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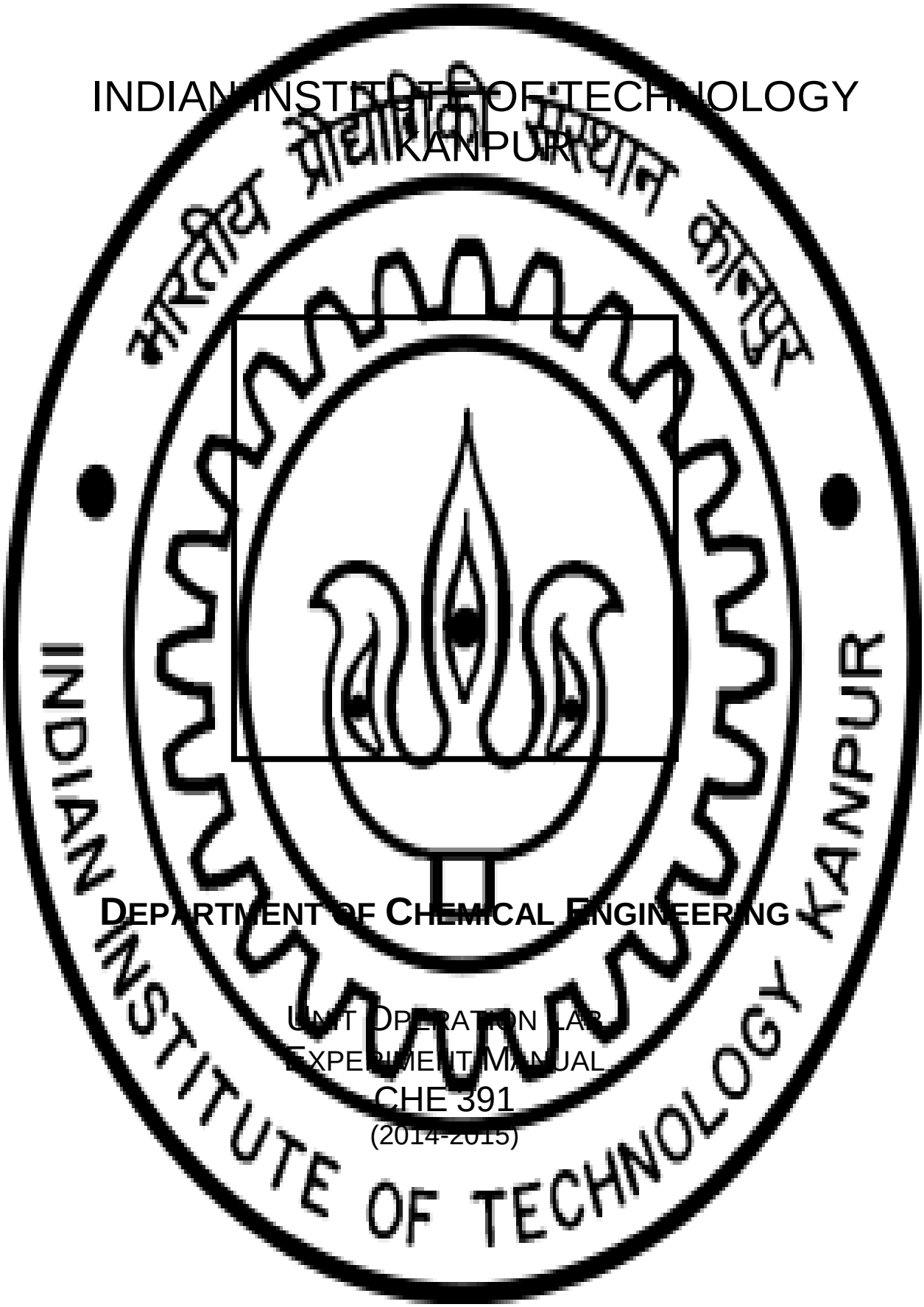


DEPARTMENT OF CHEMICAL ENGINEERING

UNIT OPERATION LAB
EXPERIMENT MANUAL
CHE 391
(2014-2015)

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

DEPARTMENT OF CHEMICAL ENGINEERING

UNIT OPERATION LAB

EXPERIMENT MANUAL

CONTENTS

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

Department of Chemical Engineering

Unit Operation Lab

The laboratory course helps the student to understand and verify by experimental work, some of the basic laws and principals in the field of chemical engineering that is fluid flow, heat transfer, mass transfer, thermodynamics etc. The course help the students to devise his own experiments, and generate data whenever it is not readily available in the literature the ideas gained in the laboratory course or long lasting and hazy notion will be dispelled by performing the experiments further the laboratory course also helps the student in developing the communication skills throw effective report writing –clear and concise reports which adequately describe the purpose of work ,the method adopted, the observations and conclusion. The engineers mostly work in groups and hence it is essential to develop inter personal skill such as communicating the ideas, planning the task, working in cooperation and in arriving at a decision. Therefore a student is considered to have under gone a satisfactory training in chemical engineering only when he is exposed to a good laboratory course.

General Instructions

1. The CHE-391 class will be divided in to groups of three students. Each group will be held responsible for the condition of the apparatus.

2. A schedule of experiments will be assigned which will be strictly followed .each group will perform a total of 11 experiments in the semester.

3. Once the experiments are assigned, the students should come prepared with sufficient background concerning the experiments .the relevant theory the procedure and data analysis should be known before starting the experiments. For some experiments instruction manual have been supplied with the instruments. The should be carefully read before starting the experiments.

4. Before starting the experiments

- **a.** Study the experimental setup thoroughly
- **b.** Plan the experiment properly –the sequence of operation to be perform and the data to be recorded

c. Get the required material issued from the laboratory assistance.

5. All data recorded on the lab record sheets- (8½"x11") plane sheets. At the completion of the experiment, obtain the signature of the instructor in charge or the teaching on the lab record sheet

6. After the completion of the experiments

a. Shut off the experiment.

b. Clean the equipment and the surrounding area

c. Close all the valve and switch off electrical connection

d. Return the material issued to you each group will be held responsible for the loss /breakage of any equipment clean all glassware before returning the same.

7. The detailed lab report (one per group) should be submitted in the proper format at the beginning of the next laboratory session.

a. The first lab should be submit in the folder in which the subsequent report will be placed

b. Used thesis size bond paper (8½"x11") for writing the reports .all reports must be return in ink (blue or blue black or black only) on one side of paper only. Any variation in the above will not be entertained.

c. The lab record should contain the original lab record sheet (with raw data) singed by the instructor in charge or teaching assistance.

d. Late submission of lab report is strictly not allowed.

8. The following format should be followed while writing the lab reports.

a. Title of the experiment

b. Introduction -should include the importance of the topic and the application of the results

c. Objective of the experiment –should clearly indicate what is the purpose

of doing the experiments

d. Theory –a brief statement of the relevant theory which forms the background of the experiment. All relevant equation should be included. Do not copy verbatim from the laboratory manual.

e. Experimental Apparatus and Procedure

A description of the apparatus with a neat sketch, together with the important relevant dimensions should be included in this section. A brief outline of the procedure indicating the sequence of operations should be given.

f. Results and Discussion

The relevant results should be presented in either tabular or graphical form

> The raw data should be included in the appendix.

> Sample calculations should be shown in detail indicating clearly each of the steps, assumptions made, source of physical properties etc.

> Discussion should indicate the reasons for the deviations from the expected trends, the nature and effect of the errors involved. As far as possible, the experimental results should be compared with published literature values or standard correlations. Any result which needs to be emphasized should be discussed with possible explanations.

> Any auxiliary problem which arises from the experiment and which can be investigated with minor modifications of the existing experimental set-up should be indicated. Recommendation for improvements in the experimental set-up and suggestions for future work can also be included.

g. Conclusions

This part should briefly indicate what conclusions can be made from *your* experimental data and analysis of this data.

h. Nomenclature

All symbols used in the report should be defined, *with proper units*. The symbols should be listed in alphabetical order, with Greek Letters listed at the end. Refer to any text book or the experiments in this manual.

i. References

The details of all references including the names of all the authors, referred to in the text should be given here. The references are listed alphabetically in the authors' names. Refer to any standard journal such as Industrial and Engineering Chemistry Research or AIChE Journal.

j. Answer the questions given in the write up of the experiment.

h. Appendix

> Raw data should be included here.

> Any computer listings and outputs should be given here whereas the main results obtained from the computer are shown in the Results and Discussion section.

> Details of any repetitive calculations.

Some General Rules of Report Writing:

1. As far as possible use third person, passive voice. For example, instead of writing '*we took a beaker*', write '*a beaker was taken*'.

2. All equations, tables and figures should be numbered. Moreover, each table or figure should have a caption. Any table or figure included in the report, should have been referred to in the text.

3. Do not use significant figures indiscriminately.

4. References in the text should be cited using author, year convention. For articles having one or two authors use the names of all authors followed by the year (e.g., Smith, 1975; Anderson and Thomas, 1981). In case, the citation has more than two authors then in the text give the surname of the first author followed by et al.(e.g. Smith et al., 1989). However, the names of all the authors should be given in the reference list. In case of any doubt, refer to journals such as Industrial and Engineering Chemistry Research or AIChE Journal.

SUGGESTED GUIDELINES FOR SAFE WORKING IN THE LABORATORY

A laboratory is built at a considerable cost to enable the students to understand and appreciate the fundamental laws and principles of chemical engineering. It is the responsibility of every student to use the facilities in the best possible manner for the benefit of all the students, including the succeeding generation of students. Many of the accidents that occur in a laboratory can be prevented by observing the safe working norms in a laboratory. Some of the suggestions for safe working in a laboratory are listed below for your reference.

1. Smoking is strictly prohibited in the laboratory.
2. Do not put on loose clothing.
3. While working in a laboratory, you should wear shoes only. No one will be allowed to wear slippers in the laboratory.
4. The following precautions should be observed when using electrical gadgets.
   (a) Use proper switches, sockets, adaptors and holders for electrical connections.
   (b) Do not insert naked wires in wall plugs.
   (c) Before starting the equipment, check if the equipment is properly grounded. If the unit is not properly grounded, it may give an electric shock.
   (d) No electric cable should be left hanging in the air. All cables should be fastened to a frame or wall.
   (e) Test a new electric gadget for leakage before use. Phase tester is available with the laboratory assistant. If any electrical defect is noticed, report it at once to the laboratory assistant.
5. The laboratory is provided with a first aid kit. In case of minor injuries, have these treated at once. In case of serious cases, notify the doctor immediately and summon the ambulance. Dial 7666/7777, health centre for ambulance.
6. In case of chemical burns, the affected area should be immediately cleared of the harmful chemicals as quickly as possible.
7. If acid gets spilled on the ground or work bench, it should be immediately neutralized by spraying sodium bicarbonate.
8. Do not use any tool with which you are not familiar. You may injure yourself and damage the tool. In case of doubt consult the laboratory staff.

9. Use the right kind of tool for specific job. Do not use a screw driver as a chisel or as a stirrer. Do not use a hammer to drive screws.

10. Do not use pipe wrenches on brass valves, nuts and bolts. Pipe wrenches should be used to tighten pipes only.

11. Never dismantle any other equipment for accessories like fittings, rotameters, pumps, thermometers etc. which you may require. Consult the laboratory staff for your requirement of materials.

12. Never lean on frames, work benches or equipment.

13. In case of fire, immediately inform the security office (Tel no. 7999) for assistance.

14. Do not spill water on the work benches, and floor. All water connections should be checked for leakage. Each water outlet should be connected to the drain.

EVALUATION:

The laboratory course will be evaluated based on the lab reports, weekly viva voce and final examination which may be conducted in the lab. The tentative weight ages for these will be as follows:

Lab reports	60
Viva Voce	10
Final Examination	30
Total	**100**

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

Department of Chemical Engineering

Unit Operation Lab

Experiment Name: Losses due to pipe fitting, sudden expansion and contraction, straight pipe and flow measurement by orifice meter

1. Objective:

To study the losses of head due to various fittings in pipelines, friction in straight pipe.

2. Aim:

2.1 To determine the loss of head in the fittings at the various water flow rates.
2.2 To determine the loss co-efficient for the pipe fittings.
2.3 To determine friction co-efficient for flow through straight pipe.
2.4 To determine co-efficient of discharge for orifice meter.

3. Introduction:

Loss of head due to change in cross-section, bends, elbows, valves and fittings of all types fall into the category of minor losses in pipe lines. In long pipe lines the friction losses are much larger than these minor losses and hence the latter are often neglected. But, in shorter pipelines their consideration is necessary for the correct estimate of losses.

4. Theory:

When there is any type of change in pipe like bend, expansion etc, the velocity of flow changes, due to which the separation of the flow from the boundary changes and also formation of eddies, takes place. Thus the energy is lost. These fittings such as elbows, tees, valves and reducers represent a significant component of the pressure loss in most pipe systems. These pressure losses of some minor equipment and pipe fittings can be calculated using the K-value method, also known as the Resistance Coefficient or Velocity Head.

The basic approach to calculate loss in piping systems is to write the Bernoulli equation between two points, connected by a streamline, where the conditions are known. For example, between the surface of a reservoir and a pipe outlet.

