University of Jordan

Faculty of Engineering and Technology

Department of Chemical Engineering

Chemical Engineering Laboratory (1)

Experiment Number -1-

Vapor-Liquid Equilibrium

Objective:

In this experiment equilibrium data for the binary system: n-hexane (1) – toluene (2) will be obtained, or for any other system assigned by the lab instructor. Subsequently, the equilibrium data are reduced to obtain the activity coefficients. The determined activity coefficients are fitted to a suitable model such as the two-suffix Margules, Van Laar, NRTL, UNIQUAC, and Wilson equations. The experimental data are to be compared with the predicted activity coefficients using the UNIFAC method, also to be compared with the reported literature values for the system assigned to the group.

Equipment:

The main features of the apparatus are illustrated in figures (1&2). It consists of a boiling chamber (A) in which the mixture under test is vigorously heated to produce a vapor-liquid mixture that passes the glass spiral tube (B) at a high velocity. The rising vapor entrains drops of the liquid which equilibrates with the vapor and this mixture emerges from the tube at equilibrium, striking the thermometer's pocket (C), which contains a thermocouple (1) to measure the boiling temperature. The vapor then rises gently through the central tube (E) while the liquid drops fall back into the chamber (F). The vapor emerging from the tube (E) passes through the annulus (G), its temperature is measured by thermocouple (2), it is then heated electrically in order to prevent condensation and therefore the entire vapor passes to the water cooled condenser (H) where they are totally condensed. The liquid so formed accumulates in the receiver (J) from which a sample of the vapor phase is obtained. When the receiver (J) is full of condensate, the condensate overflows and passes through the tube (P) to mix with the liquid flowing down the tube (K) from the chamber (F). This mixture enters the heater (A) to be re-vaporized and discharged as a mist into the spiral (B) where it is equilibrated on emerging against the thermometer pocket (C).

The apparatus also contains a refractometer, constant temperature water circulating unit and temperature reading device.

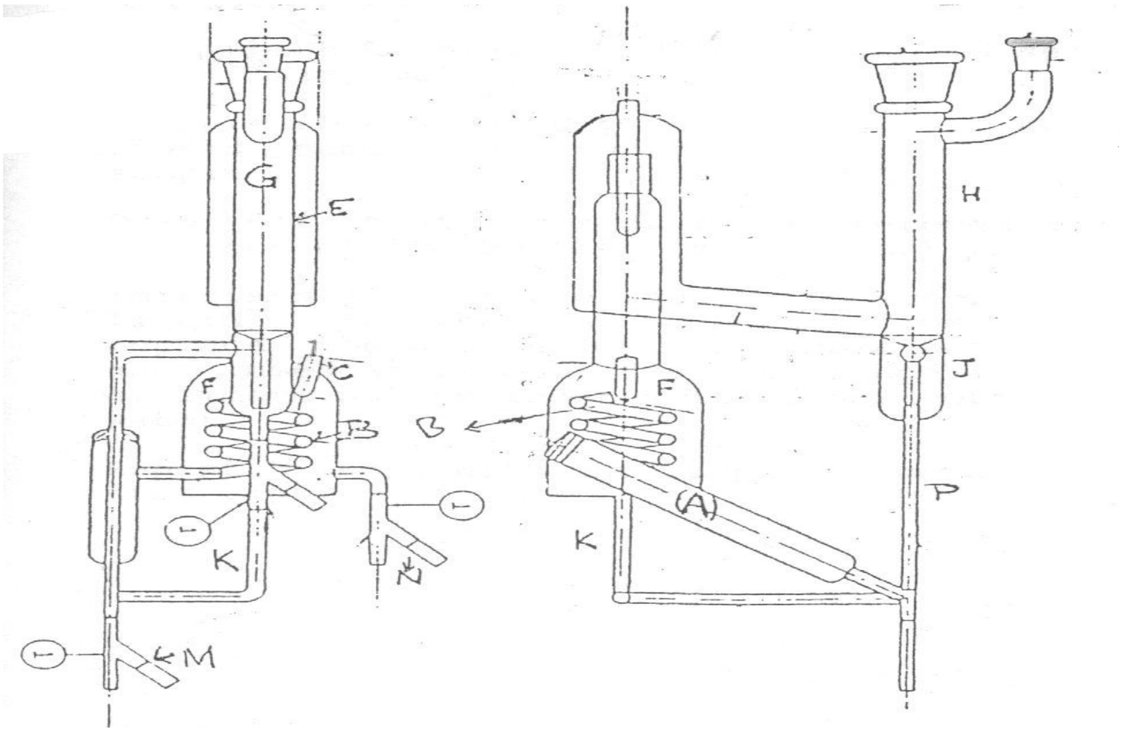
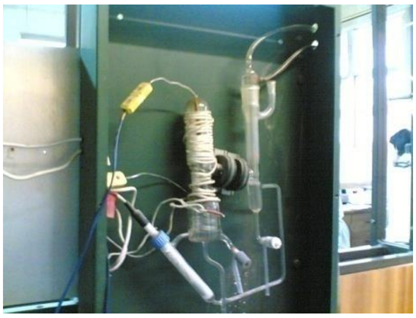


Figure (1): The vapor-liquid equilibria still.



Vapor-Liquid equilibria still

Boiling chamber

Temperature reading system

Refractometer

Photos courtesy of Dalia N. Saleh

Figure (2): Main components and accessories of vapor-liquid apparatus

Theory:

If a liquid mixture of two volatile components (A) and (B) is heated in a closed vessel, the temperature rises and the rate of vaporization of each component increases. As the temperature is raised, the vapor pressure of the liquid mixture, (P_T) increases until it is equal to the pressure applied on the system (P). At this temperature the liquid mixture starts to bubble and the temperature is called the bubble point (T_{bp}) of that mixture at the pressure (P). The first bubble of vapor is in equilibrium with the liquid mixture at that temperature (T_{bp}).

The partial pressure exerted by each component depends on the composition of the liquid mixture and the temperature. If the liquid mixture is ideal, it obeys "Raoult's Law":

$$P_T = \sum_{i=1}^{C=2} P_i = \sum_{i=1}^{C=2} x_i \, P_i^{sat}(T) \dots\dots\dots (1)$$

Where (x_i) is the mole fraction of component (i) in the liquid phase, ($P_i = y_i\, P$) is the partial pressure of component (i), (y_i) is the mole fraction of component (i) in the vapor phase, and (P_i^{sat}) is the saturation pressure of component (i) which is a function of temperature.

If the components form an ideal mixture, the composition of the liquid and the vapor in equilibrium can be predicted from Raoult's Law and Dalton's Law, and this represents the maximum separation (or purification) of the two components that could be achieved by a simple distillation comprising a single vaporization and a single condensation step. In practice most mixtures are not ideal and therefore, equation (1) must be modified by introducing an activity coefficient such that

$$P_T = \sum_{i=1}^{C=2} P_i = \sum_{i=1}^{C=2} \gamma_i \, (\boldsymbol{x}, P_{T,} T) x_i P_i^{sat}(T) \dots\dots\dots (2)$$

Equation (2) is termed the modified Raoult's law. Modified Raoult's law is strictly valid at low pressure assuming that the vapor phase forms an ideal gas mixture i.e., the nonideality is accounted for solely by the activity coefficients in the liquid phase,(γ_i). The activity coefficient of a component in a mixture varies with temperature, pressure and composition, and must therefore be determined experimentally. It is most frequently calculated from the vapor-liquid equilibria data using the modified Raoult's law in the form:

$$\gamma_i(\boldsymbol{x}, P, T) = \frac{y_i . P_T}{x_i . P_i^{sat}\ (T)} \ldots\ldots\ldots (3)$$

Thus, (x_i), (y_i), (P_T) and ($P_i^{sat}(T)$) should be known before being able to determine the activity coefficients. There are many ways to determine the composition in the vapor and liquid phases including, but not limited to: gas chromatography (GC), HPLC and refractive index. In this lab, you are going to determine the composition in the two phases by measuring the refractive indices of liquid phase and the condensate of the vapor phase in equilibrium with it. The saturation pressures as function of temperature are easily calculated from empirical equations such as the Antoine equation:

$$log P_i^{sat} = A - \frac{B}{T + C} \ldots\ldots\ldots (4)$$

Where the parameters (A), (B), and (C) are specific to a particular component and can be found from any reference book or simulation package recently.

Activity Coefficient Models

The activity coefficient of a volatile liquid component in solution can be calculated from many models. Examples of the activity coefficients models written for a binary system are:

1. Two-Suffix Margules Equation

$$ln\gamma_1 = A_{12} . {x_2}^2$$
$$ln\gamma_2 = A_{12} . {x_1}^2 \ldots\ldots\ldots (5)$$

Where (A_{12}) is the parameter in this equation specific to any binary system. This parameter can be obtained from fitting of the experimental activity coefficients with composition.

2. Van Laar Model

$$ln\gamma_1 = \frac{A_{12}}{\left[1 + \frac{A_{12}}{A_{21}} . \frac{x_1}{x_2}\right]^2}$$

$$ln\gamma_2 = \frac{A_{21}}{\left[1 + \frac{A_{21}}{A_{12}} . \frac{x_2}{x_1}\right]^2} \ldots\ldots\ldots (6)$$

Where (A_{12}) and (A_{21}) are parameters in this model specific to a binary system. These parameters can be obtained from fitting of the experimental activity coefficients with composition.

Consistency Tests

Gibbs-Duhem equation states that:

$$(x_1.dln\gamma_1 + x_2.dln\gamma_2)_{T,P} = 0 \dots\dots\dots (7)$$

From this equation, these two equations could be derived:

$$\frac{dln\gamma_2}{dx_2} = -\frac{x_1}{1-x_1}\frac{dln\gamma_1}{dx_2} \dots\dots\dots (8)$$

$$\int_0^1 \ln(\frac{\gamma_1}{\gamma_2}).dx_1 = 0 \quad \dots\dots\dots (9)$$

The consistency of data could be checked using one of these tests:

1. The differential test: This test applies at a specific composition using equation (8). If (ln γ_1) and (ln γ_2) are plotted with respect to (x_2), the slopes at any given concentration should satisfy this equation.
2. The integral test: The consistency of experimental activity coefficients which are available over the entire concentration range can be checked by plotting (ln (γ_1/γ_2)) versus (x_1). The net area beneath the curve should equal zero, as indicated by equation (9). The plot must be extrapolated and integrated in the interval x_1 Є [0, 1].

Procedure:

1. Remove the condenser and pour 120 mL of one of the pure components via a clean dry funnel to the still.
2. Replace the condenser; turn on the cooling water through the condenser.
3. Switch on the electricity to the heater and the heating jacket.
4. When boiling commences, reduce the control so that about 20 drops per minute fall from the base of the condenser into the receiver.
5. Note the temperature of the boiling liquid recorded by thermocouple number (1) and continue boiling the mixture at this constant rate until this temperature remains constant.
6. When temperature (1) is constant adjust the jacket heater so that the temperature recorded by the thermocouple number (2) registers about (0.5-1.0°C) higher than the boiling temperature recorded by thermocouple by thermocouple number (1).
7. Continue boiling for at least one hour. After this period of equilibration take samples of the liquid from tap (N) (at the bottom of the main still) and of condensed vapor from tap (M) (at the bottom of reservoir which receives the drops of condensed vapor), by the following methods:

a. Prepare four clean dry sample bottles, two for the liquid sample and two for the condensed vapor sample.
b. Draw off about 2 mL of liquid through the tap (N) into one of the bottles (this is not the sample).
c. Immediately withdraw about 2 mL of the same liquid into the second bottle from tap (N) and replace the stopper of the sample bottle quickly and immediately cool the bottle and its contents by immersing the lower half of the bottle in cold water.

8. Repeat b and c with the sample of condensed vapor from tap (M).
9. Switch on the water bath, and set the temperature as that recorded on the calibration curve supplied for the system used.
10. Measure the refractive index of the liquid and vapor by the refractometer
11. Add a known volume of the other component (B) to the pure liquid (A) and repeat steps (5 – 10) to obtain new results.
12. Add another volume of component (B) to the liquid in step (11) and also repeat steps (5-10) to obtain new results.
13. In the second period of experiment, starts with the other liquid (B) and after equilibrium of this run, add increments of the other component (A) to obtain result for many mixture of different composition.
14. At the end of the other period of experiment, switch off the apparatus, the water bath and the refractometer. Then drain the contents of the still.
15. Record the operating atmospheric pressure in the Lab.

Calculation:

1. Using the measured refractive indices, find the mole fractions of the volatile component in liquid and vapor phases at equilibrium from the calibration curve of the system.
2. Plot the boiling point-composition diagram (T_{xy}) of the system.
3. Calculate the activity coefficients of the components in the liquid phase using equation (3).
4. Fit the two-suffix Margules, van Laar, Wilson, and NRTL parameters to your data and report them. You may want to use the THERMOSOLVER software to carry out the fitting process.
5. At each equilibrium composition, estimate the activity coefficients using UNIFAC method. You may want to use Sandler's modified UNIFAC software.
6. Obtain estimates of the activity coefficients based on literature values. Go to the binary vapor-liquid equilibrium data of the Korean Thermophysical

Properties Data Bank CHERIC-KDB for experimental results of the system you have studied. The address is http://www.cheric.org/research/kdb.

7. Plot both ($\ln\gamma_1$) and ($\ln\gamma_2$) versus (x_1) using your experimental values, predicted values from the four models: two-suffix Margules, Van Laar, Wilson, and NRTL and that of UNIFAC.
8. Check the consistency of the data using the differential and integral tests.

References:

1. Balzhiser, R. E.; Samules, M. R.; and Eliassen, J. D., 'Chemical engineering thermodynamics'. Prentice-Hall, Inc. 1972.
2. Hala, E; pick, Jiri; Fried, Vojtech; and vilim, otakar, 'Vapour-Liquid Equilibrium'. Second edition, Pergamon Press, 1967.
3. Poling, B. E.; Prausnitz, J. M.; and O'connell, J. P., 'The Properties of Gases and Liquids', 5th edition, McGraw-Hill, NY, 2001.
4. Sandler, S. I., 'Chemical, Biochemical and Engineering Thermodynamics',4th edition, John Wiley and Sons, NY, 2006.
5. Smith, J. M.; Van Ness, H. C.; Abbott, M. M., 'Introduction to Chemical Engineering Thermodynamics', 7th edition, McGraw-Hill, NY, 2006.
6. Winnick, J., 'Chemical Engineering Thermodynamics', John Wiley and Sons, NY, 1997.

