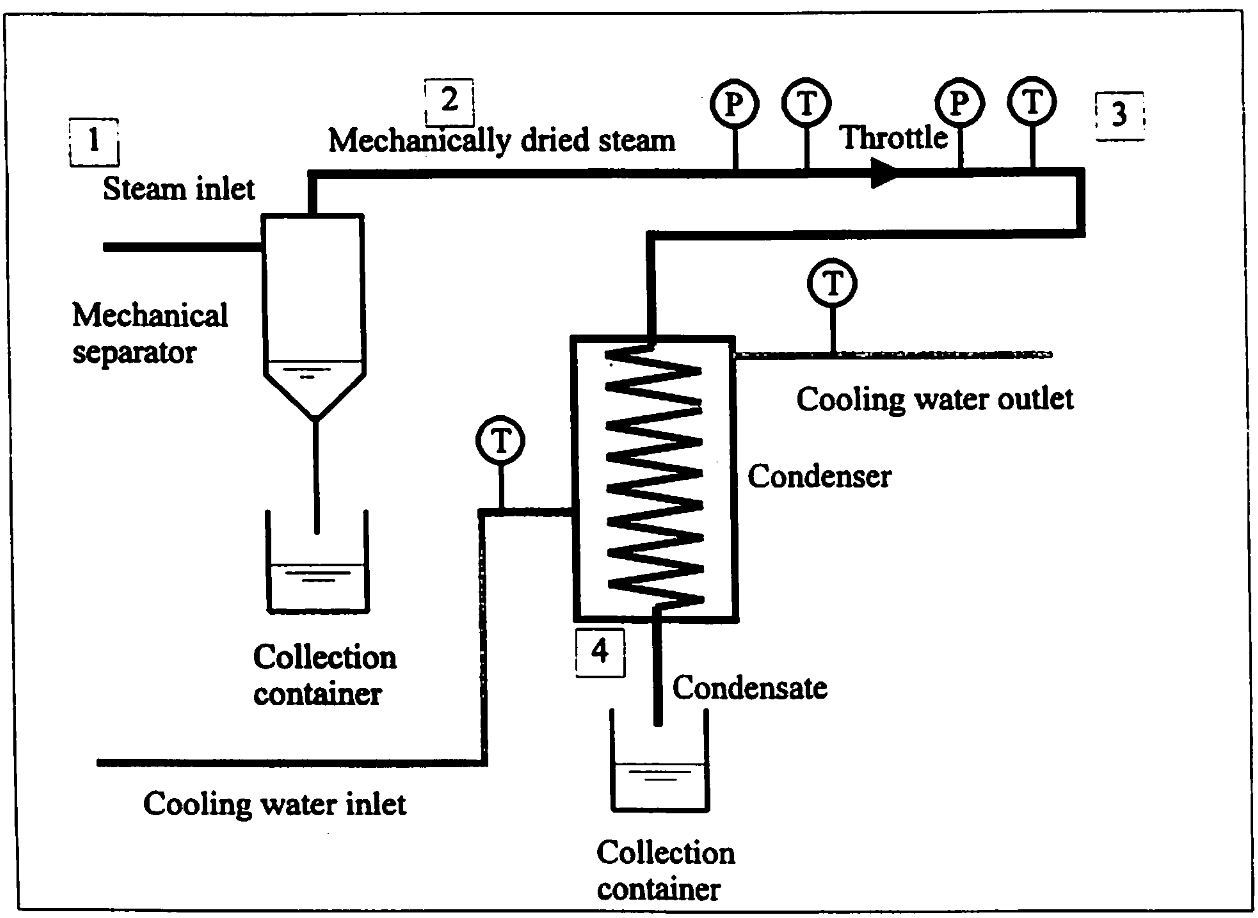


Figure 1: Steam quality measuring system schematic diagram

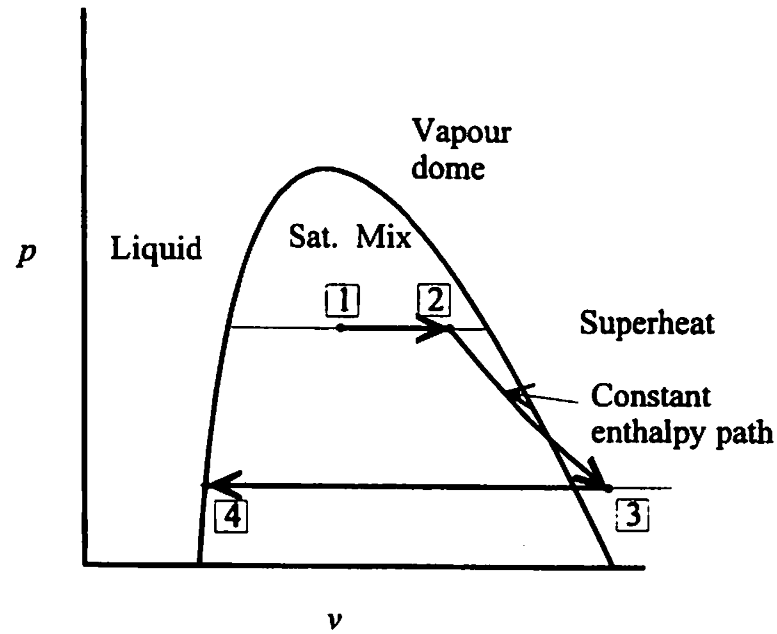


Figure 2: Process diagram

3.0 PROCEDURE

1) Turn on the cooling water to the condenser.

2) Open the steam stop valve, and slowly open the blowdown valve to blow condensed water down the drain. Continue blowing down until only steam emerges from the blowdown line, then close the blowdown valve.

3) Open the separator steam inlet valve and allow the system to operate until steady state is reached (condensate cooling water inlet and outlet temperatures steady).

4) Turn the three way valve at the separator to the drain position to empty the separator of accumulated water, then shut the valve to begin accumulating liquid and start the clock.

5) Start collecting condensate from the condenser drain line and continue collecting for the time period specified by the instructor.

6) Record all temperatures and pressures.

7) At the end of the collection period, close the separator steam inlet valve and stop collecting condensate.

8) To collect the mechanically separated water, crack the condenser steam inlet valve to slightly pressurize the system, and open the three way valve at the separator to direct the separated water to a beaker already containing a known mass of cold water to reduce burn hazard.

9) Obtain at least three sets of readings.

10) Close the steam supply valve, wait five minutes, then close the condenser cooling water valves.

CAUTION: Steam, hot condensate and hot components can cause severe burns. Use caution at all times!!

5.0 DATA REDUCTION

For each run, calculate the steam quality x_1 and x_2 using the equations given in section 2.0.

6.0 DISCUSSION

Verify equation (3). What is the measured steam quality at points 1 and 2? Sketch the process on a Molier chart as found in Figure A-8 in Moran and Shapiro: *Fundamentals of Engineering Thermodynamics 4th Ed.* (John Wiley and Sons) or any other thermodynamics text.
What are some expected sources of error in this experiment? What would be the effect of taking your measurements before steady state was reached (ie piping, valves etc. still cold)?

LAB NOTES