The K-value, Resistance Coefficient, Velocity Head or Excess Head method allows the user to characterize the pressure loss through fittings in a a pipe. The K-value represents the multiple of velocity heads that will be lost by fluid passing through the fitting.

It is more accurate than the Equivalent Length method, as it can be characterized against varying flow conditions (i.e. Reynolds Number). However it is less accurate than other methods as it does not take into account the varying geometries of fittings at different sizes. These K-values also generally assume fully developed turbulent flow, and thus are inaccurate at low Reynolds Numbers.

Formula for Calculating Head Loss from K Values:

$K = f\frac{L}{D}$, where L/D is equivalent length.

The losses of head due to fittings in pipe:

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

The minor losses in contraction can be expressed as:

$$h_L = K_L \frac{V_1^2}{2g}$$

The minor losses in expansion can be expressed as:

$$h_L = K_L \frac{(V_1 - V_2)^2}{2g}$$

Where

h_L = Minor loss or head loss
K_L = Loss coefficient
V = Velocity of fluid.
V_1 = Velocity of fluid in pipe of small Diameter.
V_2 = Velocity of fluid in pipe of large Diameter.

Straight Pipe:

It is found that the total friction resistance to fluid flow depends on the following:
1. The area of the wetted surface
2. The density of the fluid
3. The surface roughness
4. It is independent of the fluid pressure
5 .It increase with the square of the velocity

The loss of head in pipe due to friction is calculated from Darcy-Weisbach equation which has been given by:

$$h_f = \frac{4 f L V^2}{2 g d}$$

h_f = Loss of head due to friction
f = Friction factor
L = Distance between pressure point
V = Mean velocity of fluid
d = Diameter of pipe
g = Acceleration due to gravity

5. Description:

The apparatus consist of three pipes with different fittings. Bend, sudden expansion, sudden contraction, Globe valve and elbow are provided at upper pipe. Gate valve, straight pipe and Tee is provided at middle pipe. The lower pipe consists of Ball valve and Orifice meter. Pressure tapings are provided at inlet and outlet of these fittings at suitable distance. A differential manometer fitted in the line gives head loss. Supply to the pipeline is made through centrifugal pump, which deliver water from sump tank. The flow of water in pipes can be regulated by the valve provided at the end for each pipe. Discharge is measured with the help of Rota meter.

6. Utilities Required:

6.1 Electricity Supply: Single Phase, 220 V AC, 50 Hz, 0.5 kW with earth connection
6.2 Water supply
6.3 Drain Required
6.4 Floor Area Required: 1.5 m x 0.75 m
6.5 Mercury (Hg) for manometer (250 gm)

7. Experimental Procedure:

7.1 Starting Procedure:

7.1.1 Close all the valves provided.

7.1.2 Fill Sump Tank ¾ with clean water and ensure that no foreign particles are there.

7.1.3 Fill manometer with mercury up to half of its level by opening the PU pipe from the fitting connected to the bottom most point of the manometer and connect the pipe back to its position.

7.1.4 Open by-pass valve.

7.1.5 Ensure that ON/OFF Switch given on the panel is at OFF position.

7.1.6 Switch ON the main power supply.

7.1.7 Switch ON the pump.

7.1.8 Open flow control valve of, upper pipe (for bend, sudden enlargement, sudden contraction, Globe valve, elbow and Tee flow 180^o or middle pipe (for gate valve, pipe friction and Tee flow 90^o) or lower pipe (for Ball valve and orifice meter).

7.1.9 Open the pressure taps of manometer of related test section, very slowly to avoid the blow of water on manometer fluid.

7.1.10 Now open the air release valve provided on the manometer, slowly to release the air in manometer.

7.1.11 When there is no air in the manometer, close the air release valves.

7.1.12 Adjust water flow rate in desired section with the help of control valve and by pass valve.

7.1.13 Record the manometer reading.

7.1.14 Record the flow of water, by Rotameter.

7.1.15 Repeat same procedure for different flow rates of water, operating control valve and by-pass valve.

7.1.16 Repeat the experiment for other fittings of selected pipe.

7.1.17 When experiment is over for test section of selected pipe, open the by-pass valve fully. Then close the flow control valve of pipe and open the control valve of other pipe.

7.1.18 Repeat same procedure for selected test section and so on.

7.2 Closing Procedure:

7.2.1 When experiment is over, close the pressure taps of manometer

7.2.2 Switch off pump.

7.2.3 Switch off power supply to panel.

7.2.4 Drain the apparatus completely with the help of drain valves provided.

8. Observations and Calculations:

DATA:

g	=	9.81 m/s^2		
d_1	=	d_p	=	0.016 m
d_2	=	0.028 m		
d_o	=	0.008 m		
L	=	1 m		
ρ_m	=	13600 kg/m^3		
ρ_w	=	1000 kg/m^3		
ρ_{CCl4}	=	1590 kg/m^3		

OBSERVATION:

Test Section = ---------- (Bend, Sudden enlargement, Sudden contraction, Elbow, Gate valve, Tee, Globe valve, Straight pipe, Orifice meter)

OBSERVATION TABLE:

S.No	h_1, cm	h_2, cm	F_L, LPH
1.			
2.			
3.			

CALCULATIONS:

$Q = \frac{F_L}{1000 \times 3600}$, m^3/sec = ---------- m^3/sec

$h = \frac{h_1 - h_2}{100}$, m = ---------- m

$h_L = h\left(\frac{\rho_m}{\rho_w} - 1\right)$, m = ---------- m

$a_1 = \frac{\pi}{4} d_1^2$, m^2 = ---------- m^2

$a_2 = \frac{\pi}{4} d_2^2$, m^2 = ---------- m^2

$V_1 = \frac{Q}{a_1}$, m/sec = ---------- m/sec

$V_2 = \frac{Q}{a_2}$, m/sec = ---------- m/sec

$K_L = \frac{2g\,h_L}{V_1^2}$ = ---------- **(**For Sudden contraction, Bend, Elbow, Gate valve, Globe valve or Tee)

$K_L = \frac{2g\,h_L}{(V_1 - V_2)^2}$ = ---------- (For sudden enlargement)

$f = \frac{h_L\,2g\,d_1}{4LV_1^2}$ =---------- (For pipe friction)

$a_p = \frac{\pi}{4} d_p^2$, m^2 = ---------- m^2 (For orifice meter)

$a_o = \frac{\pi}{4} d_o^2$, m^2 = ---------- m^2 (For orifice meter)

$Q_t = \frac{a_p \times a_o \times \sqrt{2 \times g \times h_L}}{(a_p^2 - a_o^2)}$, m^3/sec = ---------- (For orifice meter)

$C_d = \frac{Q}{Qt}$ = ---------- (For orifice meter)

9. Nomenclature:

a_1	=	Cross-sectional area of Small diameter Pipe, m^2.
a_2	=	Cross-sectional area of Large diameter Pipe, m^2.
a_p	=	Cross-sectional area of Pipe for orifice meter, m^2.
a_o	=	Cross-sectional area of orifice, m^2.
C_d	=	Co-efficient of discharge for orifice meter.
d_1	=	Diameter of small pipe, m.
d_2	=	Diameter of large pipe, m.
d_p	=	Diameter of pipe for orifice meter, m.
d_o	=	Diameter of orifice, m
F_L	=	Flow rate of water through test section, LPH.
f	=	Friction coefficient of straight pipe.
g	=	Acceleration due to gravity, m/sec^2
h	=	Manometer difference, m
h_1, h_2	=	Manometric reading at both points, cm
h_L	=	Head loss, m of water
K_L	=	Loss coefficient.
L	=	Length of pipe between pressure taping, m.
Q	=	Discharge, m^3/sec.
Q_t	=	Theoretical discharge for orifice meter, m^3/sec.
V_1	=	Velocity of fluid in pipe of Small Diameter, m/sec.
V_2	=	Velocity of fluid in pipe of Large Diameter, m/sec.
ρ_m	=	Density of manometer fluid (Hg), kg/m^3
ρ_w	=	Density of water, kg/m^3

10. Precaution and maintenance Instructions:

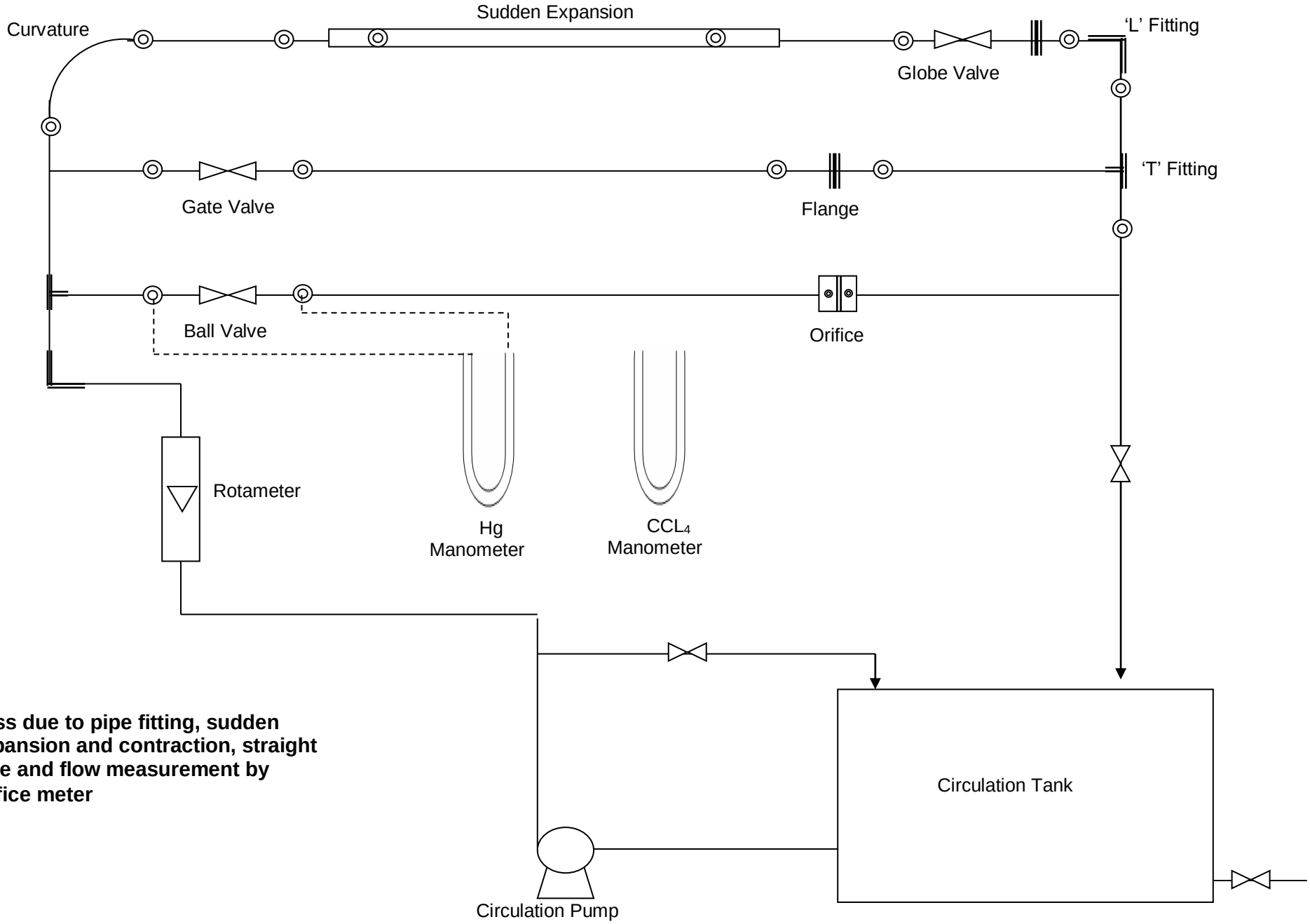
10.1. Never run the apparatus if power supply is less than 180 volts and above 230 volts.
10.2. Never fully close the flow control valves and by-pass valve simultaneously.
10.3. To prevent clogging of moving parts, Run Pump at least once in a fortnight.
10.4. Always keep apparatus free from dust.
10.5. Keep the flow rate low in case of orifice meter and globe valve to avoid high pressure drop.

11. Troubleshooting:

11.1 If pump gets jam, open the back cover of pump and rotate the shaft manually.
11.2 If pump gets heat up, switch OFF the main power for 15 minutes, avoid closing the flow control valve and by pass valve simultaneously, during operation.