Vapor-Liquid Equilibrium Data Sheet

Atmospheric pressure: --------------

Mixture used	Equilibrium Temperature	RI of vapor	RI for liquid

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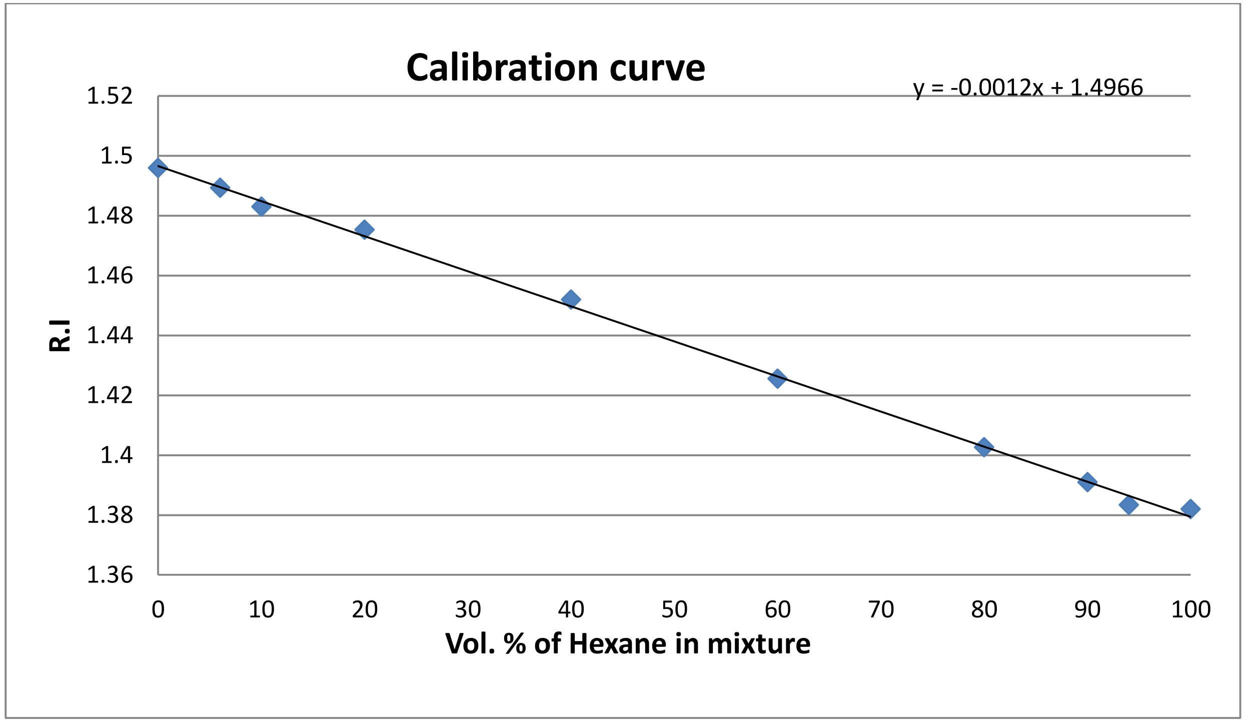

Figure (3): Refractive index Vs volume percentage for (Hexane + Toluene) system

Experiment Number -2-

Liquid-Liquid Equilibrium

Objective

To be familiar with mass transfer processes and the phase equilibria involved in liquid-liquid extraction.

Equipment

The apparatus consists of three cells. Each cell has a central 100 ml. capacity glass vessel with a side arm near the top for charging the liquids. Each glass vessel is surrounded by a glass jacket through which water is circulated to maintain the cell contents at constant temperature. The cell is provided with an agitator. It also contains a valve for emptying the contents on completion of experiment. The general arrangement of liquid-liquid equilibria apparatus is illustrated in figures (5&6).

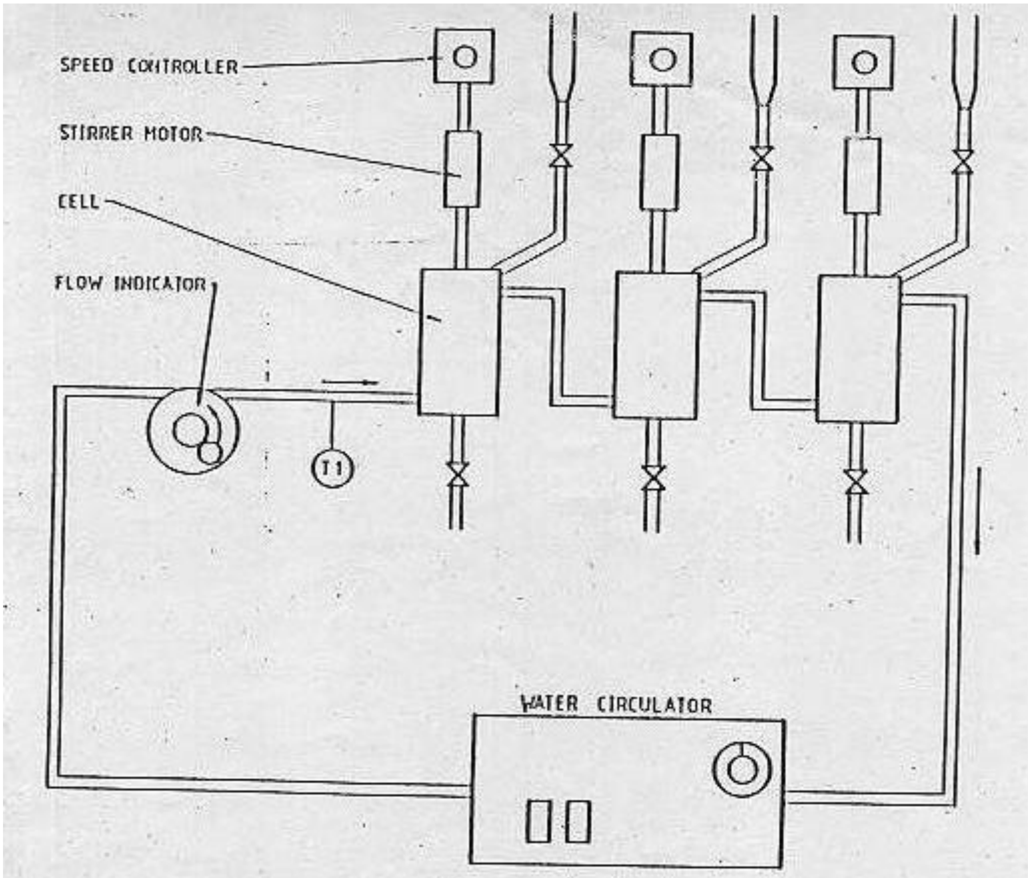

Figure (4): General Arrangement of liquid-liquid Equilibria apparatus

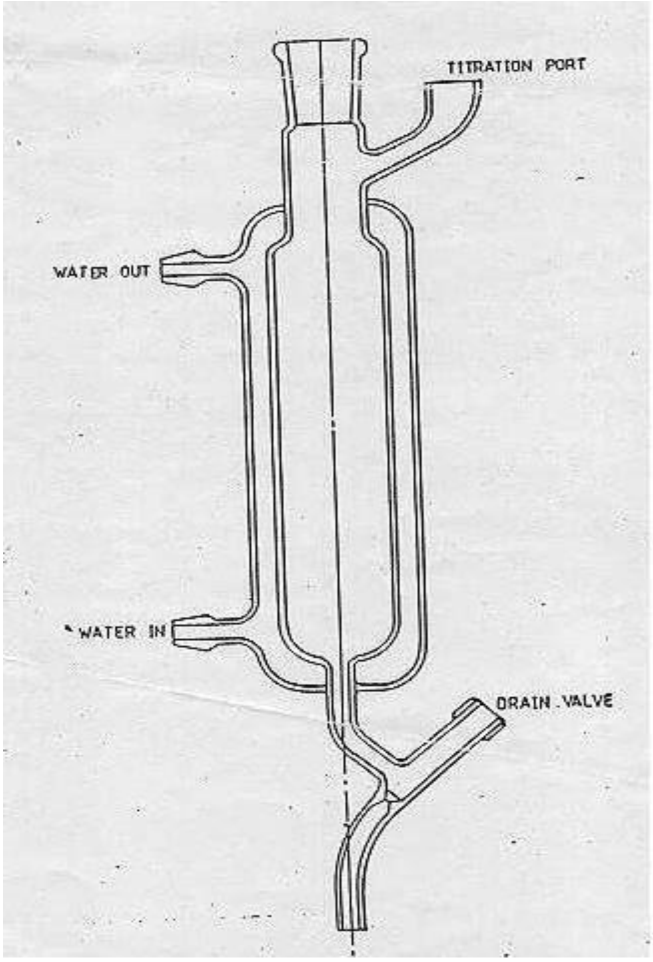

Figure (5): Agitated glass cell for liquid-liquid equilibria determinations

Theory:

Liquid- liquid extraction is the term applied to any operation in which a material dissolved in one liquid phase is transferred to a second liquid phase. The solvent must be insoluble or soluble to a limited extent only, in the solution to be extracted. If the solvent and the solution were completely miscible, there would be no opportunity for transferring the solute from the original solution to a second liquid phase. The degree of solubility of the solvent in the solution, and of the solution and its components in the solvent, are important considerations in the selection of the solvent and in the operation of the extraction process.

Liquid-liquid extraction consists of two basic steps:

1. Intimate mixing or contact of the solvent with the solution to be treated, so as to transfer the solute from the solution to the solvent.
2. Separation of the liquid solution phase from the liquid solvent phase.

The complete extraction process may involve other operations such as the separation and recovery of the solvent from the solute and of the solvent which may be dissolved in the solution, the removal and recovery of the solvent may be more important in determining the successful application of the extraction process than the degree of extraction and separation accomplished in the two basic steps, particularly when special or costly solvents are employed. The separation and recovery of the solvent may be accomplished by various methods such as distillation or simple heating or cooling to diminish the solubility of the solute or of the solvent.

Liquid-liquid-extraction is widely used for the separation of the components of a solution, particularly when:

1. The components are relatively nonvolatile.
2. The components have substantially the same volatilities from the mixture.
3. The components are sensitive to the temperatures required for the separation by distillation.
4. The desired less-volatile component is present in the solution only in relatively small amounts. In such a case, the less volatile component may be extracted solution from which it may be recovered more economically; or similar economics may be accomplished with a solvent less volatile than the desired component, even if the increase in concentration of the desired component is not particularly significant.

Usually the different distribution of the components of the feed mixture between the two layers at equilibrium is depended upon to effect the desired separation. The layer containing the greater concentration of the solvent and the smaller concentration of the feed liquid is referred to as the "extract" layer. The other layer, containing the greater concentration of the feed liquid and the smaller concentration of solvent is referred to as the "raffinate" layer.

All states of equilibrium between extract and raffinate can be represented in either a right triangle or an equilateral triangle phase diagram as you had learned before. For each state of equilibrium, there is only one specific tie line which represents it.

Reliability Using the Othmer-Tobias Correlation

The reliability of equilibrium data for any system may be tested by applying the Othmer-Tobias correlation. This correlation states that:

$$log\frac{(1-a)}{a} = n\ log\frac{(1-b)}{b} + s \ldots\ldots\ldots(1)$$

which indicates that there is a linear relation between the values of ($log\ \frac{(1-a)}{a}$) and ($log\ \frac{(1-b)}{b}$) where:

a: weight fraction of the solvent in the extract phase.
b: Weight fraction of the carrier liquid in the reffinate phase.
s:the intercept
n:slope
The system to be used in this lab will be in general: water, an organic solvent and a solute.

Procedure

A. To determine the ternary mutual solubility curve

a. For water rich phase:

1. Fill the cell with a solution consisting of 20 mls of distilled water and 5mals of the solute.
2. Switch on the thermostat unit and check that water is circulating through the jacket of the cell. Then set the temperature as required.
3. Switch on the stirrer and adjust the speed control to the midpoint of the range.
4. Allow 10 minutes for the contents of the cell to reach the set temperature.
5. Slowly titrate the organic solvent into the mixture in the cell unitl "Cloudiness" appears and persists. Record the volume of the solvent in the mixture. This is the "cloud point" at which the three components in the mixture are in equilibrium. It represents one point on the ternary curve.
6. Add another 5mls of the solute to the mixture and repeat the steps (2-5).
7. Repeat step 6.
8. Clean the cell and fill it with a solution consisting of 10mls of distilled water and 10mls of the solute. Repeat the steps (2-7). Adding 10mls of the solute each time, as shown in this table1.

Table (1): Water Rich Phase

Volume (ml)		Volume (ml)	
Water	Solute	Water	Solute
20	5	10	10
20	10	10	20
20	15	10	30

b. For the organic solvent rich phase:

Repeat the same procedure in (a) using solute-organic solvent solution and titrating with water.

Use the following compositions in table (2):

Table (2): Organic Rich Phase

Volume (ml)		Volume (ml)	
Organic Solvent	Solute	Organic Solvent	Solute
20	5	10	10
20	10	10	20
20	15	10	30

B. Tie Line determination:

1. Fill the cell with a heterogeneous mixture consisting of 20 mls of water, 15mls of the solute and 15mls of the other solvent.
2. Agitate the mixture using the mid-point speed for 20 minutes at the desired temperature.
3. Stop the agitator, and leave the mixture foe about 20 minutes to settle into two layers.
4. Withdraw a sample of each phase in a sample bottle and measure the refractive index of each sample.
5. Using the calibration curves, determine the percentage of the solute in each phase.
6. Repeat the steps (1-5) using the mixtures in Table (3).

Table (3): Tie-lines Determination

Component	mls of component			
Solute	13	8	5	3
Organic solvent	20	17	25	29
Water	18	26	20	19

Calculation

A. For ternary mutual solubility curve:
   1. Calculate the composition of each mixture at its cloud point.
   2. Plot the mutual solubility curve for the ternary system on an equilateral triangle.

B. For tie-line determination:
   1. Calculate the overall composition of each mixture.
   2. Locate on the phase diagram the point which represents the overall composition for each mixture.
   3. Find on the mutual solubility curve the points which represent the composition of the extract and the raffinate phases for each mixture.
   4. Construct the tie line corresponding to each mixture.
   5. Check the linearity of the points which represent the overall composition of each mixture, the composition of extract phase, and the composition of raffinate phase.
   6. Check the reliability of the equilibrium data.