12. References:

12.1 V.L.Streeter, E.B.Wylie, "Fluid Mechanics", 1st ed., McGraw Hill, NY, 1983, Page 134-135, 243-246, 347-349.
12.2 W.Mcabe J.Smith, "Unit Operation Of Chemical Engineering", 7th ed., McGraw Hill, NY, 2005, Page 121-124.
12.3 Dr. P.N.Modi & P.N.Seth, "Hydraulics & Fluid Mechanics Incluiding Machines," 15th ed., Rajinder K umar Jain, ND, 2005, Page 458-459.
12.4 https://neutrium.net/fluid_flow/pressure-loss-from-fittings-excess-head-k-method/



Loss due to pipe fitting, sudden expansion and contraction, straight pipe and flow measurement by orifice meter

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

Department of Chemical Engineering

Unit Operation Lab

Experiment Name: Drag Coefficient Apparatus

1. Objective:

Study of dynamic forces on a solid particle moving through a liquid

2. Aim:

(a) To determine the Drag Coefficient.
(b) To plot the graph between Drag coefficient vs Particle Reynolds's Number

3. Introduction:

In fluid flow there is a transfer of momentum which gives rise to a tangential stress or drag on a smooth surface that is oriented parallel to the flow direction. This is called skin drag. In addition to this, friction losses occur because of acceleration & deceleration of fluid. The accelerative effects occur when the fluid changes its path to pass around a solid body set in the flow path. This phenomenon is known as form drag.

4. Theory:

Under gravitational field, the motion of a particle through a fluid is due to the density difference between the particle and the fluid. Consider the motion of a spherical particle of diameter d_p, density ρ_p, through a fluid of viscosity μ and densityρ.

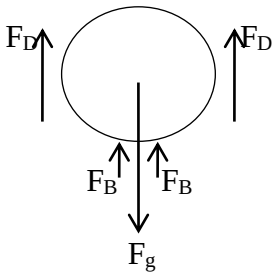
Various forces acting on the particle are:

- External force F_g
- Buoyancy force F_B
- Drag force F_D

$$F = m\left(\frac{du}{dt}\right) = F_g - F_B - F_D$$

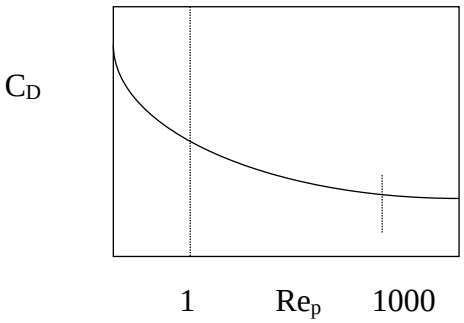
$$F_g = m\,g$$

$$F_B = m\left(\frac{\rho}{\rho_P}\right)g$$



$$F_D = \frac{C_D\,u^2\,\rho\,A_P}{2}$$

m = Mass of the spherical particle
A_p = Projected Area
u = Particle velocity



$$\frac{du}{dt} = g(\rho_\rho - \rho)\rho_\rho - (C_D u^2 \rho A_P)/2m$$

At terminal velocity condition

$\left(\frac{du}{dt} = 0, u = u_t\right)$

For a spherical particle the eqn. reduces to:

$$u_t = \sqrt{\frac{4g(\rho_\rho - \rho)d_P}{3C_D\rho}} \qquad u_t^2 = \frac{4g(\rho_\rho - \rho)d_P}{3C_D\rho} \qquad C_D = \frac{4g(\rho_\rho - \rho)d_P}{3u_t^2\rho}$$

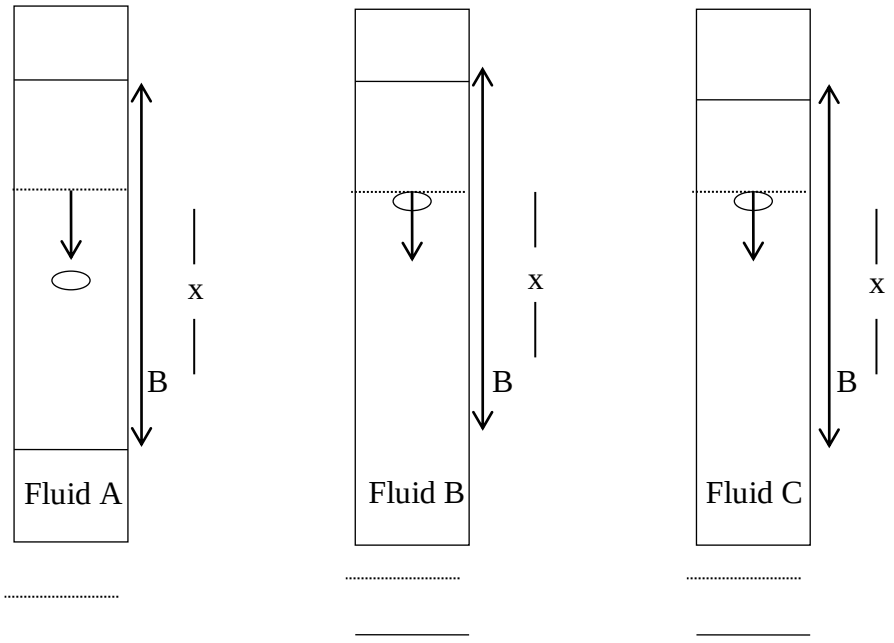
Particle Reynolds No. is

$$\mathrm{Re}_P = \frac{d_P u_t \rho}{\mu}$$

Plot of C_D vs R_{ep} (log log scale) is:

for $Re_p \leq 1$ $\qquad C_D = \frac{24}{\mathrm{Re}_P}$ (Stokes Law region)

for $1000 < Re_p < 200{,}000$ $\qquad C_D \approx 0.44$ i.e. Newton's Law Region



5. Description:

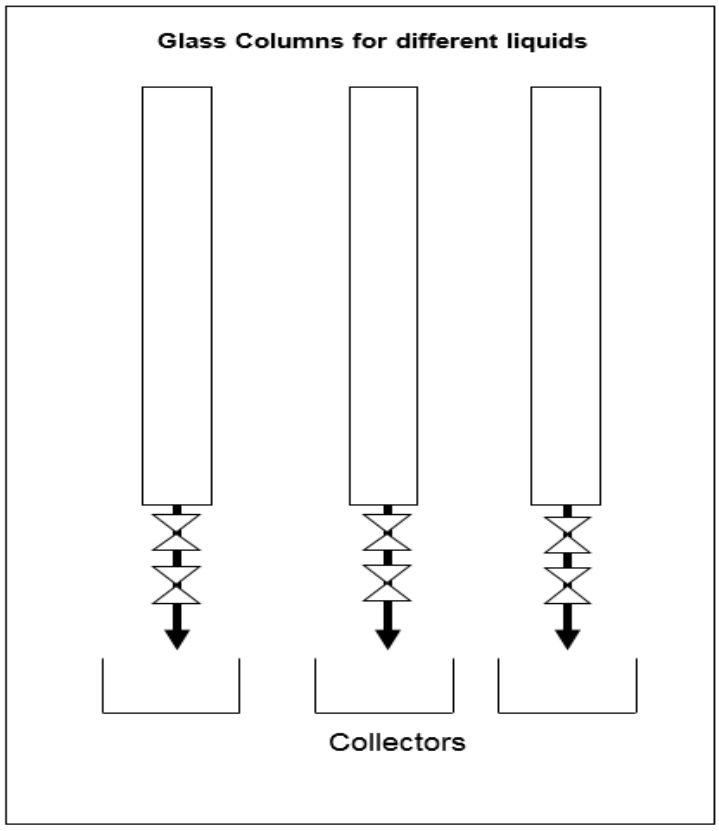
The apparatus has been designed to introduce students to the fundamental characteristics of the behavior of the particle system, in particulars the relationship between the drag coefficient of falling particles and their Reynolds number value. Particles covering a range of sizes and densities are supplied and the experiments are conducted by allowing single particles to fall through a number of different liquids contained in a vertical glass tube. The rate of fall of the

particle is determined by timing their passage between two marks on the walls of the glass tubes. Observation of the particle movement is aided by the provision of a shielded fluorescent tube light mounted on the backboard. Particles can be removed from the bottom of the tubes without the necessity of draining the liquid. A valve system is provided at the bottom of each tube to allow the particles to be removed with the minimum drainage of liquid.

Technical Details:

Column:	3 Nos., Material Borosilicate Glass, Inner Diameter 80 mm, with two marks each at 500 mm along the height.

Drag Coefficient Apparatus



6. Utilities Required:

6.1	Electricity Supply:	Single phase, 220 VAC, 50 Hz, 5-15amp Socket with earth connection.
6.2	Floor Area Required:	1.5 m x 0.75 m
6.3	Liquids of different viscosities:	Glycerol, Castor oil, Ethylene Glycol.

7. Experimental Procedure:

7.1 Select the set of balls with variety of materials and sizes.
7.2 Measure the average diameter of each ball with screw gauge.
7.3 Measure the mass of each ball with weighing balance.
7.4 Calculate the density of ball materials from the measurements.
7.5 Record the room temperature.
7.6 Fill the three tubes with three different liquids.
7.7 Measure the density of these liquids at the ambient conditions.
7.8 Now drop gently each particle in one of the columns and note down the time taken (t) by the particle to cover a distance with different liquids between two marked points on the columns.
7.9 Repeat the experiment with different liquids.

8. Observations and Calculations:

DATA:

At T, ^{o}C
μ_A, μ_B, μ_C = ---------- N sec/m^2
g = 9.81 m/sec^2

OBSERVATION TABLE:

Run No.	Fluid	Ball Material	D_P, m	X, m	t, sec
1.	A, Glycerol				
2.	B, Castor Oil				
3.	C, Ethylene Glycol				

CALCULATIONS:

For fluid A, B, C

ρ_A, ρ_B, ρ_C= ---------- kg/m^3
ρ_P = ------

$U_t = \frac{X}{t}$, m/sec = ---------- m/sec

$\text{Re}_P = \frac{D_P U_t \rho}{\mu}$ = ----------

$C_D = \frac{4 \times g \times (\rho_P - \rho) \times D_P}{3 \times U_t^2 \times \rho}$ = ----------

Plot the Re_p vs $C_D$on log- log graph.

9. Nomenclature:

C_D	=	Drag coefficient
D_P	=	Particle diameter, m
g	=	Acceleration due to gravity, m/sec^2
Re_p	=	Particle Reynolds number
t	=	Time taken by particle to travel distance X, sec
U_t	=	Particle terminal velocity, m/sec
X	=	Distance travel by particle, m
μ_A, μ_B, μ_C	=	Viscosity of fluid A, B & C, N-sec/m^2
ρ_A, ρ_B, ρ_C	=	Density of fluid A, B & C, kg/m^3
ρ_P	=	Density of particle, kg/m^3

10. Precaution and maintenance Instructions:

10.1 Reading should be taken carefully.
10.2 During experiment upper valve should open and other valve closed.
10.3 If you are not using the equipment more than a period of one month drain the fluids and clean the columns.
10.4 Closed the upper valve and open the bottom and take out the Iron balls from the column for reuse.

11. Troubleshooting:

11.1 Never run the apparatus if power supply is less than 180 volts & 230 volts.
11.2 Handle the apparatus carefully
11.3 Fill the columns carefully so as to prevent the spillage of fluids.

12. References:

12.1 W.L. McCabe, J.C. Smith, **"Unit Operations Of Chemical Engineering"**, 7th ed., McGraw Hill, NY, 2005, Page 155-159.

12.2 Dr. R.K.Bansal, **"Fluid Mechanics & Hydraulic Machines"**, 9th ed., Laxmi Publications (P) Ltd.ND, 2008, Page 652-654.

INDIAN INSTITUTE OF TECHNOLOGY KANPUR
Department of Chemical Engineering
Unit Operation Lab

Experiment Name: Rotational Viscometer

1. Objective:

Measurement of the rheological behavior of fluids and pastes

2. Theory:

2.1 Measuring Principle

The equipment is a Rotational Viscometer with a concentric cylinder measuring geometry. The material under investigation is placed in the gap between the stationary outer measuring cup and the rotating measuring bob (Searle principle). By selecting different rotational speeds, the shear rate may be varied.

The resistance of the material to flow leads to a drag on the rotating bob, which is measured as a torque on the drive shaft.

The measuring drive makes use of a direct deflection less torque measurement principle.

The measured torque in percentage is related to the shear stress and the viscosity.

2.2 Measurable Properties of Materials

The following rheological properties may be determined with the rotational viscometer-

1. Viscosity
2. Intrinsic Viscosity
3. Yield Value
4. Dilatancy
5. Thixotropy
6. Rheopexy (antithixotropy)

3. Description:

The distinguished parts of the equipment are shown in this section with their nomenclature. Numbers within bracket indicates the parts in diagram.

3.1 Measuring Unit

[11] Measuring Drive unit

[12] Instrument Housing

[13] Support

[14] Temperature Control jacket (interchangeable)

[15] Quick coupling for measuring bob

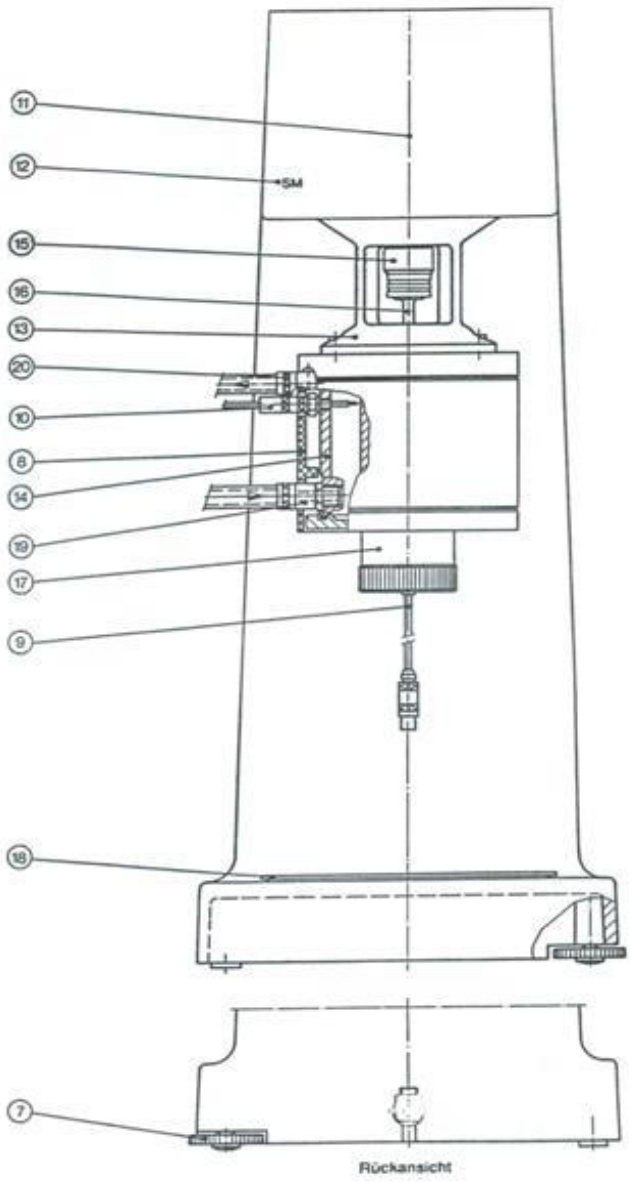
[16] Measuring bob shaft

[17] Measuring cup support screw

[18] Removable Drip tray

[19] Hose connector for fluid jacket – in

[20] Hose connector for fluid jacket - out



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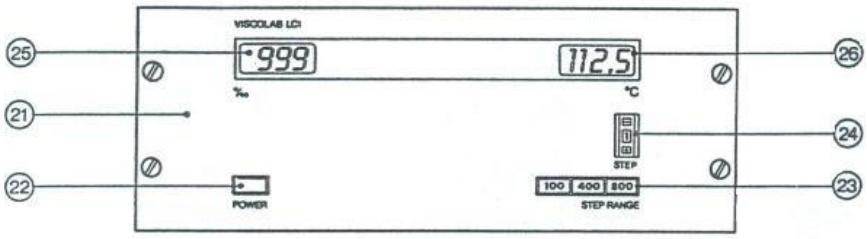


3.2 Electronics

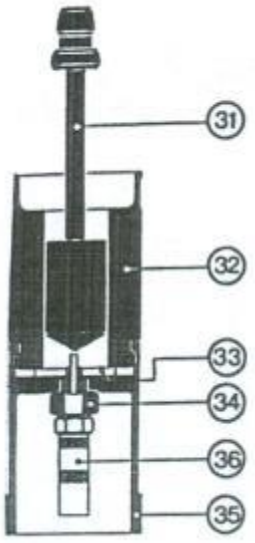
[21] Housing
[22] Mains Switch "POWER"
[23] Selector switch for speed ranges "STEP RANGE" 100, 400, 800
[24] Selector switch for rotational speed levels "STEP" 0-9
[25] Torque display 0 – 100 %
[26] Temperature display -99.9 – 199.9^{O}C

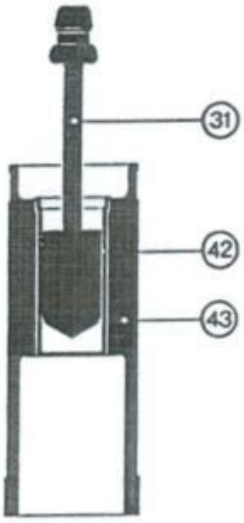
3.3 Standard Measuring System

[31] Measuring Bob
[32] Measuring cup
[33] Seal
[34] Screw thread plug
[35] Distance sleeve
[36] Screw-in resistance thermometer Pt 100, type Pt-MB (fits in position of [34])

3.4 Disposable measuring system

[31] Measuring bob
[42] Disposal measuring cup
[43] Measuring cup holder
[44] Measuring cup ejector
[4 ing cup
[4 ler





4. Experimental Procedure:

4.1 Zero Adjustment of equipment

The zero adjustment is carried out by manufacturer prior to delivery of the instrument. If it is not correct, the zero adjustment may be carried out as follows:

"STEP RANGE" to 100

"STEP" to 5

Torque display (25) is then adjusted to a reading of 000 ± 1% by Potentiometer P2 (48)

"STEP RANGE" to 800
"STEP" to 9

Torque display (25) is then adjusted to a reading of 000 ± 1% by potentiometer P3 (49)

4.2. Selection and Operation of Measuring system:

4.2.1 Select measuring system (for ranges refer to Specification of measuring geometries).
4.2.2 Fill measuring cup up to the indicated level with substance, avoid trapping of air bubbles since they may cause errors.
4.2.3 Fit measuring bob(31) into measuring cup(32).
4.2.4 Slide coupling sleeve of the quick coupling (15) into the upper position
4.2.5 Slide the measuring system into the temperature control jacket (14) from below and secure the measuring cup support screw to hold them in place. (Place the shaft of the measuring bob (16) in a vertical position.)
4.2.6 Insert measuring bob shaft into the quick fitting coupling and pull the sleeve (15) downwards. (In this position the measuring bob is coupled rigidly to the measuring drive unit.)

To dismantle the measuring system follow the procedure as detailed above, in reverse.

Caution is needed when removing the measuring system from the temperature control jacket, to prevent the system from falling when the support screw cap (17) is unscrewed.

4.3 Default switch settings

Select Rotational speed level 0
Rotational speed level switch "STEP" 0
Turn instrument on

Press "POWER" button

Select speed range (refer to section 9) with "STEP RANGE" 100/400/800

4.4 Measuring:

Select anticipated rotational speed level with switch "STEP" 1 – 9

Read torque display (25) (0 – 100 %) and record the readings into a data table for speed level (STEP 1 – 9) and corresponding torque value. The rheological properties of the sample are calculated from the measurements.

4.5 Manual assessment of Flow curves and Viscosity curves

4.5.1 Select rotational speed steps at defined time intervals using rotational speed selector "STEP"

for ascending flow curves “STEP” 1 – 9,
for descending flow curves “STEP” 9 - 1

4.5.2 Read values of the torque display (25) (0-100%) at every rotational speed level and record into a data table for speed level (STEP 1-9) and corresponding torque value.

4.5.3 Plot values and construct flow curve by connecting them.

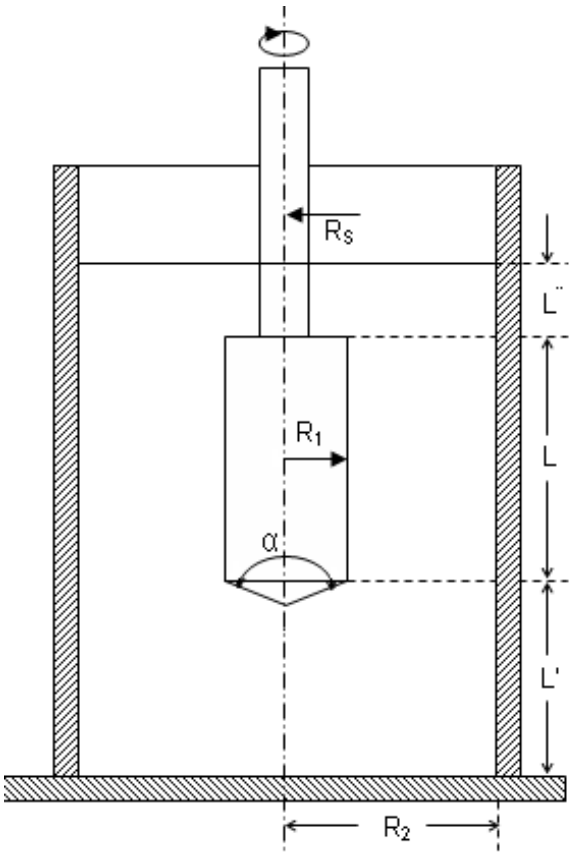
4.5.4 Compute the rheological properties from the measured data.

5. Calculations

Torque M, (%)
Shear rate γ (s^{-1})
Shear stress τ (Pa)
Viscosity η (Pas)

$$\gamma = K_\gamma n$$
$$\tau = (\tau\ \%).M$$
$$\eta = \tau / \gamma$$
$$\eta = \eta\ \%.\ M$$

where, K_γ = Shear rate factor
n = Speed (rpm)
M = Torque
τ %, η % = Shear stress and viscosity for M = 1%



Measuring System Data: Z2 DIN

			MS-	Z 4 DIN	Z 5 DIN
			K_γ / s^{-1}/min^{-1}	1.291	1.291
			τ % / Pa	6.501	34.844
STEP RANGE	STEP	n/min^{-1}	γ / s^{-1}	η % / Pas	η % / Pas
100	1	1.00	1.291	5.035631	26.9899
	2	1.78	2.298	2.828982	15.1628
	3	3.16	4.080	1.593382	8.54020
	4	5.62	7.255	0.896072	4.80276
	5	10.00	12.910	0.503563	2.69899
	6	17.80	22.980	0.282898	1.51628
	7	31.60	40.800	0.159338	0.854020
	8	56.20	72.550	0.089607	0.480276
	9	100.00	129.100	0.050356	0.269899
400	1	4.00	5.164	1.258908	6.74748
	2	7.12	9.192	0.707245	3.79069
	3	12.60	16.270	0.399570	2.14161
	4	22.50	29.050	0.223787	1.19945
	5	40.00	51.640	0.125891	0.674748
	6	71.20	91.920	0.070725	0.379069
	7	126.00	162.700	0.039957	0.214161
	8	225.00	290.500	0.022379	0.119945
	9	400.00	516.400	0.012589	0.067475
800	1	8.00	10.330	0.629332	3.37309
	2	14.20	18.330	0.3546644	1.90093
	3	25.30	32.660	0.1990508	1.06687
	4	45.00	58.100	0.1118932	0.599725
	5	80.00	103.300	0.0629332	0.337309
	6	142.00	183.300	0.0354664	0.190093
	7	253.00	326.600	0.0199050	0.106687
	8	450.00	551.000	0.0111893	0.059972
	9	800.00	1033.000	0.0062933	0.033731

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

Department of Chemical Engineering

Unit Operation Lab

Experiment Name: Centrifugal Pump Test Rig
(Variable Speed, Series & Parallel Set Up)

1. Objective:

Study of centrifugal pump in series & parallel mode

2. Aim:

2.1 To determine:

- Power input
- Shaft output
- Discharge
- Total head
- Pump Output
- Overall efficiency
- Pump efficiency

2.2 To plot the following performance characteristics;

Head vs Discharge.
Speed vs. Discharge.
Pump efficiency vs. Discharge.

3. Introduction:

The hydraulic machines, which convert the mechanical energy into hydraulic energy, are called pumps. The hydraulic energy is in the form of pressure energy. If the mechanical energy is converted into pressure energy by means of centrifugal force acting on the fluid, the hydraulic machine is called centrifugal pump.

4. Theory:

The centrifugal pump acts as a reversed of an inward radial flow reaction turbine. This means that the flow in centrifugal pumps is in the radial outward directions. The centrifugal pump works on the principle of forced vortex flow, which means that an external torque rotates a certain mass of liquid, the rise in pressure head of the rotating liquid takes place. The rise in pressure head at any point of the rotating liquid is proportional to the square of tangential velocity of (i.e. rise in pressure head = $V^2/ 2g$ or $\omega^2r^2/2g$) the liquid at that point. Thus at the outlet of the impeller where radius is more, the rise in pressure head will be more and the liquid will be discharged at the outlet with a high- pressure head. Due to this high-pressure head, the liquid can be lifted to a high level.

Centrifugal Pump is a mechanical device, which consists of a body, impeller and a rotating mean i.e. motor, engine etc. Impeller rotates in a stationary body and sucks the fluid through its axes and delivers through its periphery. Impeller has an inlet angle, outlet angle and peripheral speed, which affect the head and discharge. Impeller is rotated by motor or i.e. engine or any other device.

MULTISTAGE CENTRIFUGAL PUMP:

A centrifugal pump consisting two or more impellers; the pump is called a multistage centrifugal pump. A multi stage pump is having the following two important functions:

1. To produce a high head.
2. To discharge a large quantity of liquid.

If a high head is to be developed, the impellers are connected in series while for discharging large quantity of liquid; the impellers are connected in parallel.

5. Description:

The present Centrifugal Pump Test Rig is a self-contained unit operated on closed circuit basis containing a sump tank. The set-up consists of two Centrifugal pumps. Both pumps are coupled with individual DC Motors. Power input to these DC Motors is varied by means of Thyristor controlled DC Drives to vary the RPM of motor. RPM Indicator with separate Proximity sensors indicates the RPM of each Pump. Flow of water is measured by using Rota meter. Vacuum gauges are fitted on suction line and Pressure gauges are fitted on delivery line of each pump to measure the pressure.