References

1. Coulson, J.M.; and Richardson, J.F., "Chemical Engineering ", volume two. Pergamon Press Inc. third edition, 1978.
2. Felder, R.M.; and Roussean R.W., "Elementary Principles of Chemical Processes". John Wily and Sons. second edition, 1986.
3. McCabe, W.L.; and Smith, J.C., "Unit Operations of Chemical Engineering". McGraw-Hill, Inc. third edition, 1976.

Liquid-Liquid Equilibrium Data Sheet

Tie-Lines Determination:

Volume of water (ml)	Volume of Toluene (ml)	Volume of Acetone (ml)	RI of water layer	RI of Toluene layer
20	15	15		
18	20	13		
26	17	8		
20	25	5		
19	29	3		

Solubility curve

A. Water rich phase:

Volume of Acetone (ml)	Volume of water (ml)	Volume of Toluene (ml)
5	20	
10	20	
15	20	
10	10	
20	10	
30	10	

B. Organic solvent rich phase:

Volume of Acetone (ml)	Volume of Toluene (ml)	Volume of water (ml)
5	20	
10	20	
15	20	
10	10	
20	10	
30	10	

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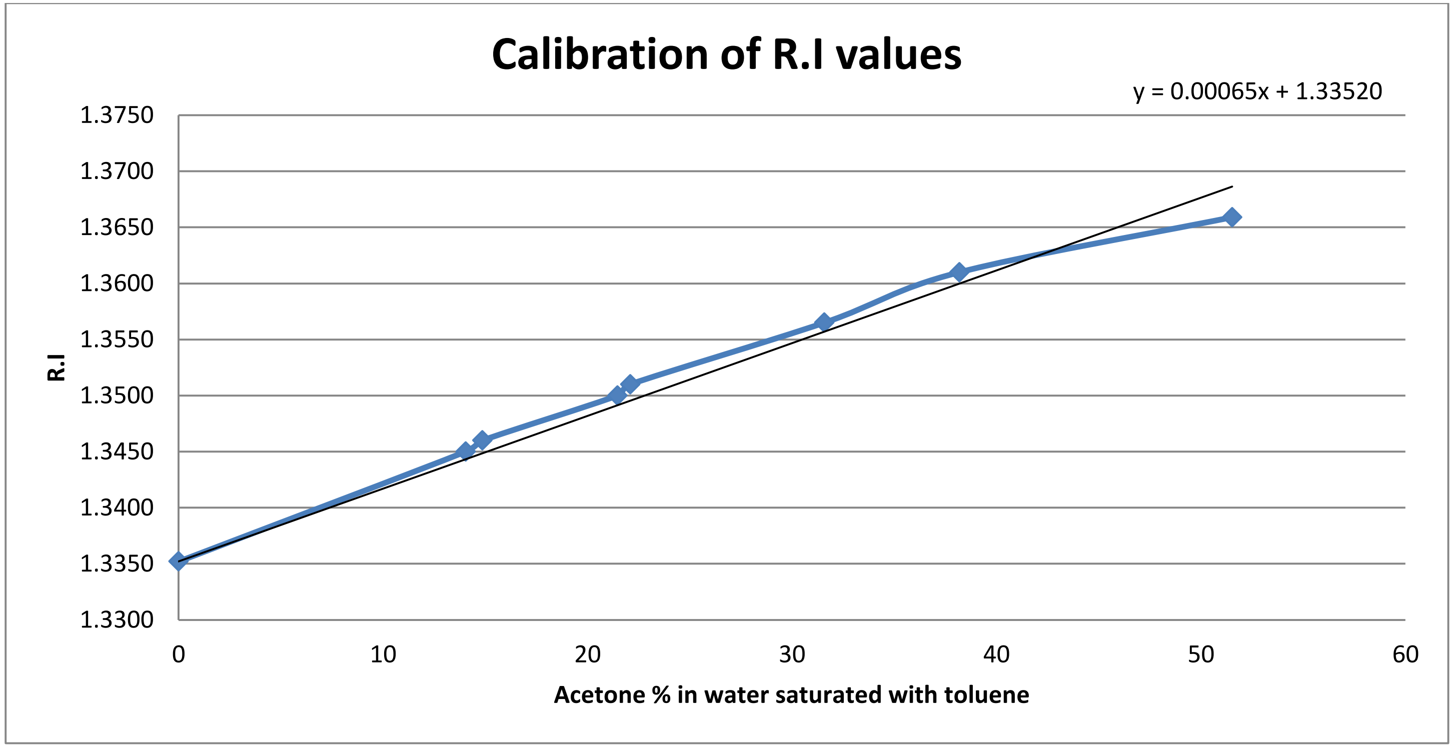

Figure (6): Wt % of Acetone in water saturated with Toluene Vs Refractive Index

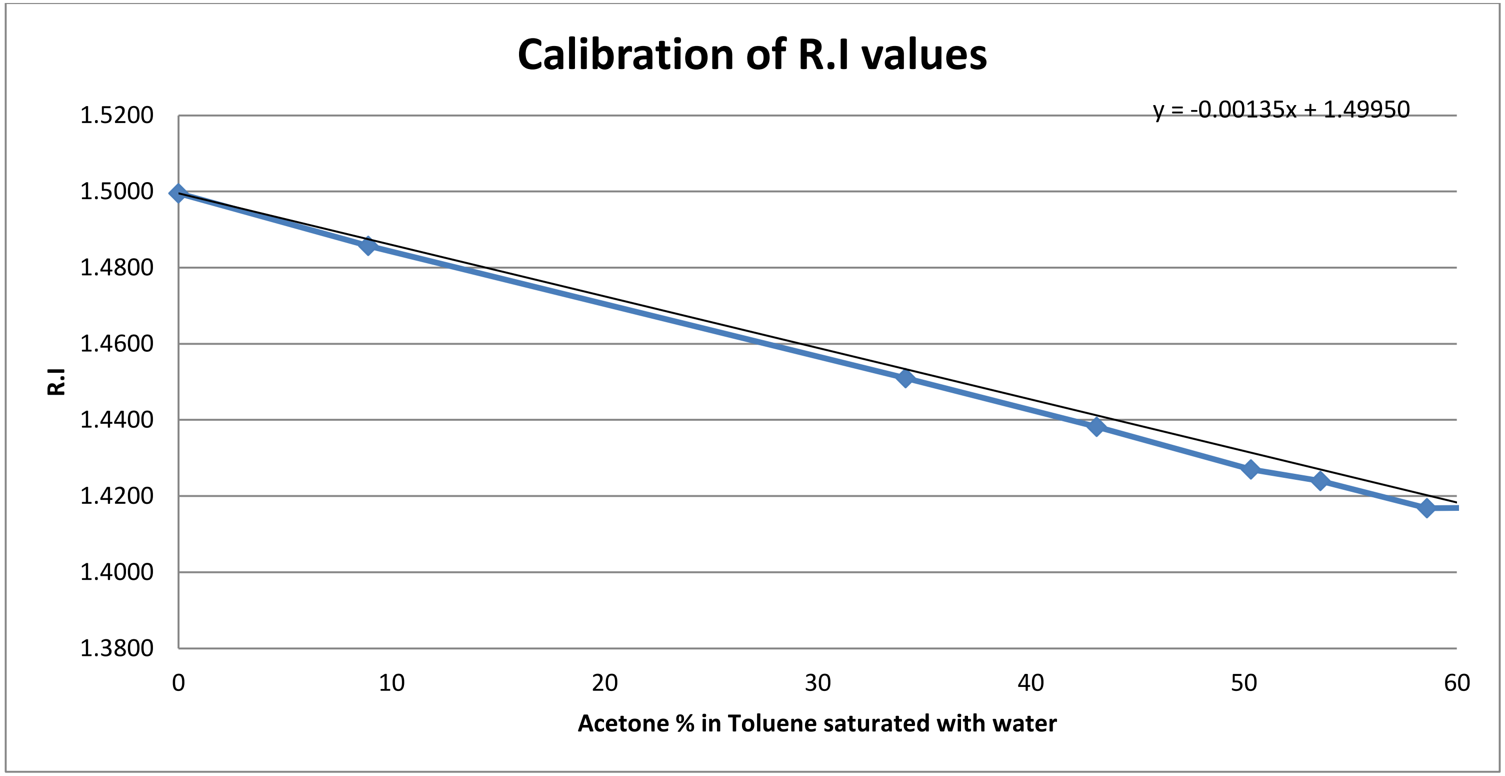

Figure (7): Wt % of Acetone in Toluene saturated with water Vs Refractive Index

Experiment Number -3-

Digital Joulemeter

Equipment

The digital Joulemeter measures electrical energy directly in joules and power in watts. It has clear digital display which is most valuable for many demonstrations.

The instrument can be used with both direct and alternating current. It has four internal shunts to give maximum current ranges of 0.7mA, 7mA, 0.7A, and 7A, with a maximum input of 15V for (a.c.) the voltage maximum for (d.c.) is 20V with corresponding maximum current of 1mA, 10mA, 1A, and 10A. A three position "JOULES" switch applies multipliers of x1, x10, and x100 to the four ranges. In the x1 setting the right hand digit of the display will be counting in the unit written above the blue external load socket in use. In the x10 setting the right hand digit of the display will count in units ten times that written above the socket. In the x100 setting the units will be one hundred times that written.

Experiment 1

Objective

To determine the specific heat capacity of a metal.

Requirements

Power supply unit 12V (a.c.), immersion heater (12V, 50A), Aluminum block, calorimeter, thermometer, micrometer and 4mm plug leads.

Procedure

1. Connect the circuit as shown in figure (9):

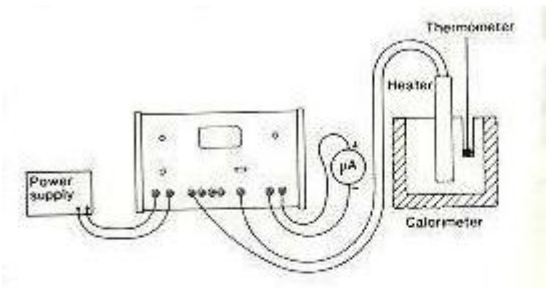

Figure (8): Specific heat capacity of metal circuit.

2. Switch on the heater and once the temperature of the block has risen to about 2ºC reset the joulemeter. When the temperature of the block has risen by about 20ºC read the thermometer and read the joulemeter.

Calculations

Refer to the basic definition of specific heat capacity to calculate it for the metal used.

Experiment 2

Objective

To determine the specific latent heat of vaporization of liquids.

Requirements

An isolated beaker, immersion heater, thermometer, power supply unit, and 4mm plug leads.

Procedure

1. Fill the beaker with a certain amount of the liquid to be tested, put its cover, and then insert the heater and thermometer in it.
2. Connect the circuit as shown in figure (10):

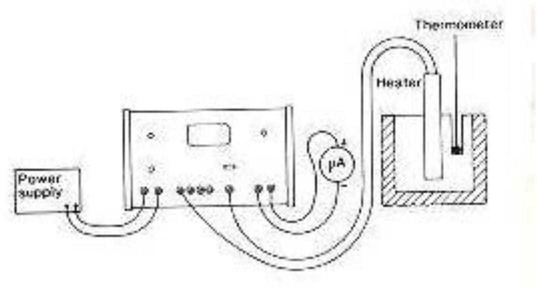

Figure (9): specific heat of vaporization of liquids circuit.

3. Switch on the heater and wait until the liquid boils and record its boiling temperature.
4. Put the beaker on a balance, record the initial weight of the beaker with the liquid in it.
5. Remove the cover of the beaker and let the liquid to vaporize, and then record the final weight of it, and the Joulmeter reading.

Calculations

Refer to the basic definition of specific latent heat of vaporization to calculate it for the liquid used.

Experiment 3

Objective

To investigate the efficiency of a small electrical motor and study its variation with load and applied voltage.

Requirements

Power supply unit (d.c.), electrical motor unit, rheostat (2A, 50A), line shaft unit, load masses, voltmeter (12V), switch (single pole), and 4mm plug leads.

Procedure

1. Connect the circuit as shown in figure (11) using the (d.c.) power supply :

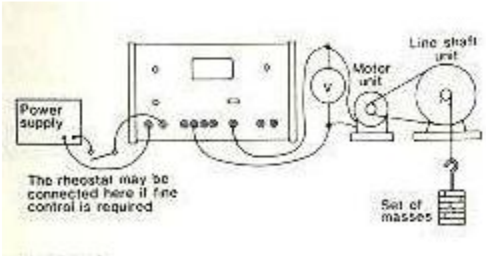

Figure (10): Efficiency of small electrical motor circuit.

2. Adjust the voltage of the power supply until the motor can lift the weight as at a convenient speed.
3. Reset the joulemeter and switch on for as long as it takes the motor to lift the weights through a measured height. Read the voltmeter during the lift.
4. Repeat the experiment at different load masses when the voltage is the same, or at different voltages when the mass lifted remains the same.

Calculations

Calculate the efficiency of the motor, and study its variation with load and applied voltage.

Digital Joulemeter Data Sheet

1. Specific heat Capacity:

Mass of AL-Block	
Joule meter reading	
T_1	
T_2	

2. Specific latent heat of vaporization:

Initial mass of liquid	
Final mass of liquid	
Temperature of liquid	
Joule meter reading	

3. Efficiency of a motor:
   Change in height=……………….cm
   Mass of hanger=………………..g

   a. At constant Voltage=…………..V

Mass lifted (g)	Joule meter reading

   a. At constant mass=…………..g

Voltage (V)	Joule meter reading

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Date:

Experiment Number -4-

Efflux Time for a Tank with Exit Pipe

Objective:

To show the dependence of the efflux time for a tank with exit pipe on pipe length and diameter.

Equipment:

The equipment consists of cylindrical tank, in a vertical position, the bottom outlet being designed to carry one of a number of pipes having a range of internal diameters and lengths. The tank is fitted with a spherical plug valve and a constant level pointer.

Specification:

Tank:
Internal diameter: 160.54mm.
Internal height: 263 mm.

Pipes:	1	2	3	4	5	6
Internal diameter (mm)	5.35	5.35	5.35	2.1	5.35	8.4
Length (mm)	318.4	163.4	87.4	623.4	623.4	623.4

The dimension, (H), (the depth of liquid in the tank) refers to the height of liquid above the bottom (inside) of the tank.

The dimension, (L), is the distance from the inside bottom of the tank to the lower extremity of the pipe. The construction of equipment is such that the dimension, (L), for a particular pipe is the length of that pipe.

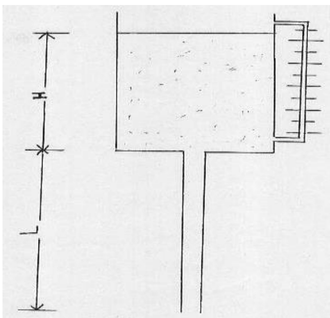

Figure (11): Efflux apparatus.

Theory:

A cylindrical tank, in a vertical position is to be drained through a pipe which is vertically attached to the bottom of the tank. Assuming a quasi steady state momentum balance and ignoring the head loss due to the entrance and exit of the pipe, the pressure drop through the pipe is:

$$\Delta P = 4f.\frac{L}{d}.\frac{\rho.\bar{v}^2}{2} \dots\dots\dots (1)$$

Where:

ΔP: Pressure drop ($N.m^{-2}$).

f: Fanning friction factor, dimensionless.

L: Pipe length, (m).

d: Pipe diameter, (m).

ρ: Liquid density, ($Kg.m^{-3}$).

$\bar{v}$: Time-average velocity through the pipe, ($m.s^{-1}$).

Since the pressure drop, (ΔP), equals (Δh.ρ.g), where (Δh), is the total head on the system (i.e. H+L, where (H) is the depth of liquid in the tank), then:

$$(L+H).\rho.g = 4f.\frac{L}{d}.\frac{\rho.\bar{v}^2}{2}$$

or

$$\bar{v}^2 = \frac{(L+H)g.d}{2.f.L} \dots\dots\dots (2)$$

when laminar flow occurs in the pipe, **(f = 16/Re)** and equation (2) becomes:

or

$$\bar{v} = \frac{(L+H)\rho.g.d^2}{32.\mu.L} \dots\dots\dots (3)$$

when turbulent flow occurs in the pipe, the Blasius equation: **($f = 0.079Re^{-0.25}$)** is applicable and equation (2) becomes:

or

$$\bar{v} = \frac{(L+H)^{4/7}.\rho^{1/7}.g^{4/7}.d^{5/7}}{(0.079\times 2)^{4/7}.\mu^{1/7}.L^{4/7}} \dots\dots\dots (4)$$

where (μ) is the fluid viscosity ($N.s.m^{-2}$).

For an incompressible fluid, flowing under isothermal conditions through a pipe of length (L), equation (4) may be written:

$$\bar{v} = (L + H)^{\frac{4}{7}}.C \dots\dots\dots (4a)$$

where

$$C = [\frac{g.d^{5/4}\rho^{1/4}}{(0.079 \times 2).L.\mu^{1/4}}]^{4/7} \dots\dots\dots (5)$$

when fluid flows through the pipe in the system under consideration the liquid level in the tank decreases and a mass balance gives:

$$\frac{dH}{dt} = -(\frac{d}{D_T})^2.\bar{v} \dots\dots\dots (6)$$

where:

t: time (s).

D_T: tank diameter (m).

Substitution of equation (3) or (4) into equation into equation (6) and subsequent integration gives the efflux time, (t_{eff}), for laminar flow:

$$t_{eff} = \frac{32.\mu.L.{D_T}^2}{\rho.g.d^4}.ln\left[\frac{L + H_1}{L + H_2}\right] \dots\dots\dots (7)$$

where:

H_1: initial depth of liquid in the tank (m).

H_2: final depth of liquid in the tank (m).

For turbulent flow through the pipe, the efflux time is given by substituting and integration:

$$t_{eff} = \frac{7}{3}.\frac{{D_T}^2}{d^2}.\frac{1}{C}.\left[(L + H_1)^{3/7} - (L + H_2)^{3/7}\right] \dots\dots\dots (8)$$

<u>Procedure:</u>

1. Note the room temperature at the beginning and end of the investigation.
2. A mixture of glycerol and water is to be used as the fluid.
3. Use of viscometer to measure the fluid viscosity, and use a 50ml density bottle to determine the density of the fluid.
4. Calculate the drop in liquid level in the tank corresponding to the removal of 1 liter from the tank and hence calculate, (H_2).
5. Connect pipe 1 to the tank base.
6. Insert the plug valve in the base of the tank and fill the tank to about 10mm above the constant level pointer with the mixture.

7. Hold a 1 liter beaker under the end of the pipe, remove the plug valve from its seat and allow the mixture to run into the beaker until the constant level pointer is just uncovered, this establishes full bore pipe flow. Immediately and simultaneously, start a stop watch. When the mixture reaches the 1 liter mark, stop the watch and simultaneously insert the plug valve in its seat.
8. Read the stop watch and record the result.
9. When the mixture has stopped dripping from the pipe, pour the contents of the 1 liter beaker into the tank; check that the tank level is about 10mm above the constant level pointer and if necessary top up with the mixture.
10. Repeat steps 7 to 9 until two results agree to within 1%.
11. Remove pipe 1 and replace with pipe 2.
12. Repeat steps 7 to 10.
13. Repeat steps 11 and 12 for the remaining five pipes.
14. Take of representative sample of the mixture and determine its viscosity.
15. Collect the mixture in the stock bottle.

Calculation:

Remember to show specimen calculations:

1. List; in tabular form the three actual times and their averaged for each pipe.
2. Calculate the time-averaged velocity and hence time-averaged pipe Reynolds number for each combination of pipe and liquid-list in tabular form.
3. Calculate the theoretical efflux time for each combination-list in tabular form.
4. Plot the ratio of experimental efflux time to the calculated efflux time (t_E/t_C) against (L) (i.e. tube length) for constant pipe diameter.
5. Plot the ratio of experimental efflux time to the calculated efflux time (t_E/t_C) against the ratio of tank diameter to tube diameter (D_T/d) for constant pipe length.
6. Confirm the dimensionality of equations (7) and (8).

Reference:

F. A. Holland. "Fluid Flow for Chemical Engineers". Published by Edward Arnold, 1980.

Efflux Time for a Tank with Exit Pipe Data Sheet

	Pipe dimensions	Time (s) Trial number 1	Time (s) Trial number 2
Same diameter	D=5.35mm L=87.4mm		
	D=5.35mm L=163.4mm		
	D=5.35mm L=318.4mm		
Same length	D=8.4mm L=623.4mm		
	D=5.35mm L=623.4mm		
	D=2.1mm L=623.4mm		

H1	
H2	
Room Temperature	
Mass of empty bottle	
Mass of bottle+ water	
Mass of bottle + mixture	
Viscosity	

Instructor signature:
Date:

Experiment Number -5-

Compressible Fluid Flow

Objectives:

For simple pipe friction duct:

1. To investigate the relation between friction loss and velocity for incompressible flow and to find an approximate value for the friction coefficient (f).
2. To investigate the relation between the friction coefficient and the Reynolds number for a given pipe.

For sudden enlargement duct:

1. To investigated the relation between the pressure recovery across a sudden enlargement and the upstream flow velocity assuming the incompressible flow.
2. To investigate the validity of the formula for the pressure rise across a sudden enlargement for compressible flow.

Equipment:

The compressible flow bench consists of a readily interchangeable test sections. The apparatus consists of the following items:

a. Fixed motor driven compressor.
b. Two inclined tube manometers.
c. Two vertical manometers filled with mercury.
d. A 13 mm bore transparent pipe friction test section.
e. A convergent-divergent test section.
f. A sudden enlargement test sections of different diameters.
g. Pipe line orifice test sections of different diameters with a number of interchangeable orifices.
h. A smooth 90^o bend.

Each of the test sections can be mounted on the inlet side of the compressor, the downstream ends of each -section being accurately machined to fit the special housing on the compressor inlet. A track is provided to slide each test section into position, the sections having feet with locking nuts to secure them firmly to the track for an experimental run. Care should be taken to ensure that the inlet nozzles on each test section are free from any neighboring obstacle that might interfere with the smooth passage of air into the test duct.

Theory:

The density of a gas can vary considerably. Equations for compressible flow taking account of density changes are more complex than those for the flow of a liquid in similar situations.

When a gas undergoes changes in pressure which are small in proportion to its absolute pressure, its density changes are also small, and its flow can be treated as incompressible; equations derived for liquids can be applied with accurate results.

The following assumptions are made throughout the subsequent theoretical development:

1. Flow variable are uniform over a cross section perpendicular to the flow direction, i.e. the duct can be considered to be a single stream tube with one dimensional flow.
2. Flow is steady.
3. Potential energy changes are negligible.

The basic equation of fluid flow may then be stated as:

* Continuity equation:

$$\dot{m} = \rho . a . V = constant \ldots\ldots\ldots (1)$$

* Energy equation for flow:

$$\dot{m} . \Delta \left[\frac{P}{\rho} + \frac{V^2}{2} + C_V . T \right] = \dot{Q} - W_{Shaft} - W_{friction} \ldots\ldots\ldots (2)$$

* Momentum equation for cylindrical duct:

$$\dot{m} . dV = \rho . a . V dV = -(adp + \tau_0 . perimeter . dx) \ldots\ldots\ldots (3)$$

* Equation of state for a perfect gas:

$$P = \rho . R . T \ldots\ldots\ldots (4)$$

* Relation between specific heats and gas constant:

$$C_p = C_V + R \ldots\ldots\ldots (5)$$

* Relation between pressure and density for an isentropic process:

$$\frac{P}{\rho^{\alpha}} = constant \text{ , } where \ \alpha = \frac{C_P}{C_V} \ldots\ldots\ldots (6)$$

* In addition for incompressible fluid flow, the usual friction loss equation will be used:

$$\frac{\Delta P}{\rho} = \frac{4 . f . L . V^2}{2 . d} \ldots\ldots\ldots (7)$$

where (ΔP) is the loss of pressure a long a length of cylindrical pipe of diameter (d).

For smooth pipe:

$$f = \emptyset.(Re) \dots\dots\dots (8)$$

where the Reynolds number Re=ρ.v.d/μ……. (9)

- Flow-rate measurement:

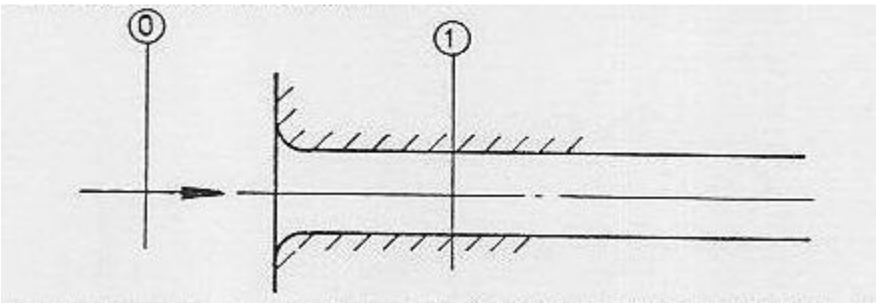

Figure (12): flow rate measurement

The experimental ducts are fitted with intake sections profiled from a plan upstream face into a parallel throat. The flow rate is determined from the pressure drop (P_0-P_1) between still atmospheric conditions and the throat. To a first order of approximation, assuming no losses, work, heat transfer, or density changes between inlet and throat and assuming uniform velocity distribution in the throat, we may write:

$$V_1 = \sqrt{\frac{2(P_0 - P_1)}{\rho_0}} \dots\dots\dots (10)$$

and $$\dot{m} = \rho_0 . a_1 . v_1 = a_1\sqrt{2.\rho_0.(P_0 - P_1)} \dots\dots\dots (11)$$

The errors arising from the above assumption are measurable and more accurate values of (v) and ($\dot{m}$) are obtainable by multiplying (P_0-P_1) by a coefficient k which depends on the Reynolds number at the throat and on the ratio ((P_0-P_1)/P_0). Thus accurate values of (v) and ($\dot{m}$) are given by:

$$v = \sqrt{\frac{2k.(P_0 - P_1)}{\rho_0}} \dots\dots\dots (12)$$

$$\dot{m} = a_1\sqrt{2.\rho_0.k.(P_0 - P_1)} \dots\dots\dots (13)$$

(k) values can be taken from tables 3.1, 3.2, 3.3,and 3.4 on pages 35and 36.

Procedure:

For simple pipe friction duct:

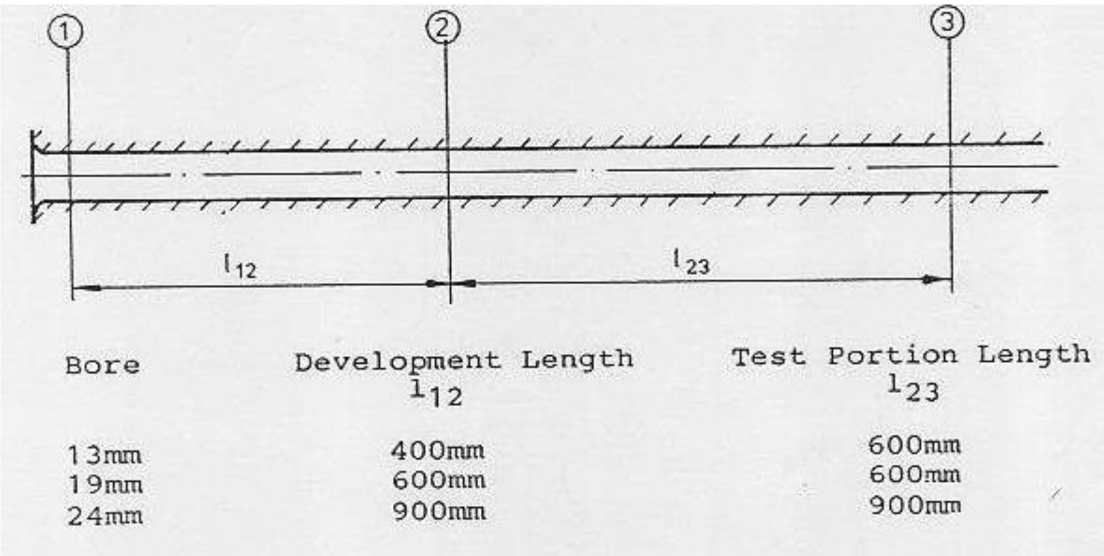

Figure (13): Simple pipe friction duct

1. Connect inclined tube manometer to read (P_0-P_1) and (P_2-P_3). Use the 50.8mm or 25.4mm ranges of the manometers. Vary the flow to give approximately equal increment of (P_0-P_1) and for each flow rate read both manometers.
   The equation which represents this case is:
   $$P_2 - P_3 = \frac{4.f.L}{d}.k.(P_0 - P_1)$$
   where
   L: The test portion length.