6. Utilities Required:

6.1	Electricity Supply:	Single Phase, 220 V AC, 50 Hz, 5-15 Amps with earth connection
6.2	Water supply for initial fill	
6.3	Floor Drain Required	
6.4	Floor Area Required:	2 m x 1 m

7. Experimental Procedure:

7.1 Starting Procedure:

7.1.1 Close the drain valves provided.

7.1.2 Fill Sump tank ¾ with clean water and ensure that no foreign particles are there.

7.1.3 Open Flow Control Valve given on the water discharge line and Control valve given on suction line.

7.1.4 Ensure that all On/Off Switches given on the Panel are at OFF position.

7.1.5 Now switch on the Main Power Supply (220 VAC, 50 Hz) and switch on the Pump.

7.1.6 Set the desired RPM of motor / pump.

7.1.7 Operate the Flow Control Valve to regulate the flow of water discharged by the pump.

7.1.8 Operate the Control Valve to regulate the suction of the pump.

7.1.9 Record discharge pressure & suction pressure.

7.1.10 Record the power consumption & discharge.

7.1.11 Repeat the same procedure for different speeds of pump.

7.1.12 Repeat the same procedure for different discharge with constant speed.

7.2 Closing Procedure:

7.2.1 When experiment is over, gate valve is proper open provided on the discharge line.

7.2.2 Reduce the RPM of the pump with the help of DC Drive.

7.2.3 Switch OFF the pump first.

7.2.4 Switch OFF Power Supply to Panel.

8. Observations and Calculations:

DATA:

EMC = 3200 pulses/k W hr

ρ = 1000 kg/m^3

h_{pg} = 1 m

g = 9.81 m/s^2

η_m = 0.8 (assumed)

OBSERVATION TABLE:

Experiment 1: Centrifugal Pump (Single Stage)

S. No.	N_1, RPM	$P_{d,}$ kg/cm^2	P_{S1}, mmHg	F_L, LPH	P	$t_{p,}$ sec
1.						
2.						
3.						

Experiment 2: Centrifugal Pump (Two Stages - Parallel Set-Up)

S. No.	N_1, RPM	N_2, RPM	P_{S1}, mmHg	P_{S2}, mmHg	P_d, kg/cm^2	F_L, LPH	P	**t_p, sec**
1.								
2.								
3.								

Experiment 3: Centrifugal Pump (Two Stages - Series Set-Up)

S. No.	N_1, RPM	N_2, RPM	P_{S1}, mmHg	P_{S2}, mmHg / kg/cm^2	P_d, kg/cm^2	F_L, LPH	P	**t_p, sec**
1.								
2.								
3.								

CALCULATIONS:

Experiment 1: Centrifugal Pump (Single Stage)

$$E_i = \frac{P}{t_P} \times \frac{3600}{EMC}, \text{ kW} = \text{----------}$$

$$E_S = E_i \times \eta_m, \text{ kW} = \text{----------}$$

$$Q = \frac{F_L}{1000 \times 3600}, \; m^3/sec = \text{----------}$$

$$H = 10 \times \left[P_d + \frac{P_{S1}}{760} \right] + h_{pg}, \; m \; of \; water = \text{----------}$$

$$E_o = \frac{\rho \times g \times Q \times H}{1000}, \text{ kW} = \text{----------}$$

$$\eta_o = \frac{E_o}{E_i} \times 100\% = \text{----------}$$

$$\eta_p = \frac{E_o}{E_S} \times 100\% = \text{----------}$$

Experiment 2: Centrifugal Pump (Two Stages - Parallel Set-Up)

$$E_i = \frac{P}{t_P} \times \frac{3600}{EMC}, \text{ kW} = \text{----------}$$

$$E_S = E_i \times \eta_m, \text{ kW} = \text{----------}$$

$$Q = \frac{F_L}{1000 \times 3600}, \text{ m}^3/\text{sec} = \text{----------}$$

$$H = 10 \times \left[P_d + \frac{\frac{P_{S1} + P_{S2}}{2}}{760} \right] + h_{pg}, \textit{ m of water} = \text{----------}$$

$$E_o = \frac{\rho \times g \times Q \times H}{1000}, \text{ kW} = \text{----------}$$

$$\eta_o = \frac{E_o}{E_i} \times 100\% = \text{----------}$$

$$\eta_p = \frac{E_o}{E_S} \times 100\% = \text{----------}$$

Experiment 3: Centrifugal Pump (Two Stages - Series Set-Up)

$$E_i = \frac{P}{t_P} \times \frac{3600}{EMC}, \text{ kW} = \text{----------}$$

$$E_S = E_i \times \eta_m, \text{ kW} = \text{----------}$$

$$Q = \frac{F_L}{1000 \times 3600}, \; m^3/sec = \text{----------}$$

$$H = 10 \times \left[P_d + \frac{P_{S1}}{760} \right] + h_{pg}, \; m \; of \; water = \text{----------}$$

$$E_o = \frac{\rho \times g \times Q \times H}{1000}, \; \text{kW} = \text{----------}$$

$$\eta_o = \frac{E_o}{E_i} \times 100\% = \text{----------}$$

$$\eta_p = \frac{E_o}{E_S} \times 100\% = \text{----------}$$

9. Nomenclature:

A	=	Area of measuring tank, m^2.
EMC	=	Energy meter constant, Pulses/kW-hr
E_i	=	Pump input, kW
E_S	=	Shaft output, kW
E_o	=	Pump output, kW
F_L	=	Flow rate, LPH.
g	=	Acceleration due to gravity, m/sec^2.
H	=	Total Head, m.
h_{pg}	=	Height of pressure gauge from suction of the pump, m.
N	=	Speed of Pump, RPM.
P	=	Pulses of energy meter.
P_d	=	Delivery pressure, kg/cm^2
P_{S1}	=	Suction pressure of pump 1, mmHg.
P_{S2}	=	Suction pressure of pump 2, mmHg / kg/cm^2.
Q	=	Discharge, m^3/sec.
t_p	=	Time taken for P pulses of energy meter, sec.
ρ	=	Density of fluid, kg/m^3.
η_p	=	Pump efficiency, %.
η_o	=	Overall efficiency, %.
η_m	=	Motor efficiency, %

10. Precaution and maintenance Instructions:

10.1. Never run the apparatus if power supply is less than 180 volts and above 230 volts.
10.2. Never fully close the Delivery line and By-Pass line Valves simultaneously.
10.3. Always keep apparatus free from dust.
10.4. Always use clean water.
10.5. If apparatus will not in use for more than half month, drain the apparatus completely.

11. Troubleshooting:

11.1. If pump does not lift the water, open the air vent provided on the pump to remove the air from pump.
11.2. If still water is not lifting the revolution of the DC motor may be reverse. Change the electric connection of motor to change the revolutions.
11.3. If panel is not showing input, check the fuse and main supply.
11.4. If RPM indicator is not displaying the rpm, check the distance of proximity switch and adjust it to 2-3 mm.

12. References:

12.1. R.S Khurmi, "Hydraulics, Fluid Mechanics & Hydraulic Machines", 11th ed., S.Chand & Company LTD., ND, 2008, Page 582-585, 587, 590.
12.2. Dr. P.N.Modi, Dr. S.M Seth,"Hydraulics & Fluid Mechanics", 15th ed., Standard book house ND, 2005, Page1081-1083.

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

Department of Chemical Engineering

Unit Operation Lab

Experiment Name: Pressure drop studies in fluidized bed

1. Objective:

1.1 To study the fluidization characteristics of a bed of sand by air.
1.2 To study the effect of particle Reynolds number on void fraction.
1.3 To calculate the fluidization efficiency

2. Aim:

To determine the fluidization efficiency

3. Introduction:

Fluidized bed represents a versatile solid fluid contacting operation. It is extensively employed in a heat exchanger, catalytic and non-catalytic reactors, ion exchange, drying coating adsorption etc. They are marked by good mixing of solids and fluid and are easy to control. Their exists excellent performance in many cases but at the same time a complete flop in some of the processes has made fluidization a particular technique and work of attention before being employed.

Now, however, in spite of the weakness of many design correlations and uncertainties of the actual flow pattern of the gas and solids, fluidized beds continue to new successes in the chemical end refining industries mainly because of high rate of heat transfer and ease of solid handling.

4. Theory:

A packed bed expands when the pressure drop due to the upward flow of fluid through a granular unrestricted bed equals the wet of packing. The individual particle moves under the influence of passing fluid. The bed has an appearance of boiling liquid and is referred to as being fluidized. When a fluid passes upward through a bed of solids there will be a certain pressure drop across the bed to maintain the fluid flow. Depending upon the bed geometry and particle characteristics the fluidization phenomenon occurs at a particular velocity.

A force balance on a bed of length L when the pressure drop equals the gravitational force is as follows

$$(-\Delta P)\left(C/L\right) = (1-\varepsilon)(\rho_S - \rho_f)g \qquad (1)$$

Where
ρ_f = Fluid velocity
ρ_S = Solid particle density
ε = porosity $= 1 - W_S / LA\rho_S$

The simplified expression for minimum fluidization velocity given by Karn and Levenspiel are as under.

For small particles

$$V_{m_f} = \frac{d_p^2(\rho_s - \rho_f)g}{1650\mu_f} \qquad \text{Re}_p \geq 20 \qquad (2)$$

And for large particles

$$V_{m_f} = \frac{d_p^2(\rho_s - \rho_f)g}{24.5\mu_f} \qquad \text{Re}_p \geq 1000 \qquad (3)$$

Where

V_{m_f}	=	superficial velocity at minimum fluidization
d_p	=	particle diameter
W_S	=	mass of solid in bed
L	=	height of bed
A	=	area of cross section of the bed
μ	=	fluid viscosity
Re_p	=	Reynolds number based on particle diameter
	=	$d_p V \rho_f / \mu$

Fraud's number, N_{FR} (= $v^2 / d_p g$) is the criterion to determine the nature of fluidization.

If N_{FR} is less than unity particulate fluidization occurs. (Particulate fluidization occurs when difference in densities between particle and fluid is small). This is typical of liquid fluidized beds.

Aggregate Fluidization (characterizes by the gas raising, through solid bed in bubble form) occurs when N_{FR} is greater than unity

Pressure drop across the fix bed (Ergun's equation)

$$\left(\frac{\Delta P}{\rho_f L}\right)\left(\frac{\varepsilon^3}{1-\varepsilon}\right)\left(\frac{d_p}{V^2}\right) = \frac{150(1-\varepsilon)\mu_f}{d_p V \rho_f} \qquad (4)$$

ε, porosity at any time = $1 - W_S / LA\rho_S$

At the onset of fluidization the pressure drop across the bed equals the weight of the bed per unit area of cross section

$$\Delta P / L = g(\rho_S - \rho_f)(1-\varepsilon) \qquad (5)$$

The minimum fluidization velocity

$$V_{m_f} = \frac{d_p^2 g(\rho_S - \rho_f)\varepsilon_{mf}^3}{150(1-\varepsilon_{mf})\mu_f} \quad (6)$$

Leva has proposed a correlation to find the minimum fluidization velocity when the gas is fluidizing medium

$$V_{m_f} = 0.0007(\mathrm{Re}_p)_{mf}^{0.063} \frac{d_p^2(\rho_s - \rho_f)g}{1650\mu_f}$$

Fluidization efficiency is defined as

$$\text{Efficiency} = \frac{G_F - G_E}{G_F}$$

G_F = mass velocity of fluid theoretically required to produce fluidization Kg/s. m^2
G_E = mass velocity of the fluid actually causing initial expansion of bed .kg/s.m^2

5. Material and Equipment

The fluidization apparatus provided with facilities for pressure drop across the bed and measurement of gas flow rate

6. Experimental Procedure:

6.1 Note down the initial heights and weight of the fixed bed.

6.2 Record the average bed height and pressure drop across the bed as a function of flow rate of the gas (air) when bed is fluidized

6.3 Repeat the experiment with 3 different initial bed heights.

6.4 Tabulate the data as follows

Inside diameter of column	density of fluid
Solid used	viscosity of the fluid
Fluid used	mass velocity
Temperature	density of particle
Pressure	particle diameter
Run No.	Volumetric flow rate of liquid
Height of bed	pressure drop across the bed

7. Observation & Calculations:

7.1 Plot a graph of log(delta P) Vs log of Rep

7.2 Plot a graph of bed height vs superficial velocity

7.3 Estimate the minimum fluidization velocity and compare the experimental value with the predicted form the given semi empirical expression

7.4 Plot e vs Rep read from the graph the value of Rep at e equal to unity

7.5 Calculate the Fraud's number at minimum fluidization velocity

7.6 Discussion

1. Discus the graph characteristics and its usefulness as a rough indication of the quality of fluidization
2. Do you observe any dependence of any fluidization velocity on the initial bed height? Discus.
3. Make comments on the results.

7.7 Questions:

1. What are advantages and disadvantages of fluidized bed over fixed beds?
2. What is the difference between aggregative and particulate fluidization /what is Fraud's number?
3. Is the quality of fluidization influenced by the type of the distributor used? What are the characteristics of good distributor?
4. What is the two phase theory of fluidization?
5. Is the conversion in the fluidized bed reactor higher than in the fixed bed reactor under similar condition?