2. Connect inclined tube manometer to read (P_0-P_1) and (P_2-P_3). Vary the flow to give approximately equal increment of (P_0-P_1) and for each flow rate read both manometers. Use all manometer settings in turn to obtain the maximum range of test conditions.
   Equations to be used:
   $$Re = \frac{d\sqrt{2\rho}}{\mu}.\sqrt{k.(P_0 - P_1)}$$
   where
   $\rho = \rho_0$ (To be calculated from the ideal gas law using the atmospheric pressure).
   $$\mu_{air} = 1.71 \times 10^{-5}\left(\frac{393}{\emptyset + 393}\right).\left(\frac{\emptyset + 273}{273}\right)^{3/2} \dots\dots (\frac{Ns}{m^2})$$
   where $\emptyset$ is the operating temperature ,(ºC).
   Blasius relation: $f=0.079Re^{-0.25}$.

Kikuradse-Von Karman relationship:

$$\frac{1}{\sqrt{f}} = 4.\log\left(Re.\sqrt{f}\,\right) - 0.396.$$

For sudden enlargement duct:

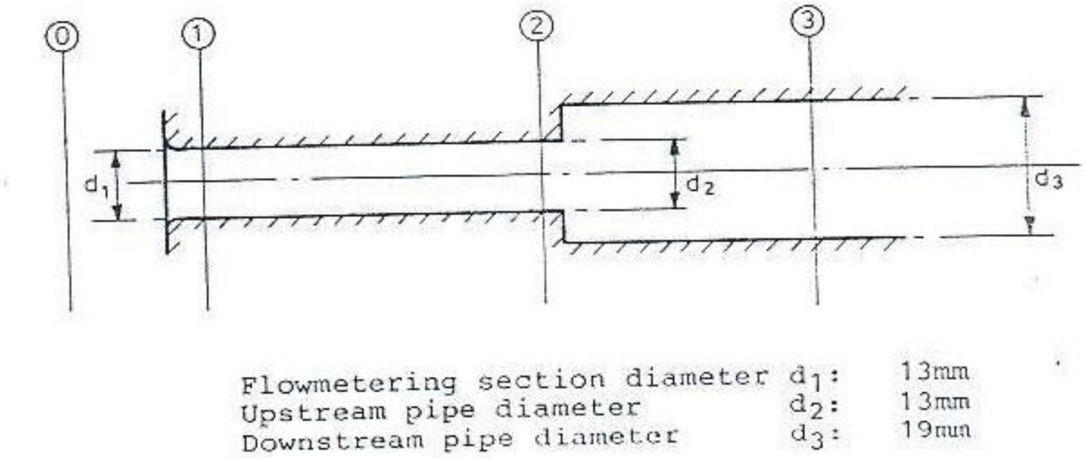

Figure (14): Sudden enlargement duct

1. Connect one inclined tube manometer to read (P_0-P_1) and another to read (P_2-P_3). Vary the flow to give approximately equal increments of (P_0-P_1) and for each flow rate read both manometers.
   The equation to be used:
   $$P_3 - P_2 = k.(P_0 - P_1).2.\left[\frac{a_2}{a_3} - \left(\frac{a_2}{a_3}\right)^2\right]$$
2. Procedure as for 1st experiment (1) above but using the mercury manometer to measure (P_0-P_1) and the 25.4mm range of the inclined tube manometer to read (P_3-P_2).
   The equation to be used is:
   $$\frac{P_3 - P_2}{k.(P_0 - P_1)} = 2.\left[\frac{a_2.\rho_0}{a_3.\rho_2} - \left(\frac{a_2}{a_3}\right)^2.\frac{\rho_0}{\rho_3}\right]$$

Calculation:

For simple pipe friction duct:

1. Plot (P_2-P_3) against k (P_0-P_1) and from the slop deduce value of (f), comment on whether (f) is constant.
2. Plot (log f) against (log Re). Dose the Blasius relation apply?
3. Plot $\frac{1}{\sqrt{f}}$ against $\log(Re.\sqrt{f}\,)$. Dose Nikuradse-Von-Karman relation apply.

For sudden enlargement duct:

1. Plot (P_3-P_2) against k (P_0-P_1). Measure the slope and compare with the theoretical value:
   $2.[\frac{a_2}{a_3} - (\frac{a_2}{a_3})^2]$
2. Plot $(\frac{P_3 - P_2}{k.(P_0 - P_1)})$ against $[\frac{a_2.\rho_0}{a_3.\rho_2} - (\frac{a_2}{a_3})^2.\frac{\rho_0}{\rho_3}]$ and measure the slope and compare with the theoretical value (2).

References:

1. Gean Koplis, " Transport Processes Momentum , Heat and Mass", Allyn and Bacon, 1983.
2. J.M. Coulson and JF Richardson," Chemical Engineering" Vol.1, third edition, 1980, pergamon prss.

Table 3.1

Values of k for inclined tube manometer on 12.7mm range (Bottom)

$d_1$mm / Scale reading KN/m^2	12.7	19.1	25.4	28.6	31.8	38.1	44.5	50.8
0.25	0.85	0.855	0.865	0.865	0.87	0.875	0.88	0.885
0.50	0.855	0.865	0.875	0.875	0.88	0.89	0.895	0.90
0.75	0.86	0.87	0.88	0.885	0.89	0.895	0.905	0.91
1.00	0.86	0.875	0.885	0.89	0.895	0.905	0.91	0.92
1.25	0.865	0.88	0.89	0.895	0.90	0.91	0.915	0.925
1.50	0.87	0.88	0.895	0.90	0.905	0.915	0.92	0.93
1.75	0.87	0.885	0.90	0.905	0.91	0.92	0.925	0.93
2.00	0.87	0.890	0.90	0.905	0.91	0.92	0.93	0.935
2.25	0.875	0.89	0.905	0.91	0.915	0.925	0.93	0.94
2.50	0.885	0.89	0.905	0.91	0.915	0.925	0.935	0.94

Table 3.2

Values of k for inclined tube manometer on 25.4mm range (Mid)

$d_1$mm / Scale reading KN/m^2	12.7	19.1	25.4	28.6	31.8	38.1	44.5	50.8
0.25	0.855	0.865	0.875	0.875	0.88	0.89	0.895	0.90
0.50	0.86	0.875	0.885	0.89	0.895	0.905	0.91	0.92
0.75	0.87	0.88	0.895	0.9	0.905	0.915	0.92	0.93
1.00	0.87	0.89	0.90	0.905	0.91	0.92	0.93	0.935
1.25	0.875	0.89	0.905	0.91	0.915	0.925	0.935	0.94
1.50	0.88	0.895	0.91	0.915	0.92	0.93	0.94	0.945
1.75	0.88	0.90	0.915	0.92	0.925	0.935	0.94	0.945
2.00	0.885	0.90	0.915	0.925	0.93	0.935	0.945	0.95
2.25	0.885	0.905	0.92	0.925	0.93	0.94	0.945	0.95
2.50	0.89	0.905	0.92	0.93	0.935	0.94	0.95	0.955

Table 3.3

Values of k for inclined tube manometer on 50.8mm range (Top)

$d_1$mm / Scale reading KN/m^2	12.7	19.1	25.4	28.6	31.8	38.1	44.5	50.8
0.25	0.86	0.875	0.885	0.89	0.895	0.905	0.91	0.92
0.50	0.87	0.89	0.90	0.905	0.91	0.92	0.93	0.935
0.75	0.88	0.895	0.91	0.915	0.92	0.93	0.94	0.945
1.00	0.885	0.90	0.915	0.925	0.93	0.94	0.945	0.95
1.25	0.89	0.905	0.92	0.93	0.935	0.94	0.95	0.955
1.50	0.89	0.91	0.925	0.93	0.935	0.945	0.95	0.955
1.75	0.895	0.915	0.93	0.935	0.94	0.95	0.955	0.96
2.00	0.90	0.92	0.93	0.94	0.94	0.95	0.955	0.96
2.25	0.90	0.92	0.935	0.94	0.945	0.95	0.955	0.96
2.50	0.90	0.92	0.935	0.94	0.945	0.955	0.955	0.96

Table 3.4

Values of k for inclined tube manometer on 254mm range (Vertical)

$d_1$mm / Scale reading KN/m^2	12.7	19.1	25.4	28.6	31.8	38.1	44.5	50.8
0.25	0.89	0.905	0.92	0.93	0.935	0.94	0.95	0.955
0.50	0.90	0.92	0.935	0.94	0.945	0.955	0.955	0.96
0.75	0.91	0.93	0.945	0.945	0.95	0.955	0.96	0.96
1.00	0.915	0.935	0.945	0.95	0.95	0.955	0.96	0.96
1.25	0.92	0.935	0.945	0.95	0.955	0.955	0.96	0.96
1.50	0.92	0.935	0.945	0.95	0.95	0.955	0.95	0.955
1.75	0.92	0.935	0.945	0.95	0.95	0.955	0.955	0.955
2.00	0.92	0.935	0.945	0.945	0.95	0.95	0.955	0.955
2.25	0.92	0.935	0.945	0.945	0.945	0.95	0.95	0.95
2.50	0.92	0.935	0.94	0.945	0.945	0.945	0.95	0.95

Compressible Fluid Flow Data Sheet

Atm P = …………mmHg.

For simple pipe friction duct:

$(P_0\text{-}P_1)$	$(P_2\text{-}P_3)$

Instructor signature:
Date:

For sudden enlargement duct:

(P_0-P_1)	(P_2-P_3)

Instructor signature:
Date:

Experiment Number -6-

Determination of Losses in Small Bore Piping System

Objective

a. Head Loss In Straight Pipe:

To obtain the following relationships:

1. Head loss as a function of volume flow rate.
2. Friction factor as a function of Reynolds number.

b. Head Loss In Sudden Expansion:

To compare the measured head rise across a sudden expansion with the rise calculated on the assumption of:

1. No head loss.
2. Head loss given by the expression $h_L = \frac{(V_1 - V_2)^2}{2.g}$.

c. Head Loss In Sudden Contraction:

To compare the measured fall in head a across a sudden contraction with the fall calculated in them assumption of:

1. No head loss.
2. Head loss given by the expression $h_L = \frac{K.{V_2}^2}{2.g}$, where (K) is a dimensionless coefficient which depends on the area ratio (A_2/A_1).

d. Head Loss In Bends:

To measure the loss coefficient (K) for five bends (90º miter, 90º elbow, 50mm radius bend, 100mm radius bend, and 150mm radius bend).

e. Head Loss In Valves:

To determine the relationship between loss coefficient and volume flow rate for a globe type valve and a gate type valve.

Equipment

The apparatus shown diagrammatically in figure (16) consists of two separate hydraulic circuits each one containing a number of pipe system components. Both circuits are supplied with water from the same hydraulic bench. The components in each of the circuits are as follows:

Dark Blue Circuit:

1. Gate Valve.
2. Standard elbow bend.
3. 90^o mitre bend.
4. Straight pipe.

Light Blue Circuit:

5. Globe Valve
6. Sudden expansion.
7. Sudden contraction.
8. 152.4mm 90^o radius bend.
9. 50.8mm 90^o radius bend.

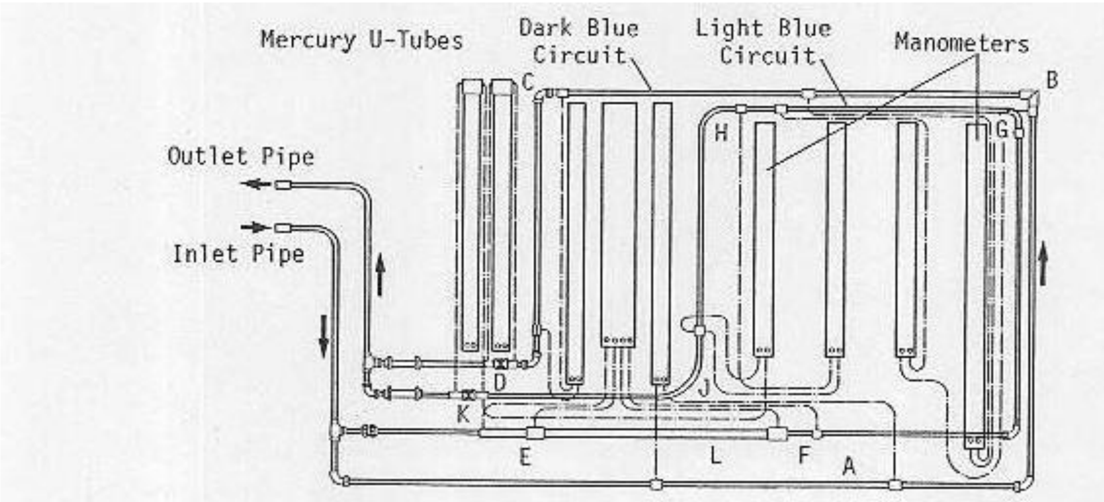

Figure (15): Schematic diagram of losses in pipe apparatus

In all cases (expect the gate and globe valves) the pressure change across each of the components is measured by a pair of pressurized piezometer tubes. In the case of the valves pressure measurement is made by U-tubes containing mercury.

Specification:

1. Straight pipe:
   L=914mm, d_i=13.7mm.
   Pipe material is copper.

2. Sudden expansion:
   d_1=13.7mm, d_2=26.4mm.
3. Sudden contraction:
   d_1=26.4mm, d_2=13.7mm.
4. Bend radius:
   For 90° mitre = 0.
   For 90° elbow = 12.7 mm.
   For 90° smooth bend = 50.8mm.
   For 90° smooth bend = 101.6mm.
   For 90° smooth bend = 152.4mm.

Theory

One of the most common problems in fluid mechanics is the estimation of pressure loss. This experiment enables pressure loss measurements to be made on several small bore pipe circuit components. The head loss in a pipe circuit falls into two categories:

a. That due to viscous resistance extending throughout the total length of the circuit.

b. That due to localized effects such as valves, sudden change in area of flow, and bends.

The overall head loss is a combination of both these categories. Because of mutual interference between neighboring components in a complex circuit, the total head loss may differ from that estimated from the losses due to the individual components considered in isolation.

Loss in Pipes

Consider a fluid flowing with a constant mean linear velocity (U) through a cylindrical pipe of length (L) and inside diameter (d_i). A pressure drop (ΔP) occurs in the pipe because of frictional viscous forces. The latter results in a shear stress (R_w) over the inside surface of the pipe.

A force balance over the pipe with no slip at the wall gives:

$$\Delta P.\frac{\pi.{d_i}^2}{4} = R_w.\pi.d_i.L \dots\dots\dots (1)$$

or

$$\Delta P = \frac{4.R_w.L}{d_i} \dots\dots\dots (2)$$

Rewrite equation (2) in the form:

$$\Delta P = 8\left(\frac{R_w}{\rho.u^2}\right).\left(\frac{L}{d_i}\right).\frac{\rho.u^2}{2} \dots\dots\dots (3)$$

where the term in the first brackets is the dimensionless basic friction factor (j_f). Thus equation (3) can be written as:

$$\Delta P = 8\, j_f.\left(\frac{L}{d_i}\right).\frac{\rho.u^2}{2} \ldots\ldots\ldots (4)$$

The basic friction factor (j_f) is half the Fanning friction factor (f). In terms of (f), equation (4) can be written as:

$$\Delta P = 4\, f.\left(\frac{L}{d_i}\right).\frac{\rho.u^2}{2} \ldots\ldots\ldots (5)$$

But (ΔP) can be written in terms of head loss (Δh_f) as:

$$\Delta h_f = \frac{\Delta P}{\rho.g} = 4\, f.\left(\frac{L}{d_i}\right).\frac{u^2}{2} \ldots\ldots\ldots (6)$$

The friction factor f is a dimensionless constant which is a function of the Reynolds number of the flow and the roughness of the internal surface of the pipe.

Minor Losses

In piping system the losses due to flow through valves or fitting are known as "Minor Losses".

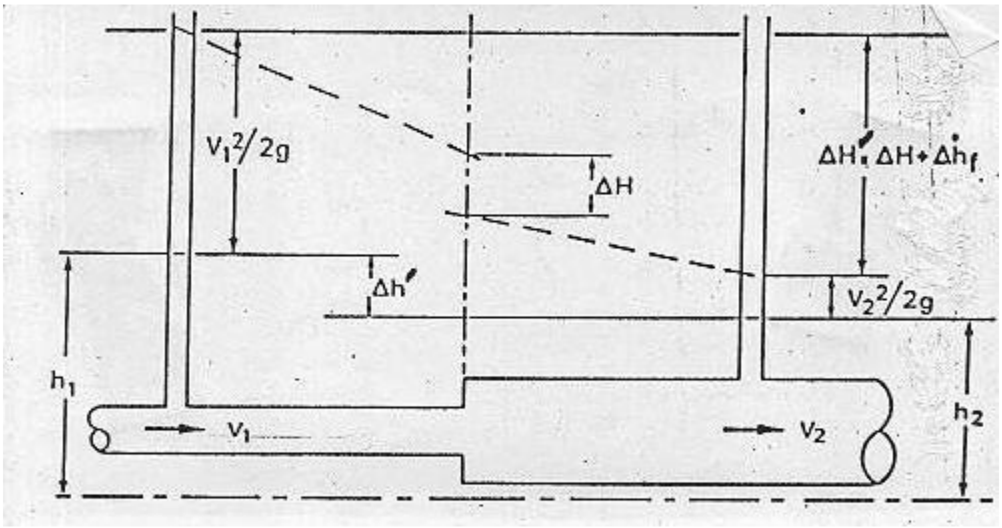

Figure (16): Minor loss in piping system

Considering a general case as shown in figure (17) in which the upstream and the downstream pipe diameters are different, the Bernoullis equation can be written as:

$$h_1 + \frac{{u_1}^2}{2g} = h_2 + \frac{{u_2}^2}{2g} + \Delta H' \ldots\ldots\ldots (7)$$

where ΔH' is the total head loss between the pressure tappings.

The Total head loss has two components:

i. Friction loss (Δh_f) in the upstream and downstream pipes.

ii. Total head loss (ΔH) due to the fitting alone.

Therefore:

$$\Delta H' = \Delta h_f + \Delta H \ldots\ldots\ldots (8)$$

Rewriting equation (7) and noting that (h_1-h_2) is the measured head loss ($\Delta h'$) recorded by the manometers, we have:

$$\Delta H = \Delta h' + \left[\frac{{u_1}^2 - {u_2}^2}{2g}\right] - \Delta h_f \ldots\ldots\ldots (9)$$

Therefore in order to obtain the total head loss due to the fitting alone we have to correct the measured head loss for the change in velocity head and also subtract the head loss due to friction. The total head loss due to the fitting is usually expressed in terms of the loss coefficient (k) defined by:

$$k = \frac{\Delta H}{u^2/2g} \ldots\ldots\ldots (10)$$

Where (u) is the velocity in the smaller pipe.

If the upstream and downstream diameters are the same (as in the case of valves and bends), then (u_1=u_2) and we have:

$$\Delta H = \Delta h' - \Delta h_f \ldots\ldots\ldots (11)$$

Procedure

1. Open fully the water control valve on the hydraulic bench.
2. With the globe valve closed, open the gate valve fully to obtain maximum flow through the Light Blue Circuit.
3. Record the readings on the piezometer tubes and the U-tube manometer.
4. Collect a sufficient quantity of water in the weighing tank to ensure that the weighing takes place over a minimum period of 60 second.
5. Repeat the above procedure for different flow rates, obtained by closing the gate valve, equally spaced over the full flow range.
6. Record the water temperature in the sump tank of the bench using a thermometer.
7. Close the gate valve, open the globe valve and repeat the experimental procedure for the Dark Blue Circuit.
8. Before switching off the pump, close both the globe valve and the gate valve. This prevents air gaining access to the system.

Calculation

1. Straight pipe:
   Plots showing the relationship between the head loss and the flowrate, and the relationship between the friction factor and Reynolds number should be presented for all measurements. The graph should also show the theoretical relationships.
2. Sudden Expansion:
   Plot (h_2-h_1) measured vs. (h_2-h_1) calculation.
3. Sudden Contraction:
   Plot (h_2-h_1) measured vs. (h_2-h_1) calculation.
4. Bends:
   Plot (k) vs. reduced bend radius (r/D) (bend radius/ pipe diameter).
5. Valves:
   Plot the loss coefficient vs. percent volume flowrate for both valves.

Conclusion

1. Dose the radius of curvature of a pipe bend have a significant influence on the head loss through it?
2. Do the loss coefficients vary with the flowrate?
3. How do your values of (k) compare with standard data?
4. Which type of valve would you choose for a low loss piping system?

References

1. Gean Koplis, "Transport Processes Momentum, Heat and Mass", Augn and Bacon, 1983.
2. J.M. Coulson and FF Richardson," Chemical Engineering" Vol.1, Third Edition, 1980, pergamon prss.

Determination of Losses in Small Bore Piping System
Data Sheet

For Gate valve

H_2-H_1 Gate valve	1-2 Std Elbow 90	3-4 Straight pipe	5-6 Miter bend 90	Mass (kg)	Time (s)

For Globe valve

H_2-H_1 Globe valve	7-8 Sudden expansion	9-10 Sudden contraction	11-12 Radius bend 100	13-14 Radius bend 150	15-16 Radius bend 50	Mass (kg)	Time (s)

Instructor signature:
Date:

Experiment Number-7 -

Pitot Tube Experiment

Objective

1. To measure the radial velocity profile for flow of air in a pipe
2. To determine mean velocity and volumetric and mass flow rates using either the radial velocity profile or the orifice discharge equation and to check the agreement between them.
3. To identify if the flow regime is laminar or turbulent based on the resulted velocity profile and Reynolds number.

Equipment

The apparatus consists of an electrically driven fan which draws air through a control valve and discharges into a 76.2 mm diameter U-shaped pipe. A British standard orifice plate 40 mm diameter is fixed in this pipe to measure the air flowrate. This pipe is connected to a copper test pipe which is 3048 mm long, 32.6 mm internal diameter, and discharges to atmosphere. A Pitot tube is traversed across the diameter of the test pipe. Its position at any point is read directly from a combined linear scale and a varnier. The Pitot tube measures the stagnation pressure only, the associated static pressure being sensed at a tapping point in the wall of the pipe. The difference between the two pressures is measured by a different ial water manometer mounted on the panel. The whole assembly is mounted on a small flange secured to the pipe in such a position that the plane of the piezometer opening is at a distance of 276 mm from the discharge end of the pipe.

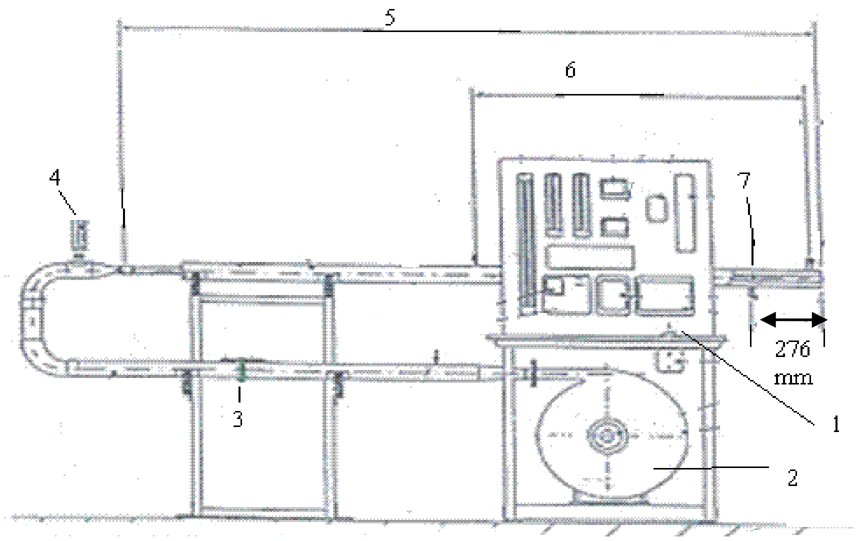

Figure (17): General arrangement of apparatus including Pitot tube assembly.

1. Main on/off switch
2. Fan
3. Orifice (40 mm diameter)
4. Thermometer
5. Copper test pipe (32.6 mm diameter, 3048 mm long)
6. Test length 1524 mm
7. Pitot tube

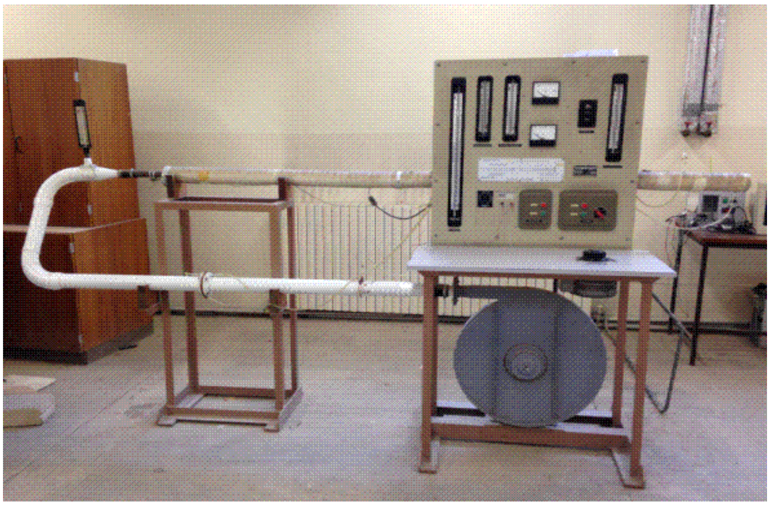

Figure (18): View of the actual apparatus

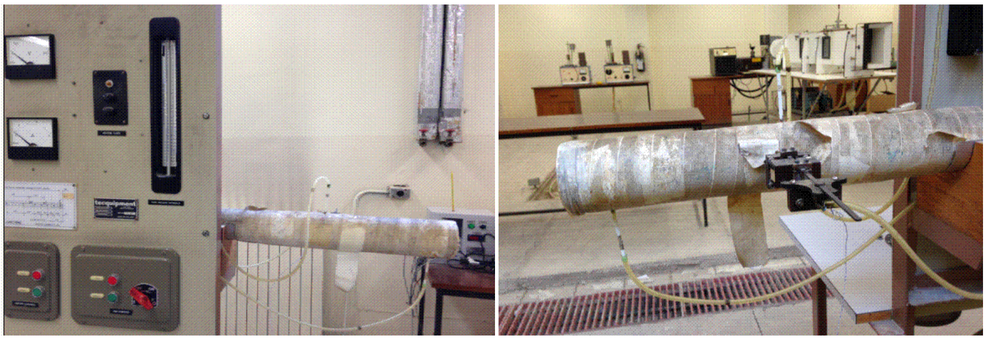

Figure (19): Pitot tube assembly front and rear views

Theory

A pitot tube is a device that measures velocity of flow at a specific location. It consists of a hollow tube positioned so that the open end points directly into the fluid stream.

When a moving fluid is caused to stop because it encounters a stationary object (i.e Pitot tube tip) a pressure is created (Stagnation pressure) which is greater than the pressure of the fluid stream (Static pressure). The magnitude of this increased pressure is related to the velocity of the moving fluid by the energy equation.

Air velocity at a point in the pitot plane, i.e local velocity, (m/s):

$$v = \sqrt{2(P_s - P)/\rho} \quad \text{.........................(1)}$$

Where:

P_s: Stagnation pressure (N/m^2)

P: Static pressure (N/m^2)

ρ: Air density in pitot tube plane (Kg/m^3)

Average air velocity in the pipe (m/s):

$$\bar{v} = \frac{W}{\rho \pi R^2} \quad \text{……………..} \quad (2)$$

Where:

ρ: Air density in the pipe (Kg/m3)

R: Pipe radius (m)

W: Mass flow rate (Kg /s)

Air mass flow rate (W) is calculated using the following discharge equation:

$$W = \rho \times \text{Orifice area} \times C_d \times \sqrt{2\Delta p / \rho} \quad \text{……….(3)}$$

Where,

Δp: pressure drop across the orifice (N/m^2)

C_d: Orifice discharge coefficient (0.613)

ρ: Air density at the orifice (Kg/m^3) which can be calculated using the ideal gas law (ρ=P/RT) where R=287.05 N.m/(kg.K)

Note that

The static pressure in the pitot plane can be taken as:

Barometric pressure + (276/1524)*test length pressure drop

Air pressure at orifice is:

Barometric pressure + Fan pressure

Procedure

1. Switch on the fan with inlet valve fully open.
2. Wait 10 minutes until system reaches steady state conditions.
3. Take the following readings:
   a) Pitot pressure at 2 mm intervals across the section of the pipe.
   b) Fan pressure.
   c) Pressure drop across the orifice plate.
   d) Pressure drop over the Test length.
   e) Atmospheric pressure and air temperature.