8. References:

8.1 Fluidization Engineering by D. kunni and D Levenspiel(1969)

8.2 Fluidization , Edited By Davidson and Harrison (1971).

8.3 Coulson J. M., and Richardson J.F. Chemical engineering, Vol. 1. 3rd Ed., Pergamon Press Ltd. , London.

Experiment Name: Pressure drop studies in Packed Bed

1. Objective:

1.1 To verify the relationship between the velocity of the fluid and pressure drop per unit length of packing

1.2 To verify Ergun's equation.

2. Introduction:

Packed beds are used extensively in absorption, distillation and liquid liquid extraction processes where large surface area is necessary to provide intimate contact between two phases – gas-liquid or liquid-liquid.

3. Theory:

As a fluid passes through the bed, it does so through empty spaces (VOIDS) in the bed. The voids form continuous channels throughout the bed. These channels need not be of same length and diameter. While the flow may be laminar through some channels, it may be turbulent in other channels. The resistance due to friction per unit length of the bed can be taken as the sum of two terms:

(1) Viscous drag force which is proportional to the first power of fluid velocity V_{CH}; and
(2) Inertial force which is proportional to the square of the fluid velocity.

Since V_{CH}, velocity in the channel is difficult to estimate, V_{CH} is substituted by V_ε , the velocity through the empty cross section of the column. V_ε is related to V_{CH} by the expression $V_\varepsilon = \varepsilon V_{CH}$, where 'ε' is the BED VOIDAGE or POROSITY. The total surface area of the particles in the bed which come in contact with the fluid is a function of SPECIFIC SURFACE of the particles, SPHERICITY and the voids in the bed. Taking all these facts into consideration, equation (1) has been derived to estimate the pressure drop for flow of fluid through a packed bed.

$$\left(\frac{\Delta P}{\rho L}\right)\left(\frac{\varepsilon^3}{1-\varepsilon}\right)\left(\frac{d_p}{V_\varepsilon^{\,2}}\right) = \frac{150(1-\varepsilon)\mu}{d_p V_\varepsilon \rho_f} + 1.75 = f_p \qquad (1)$$

$$= \frac{150(1-\varepsilon)}{(N_{\mathrm{Re}})_P} + 1.75$$

At very low values of $(N_{Re})_P$ the term $150(1-\varepsilon)/ (N_{Re})_P$ is very large compared to 1.75. In other words, viscous drag force predominates. As $(N_{Re})_P$ increases, f_p approaches 1.75. For any range of $(N_{Re})_P$ the total friction loss is additive of resistance due to viscous forces and resistance due to inertial forces.

4. Experimental Set up:

The equipment consists of a glass tube (A) 60 mm outside diameter and 4 mm wall thickness, 90 cm long. The packing is supported on a stainless steel screen mesh with 2 mm square opening held between the two bottom flanges. A 10 cm long calming section is provided to uniformly distribute the fluid in the packing. M_1 and M_2 are manometer taps connected to a mercury water manometer (when water flows through the packed bed) or an air-water manometer (when air flows through the packed bed). Packing materials may be glass spheres of size 6 mm, glass tube pieces cut out of a glass tube 6 mm OD and 1.2 mm wall thickness.

5. Experimental Procedure:

5.1 Keep the valve closed

5.2 Note the dimensions of the packing

5.3 Measure the height of packed bed between the manometers taps M_1 and M_2.

5.4 Regulate the flow of water through the bed with the globe valve G. When a steady state is reached, record the rotameter reading and the manometer reading.

5.5 Start with a minimum flow rate, increasing it a little at a time.

5.6 For each flow rate, record the rotameter and manometer readings and make visual observation of the bed. Stop increasing the flow of water when the bed just starting expanding.

5.7 Fill the bed with water is flush with the packing surface. Close valve G and open valve V and collect the water between the manometer taps M_1 and M_2. The volume of water collected is the total volume of voids.

5.8 Tabulate the data as follows:

Height of Packing	
ID of empty tower	
Volume of water collected between M_1 and M_2	
Run No.	
Rotameter Reading	
Manometer reading	

6. Calculations and Plots

6.1 Calculate voidage (ε) = $\dfrac{\text{Volume of water collected between } M_1 \text{ and } M_2}{\text{Total Volume of empty tower between } M_1 \text{ and } M_2}$

6.2 Calculate for each run $\dfrac{\Delta P}{L} = \dfrac{hg}{100L}(\rho_M - \rho_W)$

6.3 For each flow rate calculate modified Reynold's number $\left(\dfrac{d_P V_\varepsilon \rho}{\mu}\right)$ in the case of sphere.

In the case of Rasching ring, $d_P = \dfrac{6V_P}{S_P \Phi_S}$

Where Φ_S is SPHERICITY and is defined as surface area of sphere having the same volume as Rasching ring to the actual surface area of the particle.

6.4 Plot $\left(\frac{\Delta P}{\rho L}\right)\left(\frac{\varepsilon^3}{1-\varepsilon}\right)\left(\frac{d_p}{V_\varepsilon^{\,2}}\right)$ as a function of $(N_{Re})_P$

6.5 Calculate f_P using the expression $f_p = \frac{150(1-\varepsilon)}{(N_{\mathrm{Re}})_P} + 1.75$ and compare the calculated values of f_P with experimental values.

6.6 Questions

1. How will the pressure drop vary as the size of the sphere is increased?
2. What is the maximum diameter of sphere which can be used as a packing material?
3. How will the porosity be affected if the packing is made up of diameters d_1 and d_2? How will variation in porosity affect the pressure drop through the bed?

7. Nomenclature

d_P	=	Diameter of particle used as packing material, m
ε	=	Fraction voidage in the bed, dimensionless
f_P	=	Friction factor, dimensionless
g	=	Acceleration due to gravity, m/s^2
h	=	Manometer reading, cm of manometric fluid
L	=	Bed Height, m
ΔP	=	Pressure Difference, N/m^2
S_P	=	Surface area of particle m^2
V_{CH}	=	Velocity through channels in bed, m/s
V_ε	=	Velocity through empty cross section of tower, m/s
$(N_{Re})_P$	=	Modified Reynolds Number, $\left(\frac{d_P V_\varepsilon \rho}{\mu}\right)$
ρ	=	Density of fluid, kg/m^3
ρ_M	=	Density of manometric fluid, kg/m^3
ρ_W	=	Density of water, kg/m^3
α	=	Viscosity of fluid, $N\text{-}s/m^2$
Φ_S	=	Sphericity of a particle, dimensionless

Experiment Name: Pressure drop studies in Spouted Bed

1. Objective:

To determine pressure drop per unit bed length as a function of superficial air velocity.

2. Introduction:

Consider a vessel open at the top and filled with relatively coarse particulate solids. Suppose fluid is injected vertically through a centrally located small opening at the base of the vessel (see figure 1). If the fluid injection rate is high enough the resulting high velocity jet causes a stream of particles to rise rapidly in a hollowed core within the bed of solids. These particles after reaching somewhat above the peripheral bed level remain back onto the annular region between the hollowed core and the column wall, where they slowly travel downward and, to some extent, inward as a loosely packed bed. As the fluid travels upward, it flares out into the annulus. The overall bed thereby becomes a composite of dilute phase central core with upward moving solids entrained by a concurrent flow of fluid, and a dense phase annular region with counter current percolation of fluid.

A systematic cyclic pattern of solid movement is thus established, giving rise to a unique hydrodynamic system which is more suitable for certain applications than more conventional fluid-solid configurations.

This system is termed as a spouted bed, the central core is called a 'spout' and the peripheral annular region is referred to as the annulus. To enhance the solids motion and eliminate dead spaces at the bottom of vessel it is common to use a diverging conical base, with fluid injection at the truncated apex of the cone.

The spouted bed was originally conceived and has hitherto been regarded primarily as a modified version of a fluidized bed, the need for modification arising from the poor quality of fluidization encountered with uniformly coarse particles.

4. Theory:

Spouting Pressure Drop:

In the spouted state the pressure drop across the bed arises out of two parallel resistances, namely that of the spout in which dilute phase transport is occurring, and that of the annulus, which is downward moving packed bed with counter flow of gas. Since the gas entering the base flares out along radius from the axial zone into the annulus as it travel upward the vertical pressure gradient increases from zero at the base to a maximum at the top of the bed. The total pressure drop across the bed can therefore be obtained by integrating the longitudinal pressure gradient profile over the height of the bed.

The frictional pressure gradient for minimum fluidization is given by

$$\left(-\frac{dp}{dz}\right)_{mf} = \left(\rho_S - \rho_f\right)\left(1-\varepsilon_{mf}\right)g \qquad (1)$$

Since fluidization of bed is only approached in the upper part of the bed the total pressure drop across a spouted bed $-\Delta P_S$ is always less than the pressure drop which would arise if the same solids were fluidized given by the following equation:

$$-\Delta P_m = H(\rho_S - \rho_f)(1-\varepsilon)g \qquad (2)$$

Where ε = bed porosity

H = height of the bed

Relation between spouting pressure drop and fluidization pressure drop:

For a bed of height H the minimum fluidization pressure drop is given by

$$-\Delta P_f = H(\rho_S - \rho_f)(1-\varepsilon)g \qquad (3)$$

Assuming the annulus is essentially a loose bed with viscous flow Mumuro and Hattori (1) showed that the pressure gradient along the bed length is

$$-\frac{dp}{dz} = (\rho_S - \rho_f)(1-\varepsilon_{mf})g\left[1-\left(1-\frac{z}{H}\right)^3\right]$$

Which on integration from z = 0 to z = H gives

$$-\Delta P_S = (\rho_S - \rho_f)(1-\varepsilon_{mf})g\left(\frac{3}{4}H\right) \qquad (4)$$

which is the spouting pressure drop for a bed of height H.

Comparing equation (3) and (4) we see that

$$\frac{\Delta P_S}{\Delta P_f} = 0.75$$

For practical spouted beds the particle Reynolds number in the annulus is of the order of 100 for which the viscous flow in annulus is given by

$$-\Delta P_S = (\rho_S - \rho_f)(1-\varepsilon_{mf})g\left(\frac{9}{14}H\right) \qquad (5)$$

In this case spouting to fluidization pressure drop ($\Delta P_S / \Delta P_f$) is 0.643.

4. Experimental Procedure:

4.1 Note down the initial height and weight of the fixed bed.

4.2 Record the pressure difference across the bed when spouting occurs at the top of bed.

4.3 Repeat the experiment with 3 different initial bed heights.

4.4 Tabulate the following data

1	Inside Diameter of column	
2	Solids Used	
3	Fluids Used	
4	Temperature and Pressure	
5	Run Number	
6	Height of bed	
7	Density of fluid	
8	Mass of solids	
9	Density of solids	
10	Volumetric flow rate of fluid	
11	Pressure Drop across bed	

5. Results:

Calculate the pressure drop for spouting using equation (4) and (5) assuming viscous and turbulent flow respectively. Compare these values with the experimentally measured pressure drop.

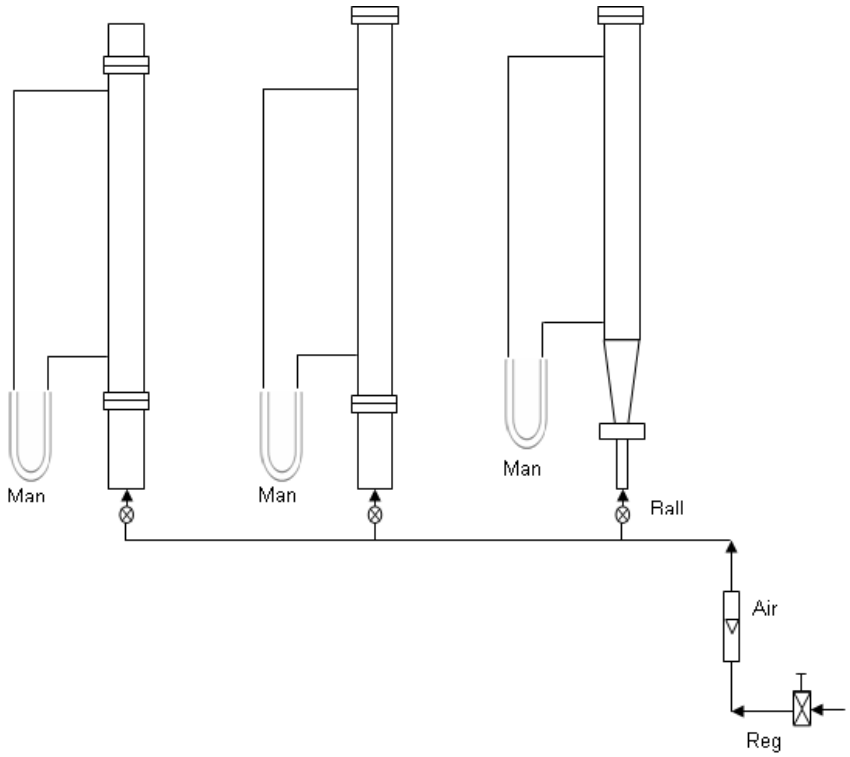
6. Questions:

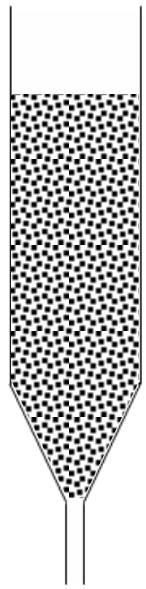
1. Write down the system where spouted bed can be used.
2. What is difference between moving and spouted bed?
3. Define the following terms:
   a) Minimum and maximum spouting velocity
   b) Maximum spouting pressure drop.