Calculations

1. Calculate the mass flow rate using the discharge equation, Eq. no. 3
2. Calculate the average air velocity in the pipe using equation no. 2
3. Calculate the local velocity using equation no.1
4. Plot the radial velocity profile (local velocity (v) vs radial location (r)).
5. Plot (v*r) vs. r and use the plot together with the following definition to find the mass flow rate:

$$W = \rho Q = \rho \int_0^R v dA = \rho Q = 2\pi \rho \int_0^R v r dr$$

6. Use this mass flow rate to calculate the air average velocity.
7. Compare the results of discharge Eq. with the corresponding results using graphical method.
8. Calculate the average Reynolds number using:

$$\mathrm{Re} = \frac{\rho \bar{v} D}{\mu}$$

9. Is the flow laminar or turbulent? Why?

References

1. Clayton T. Crowe, Donald F. Elger, John A. Roberson, *Engineering Fluid Mechanics*, John Wiley & Sons, 9th edition, 2010.
2. Noel de Nevers, *Fluid Mechanics for Chemical Engineers*, McGraw-Hill, 3rd edition, 2005.
3. Mohammad Al-Shannag, *Fluid Mechanics Course Handouts*.

Pitot tube Data Sheet

Atmospheric Pressure: ……………………………………

Air Temperature: ……………………………………………

Fan Pressure: …………………………………………………..

Pressure drop across the Orifice: …………………………………….

Pressure drop over the Test length: …………………………………

Pitot Tube position (mm)	Vernier reading (mm)	Pressure Difference (P_S – P) (mmH_2O)

Experiment Number -8-

Positive Displacement Pumps Characteristics

Objective

To demonstrate how pumps work and show the performance of a selection of positive displacement pumps at constant and variable speeds.

Apparatus

The apparatus consists of the Positive Displacement Pump Module, the Universal Dynamometer, an optional pump (a Vane pump is used here) and TecQuipment's Versatile Data Acquisition System (VDAS). Figure (1) shows the apparatus with its main parts.
The Positive Displacement Pump Module uses oil as the working fluid. The Universal Dynamometer turns the pump which in turn forces the oil around a circuit. The oil comes from an oil reservoir, through an inlet valve and through the pump. It then passes through a pressure relief valve and a delivery valve. It then passes through a gear-type flowmeter and back to the oil reservoir.
Electronic pressure transducers in the circuit measure the oil pressures at the inlet to the pump and at the outlet. A thermocouple mesaures the oil temperature and a flowmeter measures the oil flow in the circuit.
The trancducers, the thermocouple and the flowmeter all connect to a digital display that shows the pressures, temperature and flow.
The TecQuipment's Versatile Data Acquisition System (VDAS) will display, store, chart and export all the important readings from the tests.

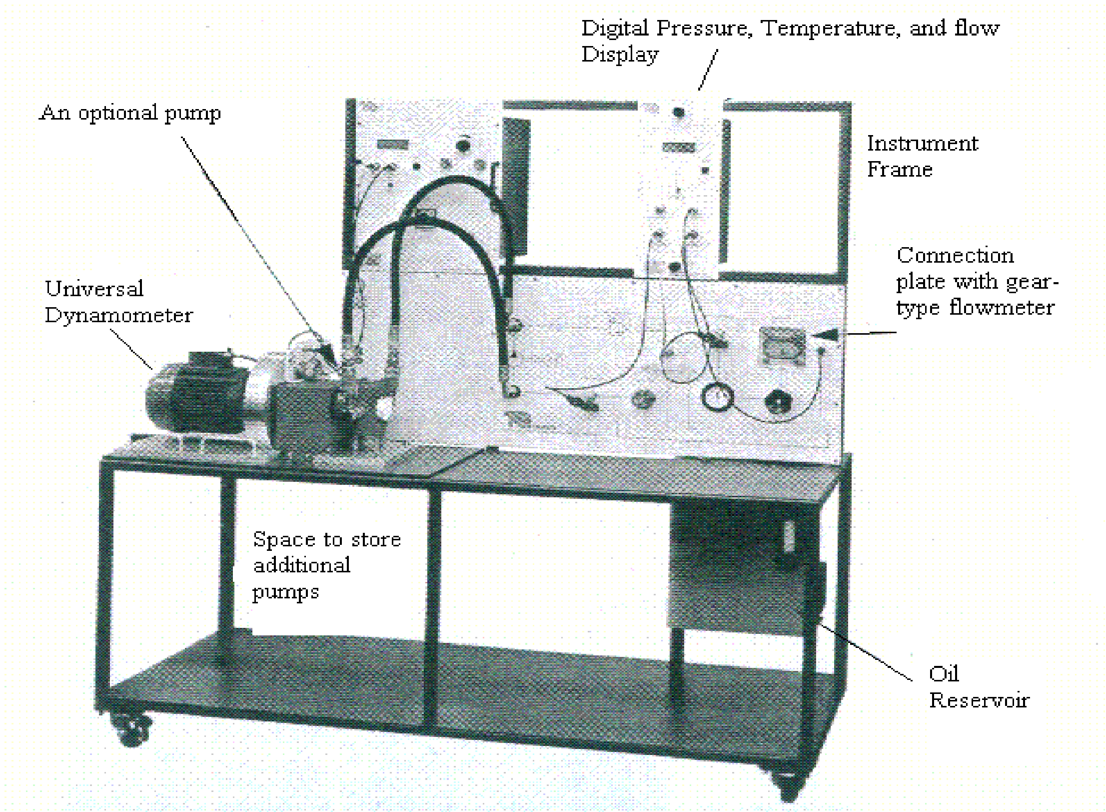

Figure (20): The Positive Displacement Pump Module with its main parts.

Theory

The pressure increase (or head) and flow rate caused by a pump are its two most important qualities. Next most important are its efficiency and power needs. Different types of pumps are designed to process fluids under variable engineering condition.

The pressure increase is simply the difference between the pressures before and after the pump. The flow rate is the amount of fluid that passes through the pump.

Mechanical power (into pump):
This is simply the shaft power at the pump (W_D).

Hydraulic power (from the pump):
The hydraulic power that the pump adds to the fluid is a product of the flow through the pump and the increase in pressure it gives.

$$W_P\ (kW) = (p_2 - p_1) * Qv \quad \ldots\ldots\ldots (1)$$

Where:
$(p_2 - p_1)$: Delivery pressure-suction pressure (Pa).
Qv : Volumetric flow rate (m^3/s).

Overall pump efficiency:

$$\eta p = (W_P / W_D)*100 \quad \ldots\ldots\ldots (2)$$

Volumetric efficiency:
Volumetric efficiency= (Actual volumetric flow rate/Expected volumetric flow rate)* 100

$$\eta v = [\, Qv / (V_S * N_P)\,] * 100 \ldots\ldots\ldots (3)$$

Where:
V_S : Swept volume (cm^3/rev).
N_P: Speed of the pump (rev/min).

Procedure

1. Turn the "Positive Displacement Pump Module" on.
2. To start the software, double click the "TecQuipment VDAS" icon on the desktop. Then click the "connection" button to connect the software to the device.
3. In the" Pump Information" section, fill the pump type and (cc/rev) depending on the type of pump connected to the module.
4. The experiment consists of three parts, follow the instructions illustrated in each part carefully. **And before you start always do the following:**
   a. Fully open the inlet and delivery valves.
   b. Use the button on the pressure display to zero all pressure readings.
   c. Zero the torque reading of the MFP100 Universal Dynamometer.

Part 1: The Effect of Delivery Pressure at Constant Speed.

Aim:
To find how the pump performs for a range of delivery pressures (varied load) at a constant speed.

Procedure

1. Press the start button of the Motor Drive and run the speed to 1600rpm (+/- 5 rpm) for at least five minutes and monitor the oil temperature until it stabilizes. Check that any air bubbles have moved away from the flow meter.
2. Slowly shut the delivery valve and maintain the speed until the delivery pressure reaches 2 bar. Allow a few seconds for conditions to stabilize. Click on the record data values button, to record all data automatically (use 15 seconds time intervals).
3. Continue increasing the delivery pressure in 1 bar steps (while keeping the speed constant) to a maximum of 15 bar. At each step. Allow a few seconds for conditions to stabilize.
4. Take a print out of the results that contains speed, shaft power, swept volume, inlet and outlet pressures and flow rate readings.

5. At the end of test, fully open the delivery valve and slowly decrease the speed to zero before you stop the motor.
6. Repeat the test at two other lower speeds. 1200 rpm and 800 rpm are recommended.

Results Analysis:

At each speed:

1. Find the pressure differences across the pump and calculate the hydraulic power.
2. Calculate the expected flow for the speed of your test and the overall and volumetric efficiencies.
3. Plot curves of (flow rate, shaft power, volumetric and overall efficiencies) against pressure difference and discuss your results.
4. Compare the results at different speeds.

Part 2: The Effect of Speed at Constant Delivery Pressure.

Aim:

To find how the pump performs for a range of speeds at a constant delivery pressure (load).

Procedure:

1. Press the start button of the Motor Drive and run the speed to 1600 rpm (+/- 5 rpm) and run the pump for at least five minutes and monitor the oil temperature until it stabilizes.
2. Wait for any trapped air bubbles to move away from the flowmeter before you continue.
3. Slowly shut the delivery valve and maintain the speed until the delivery pressure reaches 15 bar.
4. Allow a few seconds for conditions to stabilize, then click on the record data values button, to record all data automatically (use 15 seconds time intervals).
5. Reduce the speed by 100 rpm steps while adjusting the delivery pressure to keep it constant at 15 bar until you reach 800 rpm. At each step, allow a few seconds for conditions to stabilize.
6. Take a print out of the results that contains speed, shaft power, swept volume, inlet and outlet pressures and flow rate readings.
7. At the end of test, fully open the delivery valve and slowly decrease the speed to zero before you stop the motor.
8. Repeat the test at two other lower fixed delivery pressures. 5 and 10 bar values are recommended.

Results Analysis:

At each delivery pressure:

1. Find the pressure differences across the pump and calculate the hydraulic power.
2. Calculate the expected flow for each speed and the overall and volumetric efficiencies.
3. Plot curves of (flow rate, shaft power, volumetric and overall efficiencies) against pump speed and discuss your results.
4. Compare the results at different delivery pressures.

Results Analysis:

1. Find the pressure differences across the pump and calculate the hydraulic power.
2. Calculate the expected flow for the speed of your test and the overall and volumetric efficiencies.
3. Plot curves of (flow rate, shaft power, volumetric and overall efficiencies) against the inlet pressure.

References:

1. F.A. Holland, "Fluid Flow for Chemical Engineers ", Arnold, 1980.
2. J.M. Coulson and FF Richardson," Chemical Engineering" Vol.1, Third Edition, 1980, Pergamon Press.

Experiment Number -9-

Comparative Fluid Flow Measurement

Objective:

1. Application of Bernoulli's equation for incompressible fluid.
2. Determination of the discharge coefficient (C_d) of an orifice meter and a venturi meter at different Reynolds numbers (Re).
3. Comparison of pressure drops across the orifice meter and the venturi meter.
4. To construct a calibration curve for the rotameter.

Equipment:

1. Hydraulic Bench.
2. Flow measuring apparatus.
3. Stop watch.
4. Manometers.

Water enters the apparatus through the lower left hand end in fig (20) it flows first through the venturi meter, then through the orifice meter and so through the rotameter. On leaving the Rotameter, water flow via a control valve to the weigh–tank of the Hydraulics Bench.

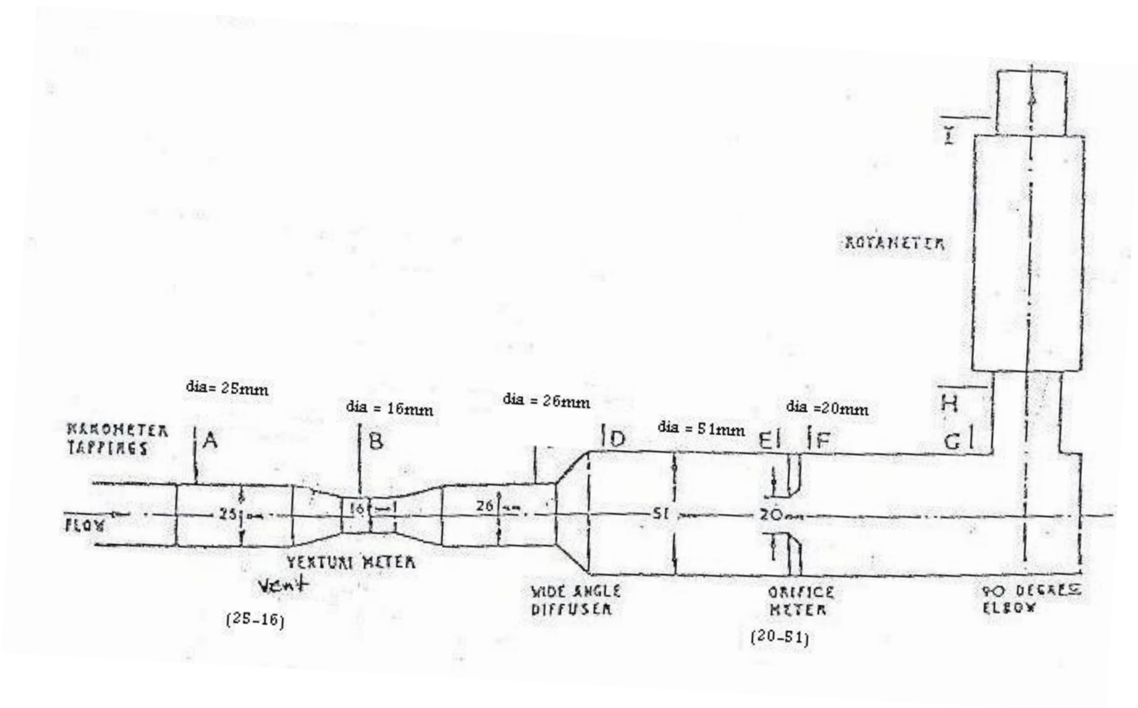

Figure (21): Schematic diagram for flow measurement apparatus

Theory:

The venturi meter, the orifice plate meter and the Rotameter are all dependent upon Bernoulli's equation, for their principle of operation. Bernoulli's equation is given by:

$$\frac{P_1}{\rho.g}+\frac{{u_1}^2}{2.g}+z_1=\frac{P_2}{\rho.g}+\frac{{u_2}^2}{2.g}+z_2+\Delta h_{12} \ldots\ldots\ldots (1)$$

Where (Δh_{12}) is head loss due to friction and localized effects (area change or fitting).