7. References:

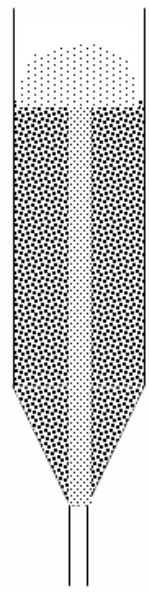
7.1 Spouted Beds by Kishan B Mathur and Normal Epstein, academic Press (1974).

7.2 Fluidization Engineering by D Kunii and O Levenspiel (1969).

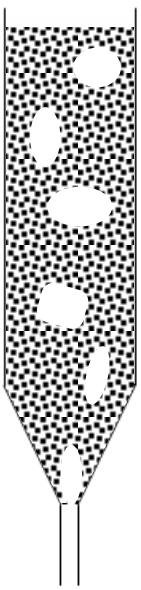




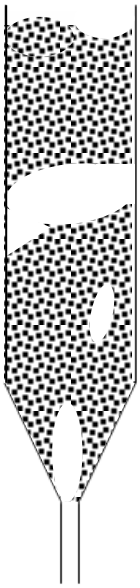
Packed Bed



Spouted Bed



Bubbling Bed



Slugging Bed

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

Department of Chemical Engineering

Unit Operation Lab

Experiment Name: Vapor Liquid Equilibrium Set Up

1. Objective:

To study about the vapor liquid equilibrium curve

2. Aim:

To plot the Vapor-Liquid Equilibrium Curve for Carbon Tetrachloride–Toluene system.

3. Introduction:

The design of distillation and other contacting equipment requires reliable VLE data. It shows the relationship between the composition of the vapor and that of liquid in equilibrium with the vapor for a binary mixture at constant pressure or constant temperature. Although relatively few ideal solutions are known whose equilibrium relations can be calculated from vapor pressure – temperature data of the pure components, by far the larger numbers of systems of industrial importance are non-ideal; and attempts to predict the equilibrium compositions of such mixtures from theoretical considerations alone have not proved to be successful. It has been the practice to determine such data experimentally under various conditions.

4. Theory:

Vapor liquid diagram shows relationship between the composition of the vapor and that of liquid in equilibrium with the vapor for a binary mixture at constant pressure or constant temperature. The basic data of any distillation problem are the equilibrium between the liquid and Vapour phases of the system subjected to distillation. Hence it is of great importance to study the Vapour-liquid equilibrium. If liquid and vapor behave ideally, such curves are calculated as follows:

From Raoult's law:

$$P_1 = P_1 x_1$$

$$P_2 = P_2 x_2$$

Where p_1 and p_2 are partial pressures of components 1 and 2 in the mixture

From Dalton's law of partial pressures:

p_1 and p_2 are vapor pressure of pure components at the same temperature as mixture.

$$P_1 = P y_1$$

$$P_2 = P y_2$$

y_1 and y_2 are the mole fractions of components in vapor

From these equations we have:

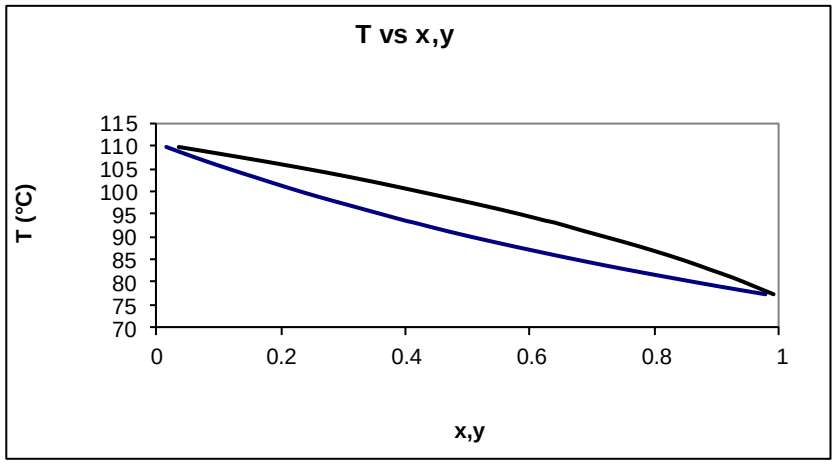
$$x_1 = \frac{P - P_2}{P_1 - P_2}$$

$$y_1 = \frac{P_1 x_1}{P}$$

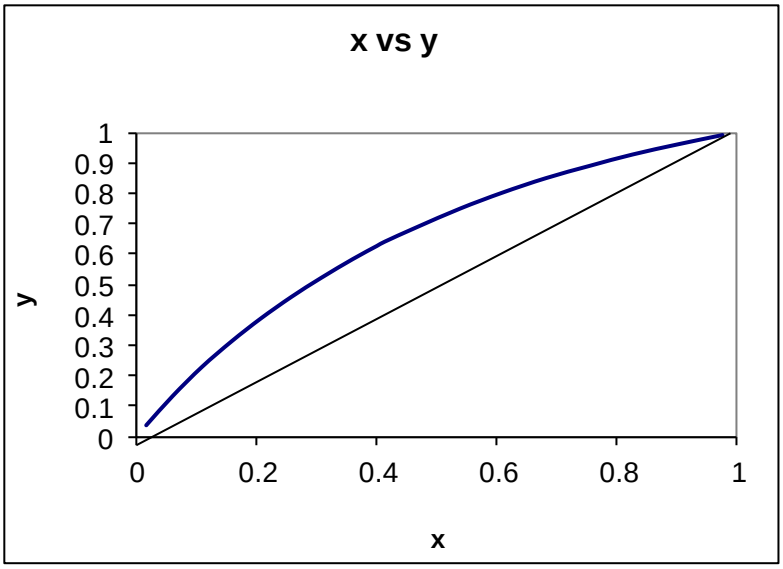
Theoretical VLE curve can thus be calculated by choosing various boiling points of the mixture and calculate x and y as shown above. Carbon tetrachloride – toluene system closely follows ideal behavior.

Temperature	Mole Fraction		Mass Fraction (g/g)		Volume Fraction (mL/mL)	
(C)	Liquid (x)	Vapour (y)	Liquid (x)	Vapour (y)	Liquid (x)	Vapour (y)
95.5	0.019	0.170	0.0472	0.3437	0.0591	0.3990
89	0.072	0.389	0.1657	0.6196	0.2012	0.6736
86.7	0.097	0.438	0.2147	0.6654	0.2573	0.7160
85.3	0.124	0.470	0.2654	0.6943	0.3141	0.7422
84.1	0.166	0.509	0.3374	0.7260	0.3923	0.7705
82.7	0.234	0.545	0.4381	0.7535	0.4971	0.7948
82.3	0.261	0.558	0.4743	0.7635	0.5334	0.8036
81.5	0.327	0.583	0.5544	0.7811	0.6119	0.8189
80.7	0.397	0.612	0.6269	0.8014	0.6804	0.8365
79.8	0.508	0.656	0.7252	0.8301	0.7698	0.8609
79.7	0.520	0.660	0.7346	0.8322	0.7782	0.8628
79.3	0.573	0.684	0.7745	0.8470	0.8132	0.8753
78.74	0.676	0.739	0.8423	0.8784	0.8713	0.9015
78.24	0.747	0.782	0.8831	0.9014	0.9055	0.9206
78.15	0.894	0.894	0.9558	0.9558	0.9648	0.9648

T vs x,y Curve



x vs y Curve



5. Description:

The set-up consists of distillation still with a heating element. An electrical Dimmer stat is connected to heating element for varying heat input. The vapour form the top of column is condensed in the concentric tube type condenser by circulating cooling water. The condensate is feedback to column as reflux. A tank with pump is provided to circulate cold water to condenser. Flow rates can be regulated through control valve fitted. Instrumentation is done to measure the temperatures at different points.

6. Utilities Required:

6.1. Electrical supply: Single Phase, 220 V AC, 50 Hz, 5-15 Amps socket with earth connection.
6.2. Water Supply (Initial Fill).
6.3. Drain required.
6.4. Floor Area Required: 1 m x 0.5 m.
6.5. Refractometer for analysis.
6.6. Chemicals Required:

Carbon tetrachloride
Toluene

7. Experimental Procedure:

7.1. Prepare solution of Toluene-CCl_4 about 500 ml with low composition of CCl_4.
7.2. Charge the feed solution in the vessel from the funnel provided at the top of the vessel.
7.3. Ensure that switches provided on the panel are at OFF position.
7.4. Switch ON the supply and then heater.
7.5. Gradually increase the dimmer stat and observe temperature T_2.
7.6. When temperature T_2 starts increasing switch ON the pump and allows cooling water to pass through the condenser.
7.7. Maintain T_2 above 70 and below 100 ^oC by adjusting the heat input from the dimmer stat.

7.8. After observing constant temperature T_1 and T_2 take sample of distillate and residue from the valve provided at the bottom of condenser and still respectively.

7.9. Set the dimmer stat to zero and recharge the still with another feed mixture (Increase the composition of CCl_4).

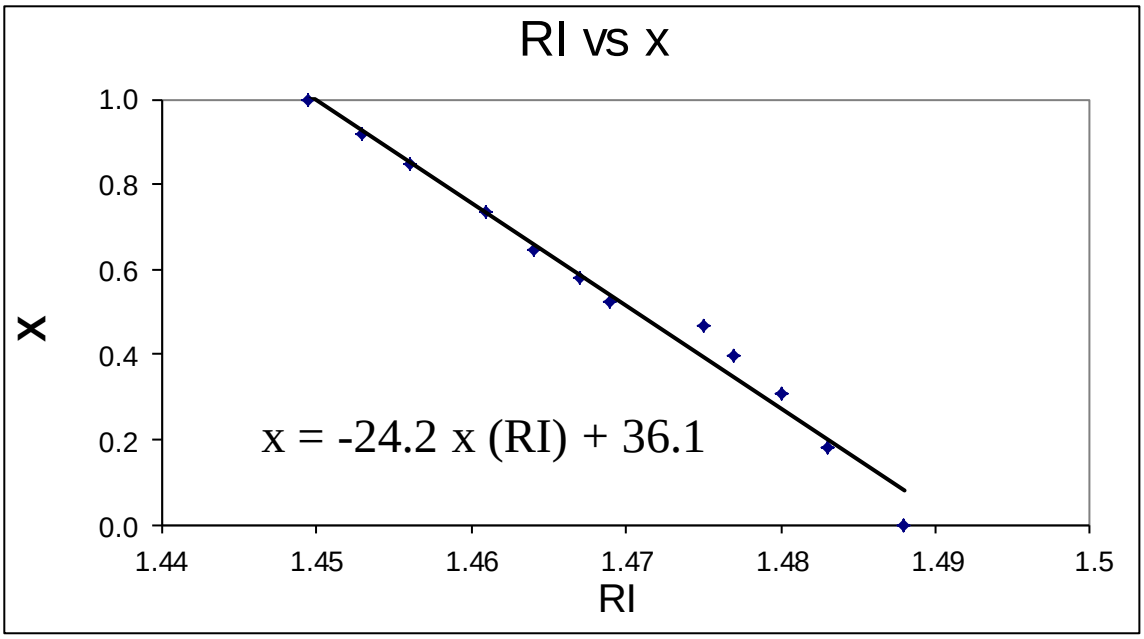
7.10. Repeat step 6 to 10 for different feed mixtures.

7.11. Make a calibration chart for the feed solution with different composition of toluene.

8. Observations and Calculations:

Data:

Refractive Index Calibration data for CCl_4-Toluene system (at 25 ^oC):



X	1.000	0.917	0.846	0.733	0.647	0.579	0.524	0.468	0.397	0.306	0.180	0.000
R.I.	1.4495	1.453	1.456	1.461	1.464	1.467	1.469	1.475	1.477	1.48	1.483	1.488

OBSERVATION TABLE:

S.No	T ^oC	$R.I_R$	$R.I_D$	x	y

x and y are calculated from the calibration chart given above. A smooth curve is plotted between T, x and y to get a curve similar to that in the theory.

9. Nomenclature:

$R.I_R$	=	Refractive index of residue
$R.I_D$	=	Refractive index of distillate
T	=	Temperature of the vapour, ^oC
x,y	=	Mole fraction of component

10. Precaution and maintenance Instructions:

10.1. Fill the still atleast half of the capacity.
10.2. Drain the still and water tank after completion of the experiment.
10.3. Don't run the pump before filling the tank with water.
10.4. Don't start the heater before fill the chemical into the still.