In order to obtain the total head loss due to fitting we therefore have to correct the measured head loss for the change in velocity head also substract the head loss due to friction:

$$\Delta H=(h_1-h_2)+\frac{{u_1}^2-{u_2}^2}{2.g}-\Delta h_f \ldots\ldots\ldots (2)$$

where $\Delta h_{12}=\Delta H+\Delta h_f \ldots\ldots\ldots (3)$

where (ΔH) is the head loss due to fitting and (Δh_f)is the head loss due to friction. If the length is small, (Δh_f) can be neglected. The head loss is usually expressed in terms of the loss coefficient (K) defined as:

$$k=\frac{\Delta H}{\left({u^2}/{2g}\right)} \ldots\ldots\ldots (4)$$

where (u) is the velocity in the smaller pipe:

a. Venturi Meter:
   Since(Δh_{12}) is negligibly small between the ends of a contracting duct application of equation (1) between pressure tapping's (A) and (B) gives:

$$\frac{P_A}{\rho.g}+\frac{{u_A}^2}{2.g}=\frac{P_B}{\rho.g}+\frac{{u_B}^2}{2.g} \ldots\ldots\ldots (5)$$

   and since, by continuity:

$$\dot{m}_A=\rho.u_A.A_A=\dot{m}_B=\rho.u_B.A_B \ldots\ldots\ldots (6)$$

   Sub (6) into (1) to get:

$$u_B=\left[\frac{2g}{(1-(A_B/A_A)^2)}\times\left(\frac{P_A}{\rho.g}-\frac{P_B}{\rho.g}\right)\right]^{\frac{1}{2}} \ldots\ldots\ldots (7)$$

   Now
   $Q_{Th}=A_B.u_B$

$$Q_{Th} = A_B.\left[\frac{2g}{(1-(A_B/A_A)^2)} \times \left(\frac{P_A}{\rho.g} - \frac{P_B}{\rho.g}\right)\right]^{\frac{1}{2}} \dots\dots\dots (8)$$

This is theoretical valve.

$$Q_{act} = C_v.A_B.\left[\frac{2g}{\left(1-\left(\frac{A_B}{A_A}\right)^2\right)} \times (h_A - h_B)\right]^{\frac{1}{2}} \dots\dots\dots (9)$$

where (Q_{act}) is the actual flow rate.
(C_v) may found from experiment.

b. Orifice Meter:
The head losses (Δh_{12}) in equation (1) is by no means negligible when applied between (E) and (F). Rewrite the equation with the appropriate symbols.

$$\frac{{u_F}^2}{2.g} - \frac{{u_E}^2}{2.g} = \frac{P_E}{\rho.g} - \frac{P_F}{\rho.g} \dots\dots\dots (10)$$

Reducing equation (10) in exactly the same way as for venturi meter, the following equation will be obtained:

$$Q_{act} = C_d.A_F.\left[\frac{2g}{\left(1-\left(\frac{A_F}{A_E}\right)^2\right)} \times (h_E - h_F)\right]^{\frac{1}{2}} \dots\dots\dots (11)$$

where C_d is the coefficient of discharge.

Procedure:

1. Stand the apparatus on the top of the hydraulic bench, connect the bench supply hose to the inlet pipe and secure it with clip. Connect a hose to the outlet pipe and put the other end of the hose into the hole leading to the bench weighing tank.
2. Open the outlet valve, then switch on the bench pump and open the bench supply valve to admit water to the apparatus.
3. Partly close the outlet valve so that water is driven into the manometer tube. The carefully close both valves so that you stop the flow while keeping the level of water in the manometer somewhere within the range of the manometer scale.
4. Level of apparatus by adjusting the levelling screws until the manometer read the same level.
5. Open the valves and carefully adjust each one in turn until you open the maximum differential reading (h_A-h_B), and (h_E-h_F), while keeping all the water

levels within the range on the manometer scale. If necessary adjust the general level by pumping air into the reservoir or releasing air from it.

6. Record the manometer reading h_A, h_B, h_E, h_F, and Rotameter reading.
7. Measuring the flow rate by timing collection of water in the each weighing tank.
8. Tabulate your results as shown in data sheet table.

Calculation:

1. Calculate (C_v), (C_d), (ΔH), and k for each of (Q).
2. Plot (ΔH) against ($u^2/2g$).
3. Plot (C_v), (C_d), against Re.
4. Which type of flow meter would you choose for a low loss piping system?
5. Plot the actual flow against the rotameter scale reading.

References:

1. F.A. Holland, “Fluid Flow for Chemical Engineers ", Arnold, 1980.
2. J.M. Coulson and FF Richardson," Chemical Engineering" Vol.1, Third Edition, 1980, pergamon press.
3. W.L. McCabe and J.C. Smith, “Unite Operations of Chemical Engineering”, 3rd Edition, 1976.

Comparative Fluid Flow Measurement Data Sheet

Atmospheric pressure: ……………………..

Atmospheric temperature: ………………….

Scale	Time(sec)	h_A (mmH_2O)	h_B (mmH_2O)	h_E (mmH_2O)	h_F (mmH_2O)

Instructor signature:	
Date:	

Experiment Number -10-

The Performance of a Radial Fan

Objective:

To examine the performance of a radial flow rotor in air over a wide range of operating conditions for impeller with radial blades.

Equipment:

The apparatus consists of:

1. Single stage radial flow fan equipped with interchangeable impellers with forward-curved, backward and radial blades.
2. A variable speed D.C. electric motor with swinging field dynamometer.
3. Counter for speed measurements.
4. Three single column manometers.
5. Standard 75mm nozzle.

The fan draws air from the atmosphere through a measuring nozzle, a flow straightener and diffuser, while the fan discharge into the atmosphere is regulated by a throttle valve.

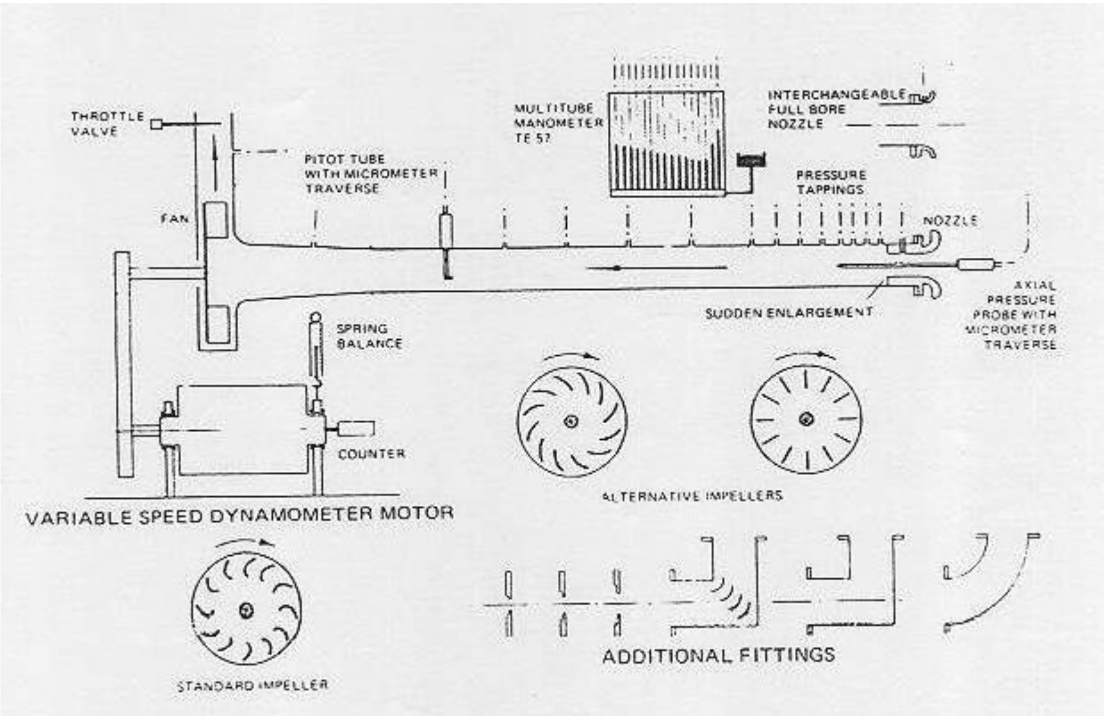

Figure (18): Schematic diagram for radial fan apparatus

Theory:

Any pumping job can be done with roto-dynamic machines, having rotating elements called impellers. Roto-dynamic machines are classified as radial, mixed (centrifugal) or axial flow. Centrifugal machines are preferred when high pressure differences are required. Very high pressure may be produced by multi-stage radial flow machines. The air compressor for a jet engine is an example of multi-stage fan.

The fan total pressure is defined as the different between the total pressure at fan outlet and fan inlet i.e. it is a measure of the total pressure difference imposed on air by fan. In this apparatus the cross sectional area at inlet and exit of the fan are equal. It follows that velocity heads at inlet and outlet are equal and the fan total pressure is equal to the difference between the corresponding static pressures.

Fan total pressure = outlet static pressure – inlet static pressure.

$$\Delta P_s = \rho . g . (h_{out} - h_{in}) \dots \dots \dots (1)$$

$$\Delta P_s = 98.1 \frac{\frac{N}{m^2}}{1 cm H_2O} \times (h_{out} - h_{in})\ cm\ H_2O \dots \dots \dots (2)$$

The velocity (u) developed by a gas of density (ρ) expanding freely from rest under the influence of a pressure difference (P) when (P) is sufficiently small (as in the present case) for compressibility to be neglected is given by:

$$\frac{\rho . u^2}{2} = P \dots \dots \dots (3)$$

The pressure difference (h) is measured in centimeters of water and since (1cm H_2O=98.1N/m^2) equation (3) becomes:

$$\frac{\rho . u^2}{2} = 98.1 \left(\frac{\frac{N}{m^2}}{cm\ H_2O} \right) \times h\ (cm\ H_2O) \dots \dots \dots (4)$$

The density of air under pressure (Pa) (atmospheric pressure), and at temperature (T) is given by the ideal gas equation:

$$\rho = \frac{Pa}{R.T} \dots \dots \dots (5)$$

where R =287 J/kg air . K

Substitute equation (5) in equation (4) and calculate (u):

$$u = \left(\frac{2 \times 98.1 \times h}{\rho} \right)^{1/2} = \left(\frac{2 \times 98.1 \times h \times RT}{P_a} \right)^{1/2}$$

$$u = 273.3 \left(\frac{h.T}{P_a} \right)^{\frac{1}{2}} \dots \dots \dots (6)$$

The volumetric rate of flow at inlet (atmospheric pressure) is then given by:

$$Q\left(\frac{m^3}{sec}\right)=\frac{\pi.d^2}{4}\times k\times 273.3\ \left(\frac{h.T}{P_a}\right)^{\frac{1}{2}}\ldots\ldots\ldots(7)$$

where (k) is the discharge coefficient of the nozzle. For the fitted nozzle (75mm), (k=0.96), so equation (7) becomes:

$$Q\left(\frac{m^3}{sec}\right)=\frac{\pi.d^2}{4}\times 0.96\times 273.3\ \left(\frac{h.T}{P_a}\right)^{\frac{1}{2}}\ldots\ldots\ldots(7)$$

$$Q=1.16\left(\frac{h.T}{P_a}\right)^{\frac{1}{2}}\ldots\ldots\ldots(8)$$

where :

h:is the fall in static pressure across the nozzle measured, (cmH_2O).

T: is the air temperature measured, (k).

P_a: is the atmospheric pressure, (N/m^2).

The total air power of the fan or the useful work done is equal to the product of fan total pressure and volumetric rate of flow.

$$Air\ Power=98.1(h_{out}-h_{in})\times Q\ldots\ldots\ldots(9)$$

The power input from the dynamometer is given by:

$$Shaft\ power=I.\frac{N}{K}\ldots\ldots\ldots(10)$$

where:

I: Torque = Load * r.

N: Angular velocity.

K: Brake constant, assuming k = 1.

The losses in the driving belt and fan bearing may be measured by driving the fan with impeller removed and subtracting the resulting loss from the shaft power to give the impeller power.

$$The\ net\ efficiency=\frac{Total\ air\ power}{Impeller\ power}\ldots\ldots\ldots(11)$$

Procedure:

The fan is to run at a series of constant speeds not exceeding 3000 rev/min, and the flow rate is to be varied in each test by means of the throttle valve. Measure the speed (N), torque (I) by noting the balancing force, the pressure rise (H) generated by the fan (i.e. h_{out} - h_{in}) measured by the manometers. For each run keep (N) constant and alter the throttle from open to fully shut, thus changing (I),(H),and (Q).

Calculation:

1. Plot (h_{out} - h_{in}), total air power, against (Q) for each fan speed.
2. Plot (h_{out} - h_{in})/N^2, total air power /N^3, and (η) against (Q/N).
3. Comment on any points of general interest which arise from the test results.
4. Can this type of fan test be used to predict the performance of a geometrically similar pump proposed for drainage scheme?

References:

1. F.A. Holland, “Fluid Flow for Chemical Engineers ", Arnold, 1980.
2. J.M. Coulson and FF Richardson," Chemical Engineering" Vol.1, Third Edition, 1980, pergamon press.

The Performance of a Radial Fan Data Sheet

Speed:……………..

Temperature:……………….

Atmospheric pressure:…………….

Gate opening , %	h_1 Inlet	h_2 Suction	h_3 Discharge	Force
100				
90				
80				
70				
60				
50				
40				
30				
20				
10				

Instructor signature:
Date:

The Performance of a Radial Fan Data Sheet

Speed:……………..

Temperature:……………….

Atmospheric pressure:…………….

Gate opening , %	h_1 Inlet	h_2 Suction	h_3 Discharge	Force
100				
90				
80				
70				
60				
50				
40				
30				
20				
10				

Instructor signature:
Date

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