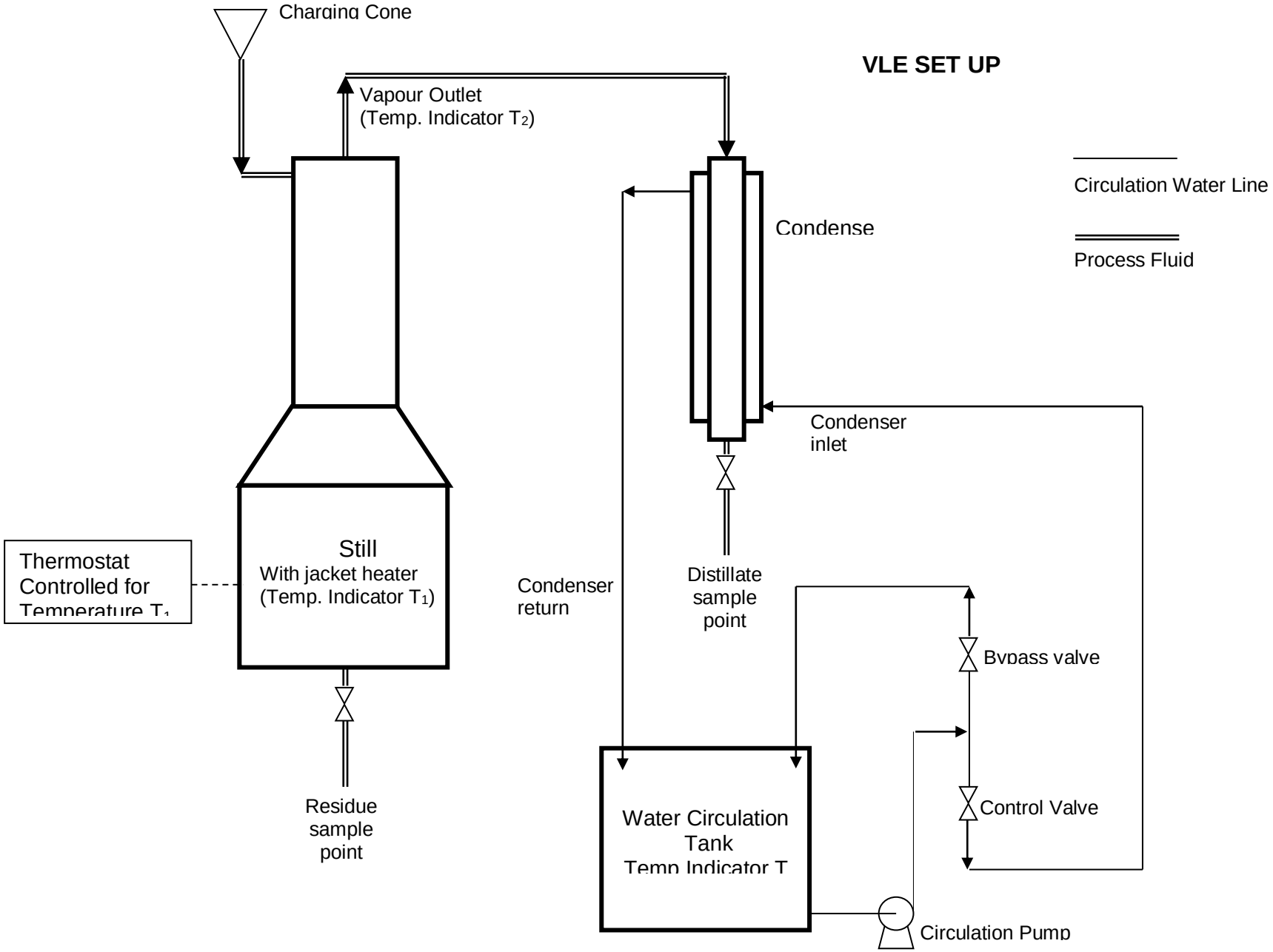
.

11. Troubleshooting:

If electric panel is not showing the input on the mains light, Check the fuse and also check the main supply.

12. References:

12.1. Coulson & Richardson, **"Chemical Engineering Vol-2",** 4th ed, Asian Books Pvt.Lt, ND, 1991, Page 428-429.
12.2. Treybal, R.E, **"Mass-Transfer Operations"**, 3rd ed, McGraw-Hill, NY, 1981, Page 343-348.


Charging Cone
VLE SET UP
Vapour Outlet
(Temp. Indicator T2)
Circulation Water Line
Process Fluid
Condense
Condenser
inlet
Still
With jacket heater
(Temp. Indicator T1)
Thermostat
Controlled for
Temperature T1
Condenser
return
Distillate
sample
point
Bypass valve
Residue
sample
point
Water Circulation
Tank
Temp Indicator T
Control Valve
Circulation Pump

INDIAN INSTITUTE OF TECHNOLOGY KANPUR
Department of Chemical Engineering
Unit Operation Lab

Experiment Name: Shell and Tube Heat Exchanger

1. Objective:

To study of heat transfer in Shell and Tube Heat Exchanger

2. Aim:

To calculate overall heat transfer coefficient for shell & tube heat exchanger.

3. Introduction:

Heat Exchanger is device in which heat is transferred from one fluid to another. The necessity for doing this arises in a multitude of industrial applications. Common examples of heat exchangers are the radiator of a car, the condenser at the back of a domestic refrigerator and the steam boiler of a thermal power plant.
Heat Exchangers are classified in three categories:
1) Transfer Type.
2) Storage Type.
3) Direct Contact Type.

4. Theory:

A transfer type of heat exchanger is one on which both fluids pass simultaneously through the device and heat is transferred through separating walls. In practice, most of the heat exchangers used are transfer type ones.

The transfer type exchangers are further classified according to flow arrangement as -
1. Single Pass.
2. Multiple Pass

A simple example of transfer type of heat exchanger can be in the form of a tube type arrangement in which one of the fluids is flowing through the inner tube and the other through the annulus surroundings it. The heat transfer takes place across the walls of the inner tube.

The heat lost by the hot fluid can be calculated

q_h = Heat Transfer rate to the hot water.

$$q_h = m_h C_{ph}(T_{hi-}T_{ho})$$

Heat taken by the cold fluid can also be calculated

q_c = Heat Transfer rate to the cold water.

$$q_c = m_c C_{pc}(T_{co-}T_{ci})$$

$$Q_{avg} = \frac{q_c + q_h}{2} \qquad U_o = \frac{Q_{avg}}{A_o \, \Delta T_m}$$

5. Description:

The apparatus consists of 1-2 Pass Shell and Tube heat exchanger. The hot fluid is hot water, which is attained from an insulating water bath using a magnetic drive pump and it flow through the inner tube while the cold water flowing through the annuals. For flow measurement

Rotameters are provided at inlet of cold water and outlet of hot water line. The Hot water bath is of recycled type with Digital Temperature Controller.

TECHNICAL DETAIL:

Shell	:	Material SS, ID 146 mm, length 500 mm with 4, 25 % cut baffles.
Tube	:	24 Nos., Material SS, OD 12.7 m, ID 9.5 m, Length 500 mm.

6. Utilities Required:

6.1 Electricity Supply: Single Phase, 220 V AC, 50 Hz, 32 Amps MCB with earth connection.
6.2 Water Supply: Continuous @ 5 LPM at 1 Bar.
6.3 Floor Drain Required.
6.4 Floor Area Required: 1.5 m x 0.75 m.

7. Experimental Procedure:

7.1 Starting procedure:

7.1.1 Close all the valves provided on the set up.
7.1.2 Open the lid of hot water tank, fill the tank with water and put the lid back to its position.
7.1.3 Ensure that switches given on the panel are at OFF position.
7.1.4 Connect electric supply to the set up.
7.1.5 Set the desired water temperature in the DTC by operating the increment or decrement and set button of DTC.
7.1.6 Open by pass valve and Switch ON the pump.
7.1.7 Switch ON the heater and wait till desired temperature achieves.
7.1.8 Connect cooling water supply to the set up.
7.1.9 Connect outlet of cooling water from heat exchanger to drain.
7.1.10 Allow cold water to flow through heat exchanger and adjust the flow rate by Rotameter and control valve.
7.1.11 Allow hot water to flow through heat exchanger and adjust the flow rate by Rotameter, control valve and by pass valve.
7.1.12 At steady state (constant temperature) record the temperatures & flow rate of hot and cold water.
7.1.13 Repeat the experiment for different flow rate of hot & cold water.
7.1.14 Repeat the experiment for different bath temperature.

7.2 Closing procedure:

7.2.1 When experiment is over switch OFF heaters.
7.2.2 Switch OFF pump.
7.2.3 Switch OFF Power Supply to Panel.
7.2.4 Stop cooling water supply.
7.2.5 Drain hot water tank by the drain valve provided.
7.2.6 Drain Cold and Hot water from the heat exchanger with the help of given drain valves.

8. Observations and Calculations:

DATA:

D_i = 0.0095 m
D_o = 0.0127 m

L = 0.5 m
N = 24

OBSERVATION TABLE:

S. No.	F_h LPH	T_1 °C	T_2 °C	F_c LPH	T_3 °C	T_4 °C
1.						
2.						

CALCULATIONS:

Find the properties of water (C_{ph}, ρ_h) at $T_h = \frac{T_1 + T_2}{2}$ and (C_{pc}, ρ_c) at $T_c = \frac{T_3 + T_4}{2}$ from data book.

C_{ph} = ---------- J/kg °C
C_{pc} = ---------- J/kg °C
ρ_h = ---------- kg/m^3
ρ_c = ---------- kg/m^3

$M_h = \frac{F_h \times \rho_h}{3600 \times 1000}$, kg/s =---------- kg/s $\qquad$ $Q_h = M_h C_{ph}(T_1 - T_2)$, W = ---------- W

$M_c = \frac{F_c \times \rho_c}{3600 \times 1000}$, kg/s =---------- kg/s $\qquad$ $Q_c = M_c C_{pc}(T_4 - T_3)$, W = ----------W

$Q = \frac{Q_h + Q_c}{2}$, W = ---------- W

$\Delta T_1 = T_1 - T_4$, °C = ---------- °C $\qquad$ $\Delta T_2 = T_2 - T_3$, °C = ----------°C

$\Delta T_m = \frac{\Delta T_2 - \Delta T_1}{ln \frac{\Delta T_2}{\Delta T_1}}$, °C = ---------- °C

$A_i = N \pi D_i L$, m^2 = ---------- m^2 $\qquad$ $A_o = N \pi D_o L$, m^2 = ---------- m^2

$U_i = \frac{Q}{A_i \Delta T_m}$, W/m^2 °C = ---------- W/m^2 °C

$U_o = \frac{Q}{A_o \Delta T_m}$, W/m^2 °C = ---------- W/m^2 °C

9. Nomenclature:

A_i = Inside heat transfer area, m^2
A_o = Outside heat transfer area, m^2
C_{ph} = Specific heat of hot fluid at mean temperature, J/kg °C

C_{pc}	=	Specific heat of cold fluid at mean temperature, J/kg ^oC
D_o	=	Outer diameter of tube, m
D_i	=	Inner diameter of tube, m
F_h	=	Flow rate of hot water, LPH
F_c	=	Flow rate of cold water, LPH
L	=	Length of tube, m
M_h	=	Mass flow rate of the hot water, kg/s
M_c	=	Mass flow rate of the cold water, kg/s
N	=	Number of tubes.
Q	=	Average heat transfer from the system, W
Q_c	=	Heat gained by the cold water, W
Q_h	=	Heat loss by the hot water, W
T_h	=	Mean temperature of hot water, ^oC
T_c	=	Mean temperature of cold water, ^oC
T_1	=	Inlet temperature of the hot water, ^oC
T_2	=	Outlet temperature of the hot water, ^oC
T_3	=	Inlet temperature of the cold water, ^oC
T_4	=	Outlet temperature of the cold water, ^oC
ΔT_m	=	Log mean temperature difference, ^oC
U_i	=	Inside overall heat transfer coefficient, W/ m^2 ^oC
U_o	=	Outside overall heat transfer coefficient, W/ m^2 ^oC
ρ_c	=	Density of cold water at mean temp, kg/m^3
ρ_h	=	Density of hot water at mean temp, kg/m^3

10. Precaution and maintenance Instructions:

10.1 Never run the apparatus if power supply is less than 180volts and above than 230volts.

10.2 Never switch ON mains power supply before ensuring that all the ON/OFF switches given on the panel are at OFF position.

10.3 Operate selector switch off temperature indicator gently.

10.4 Always keep the apparatus free from dust.

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11. Troubleshooting:

If electric panel is not showing the input on the mains light, check the main supply.

12. References:

12.1 Holman, J.P., **"Heat Transfer"**, 9th ed., McGraw Hill, NY, 2008, Page 525-527, 528-531.

12.2 McCabe, Smith, J.C., Harriott, P., **"Unit Operations of Chemical Engineering"**, 7th ed. McGraw Hill, NY, 2005, Page 441-447,

PROPERTIES OF WATER

Arora. Domkundwar, **"A Course in Heat & Mass Transfer"**, 6th ed., Dhanpat Rai & CO.(P) LTD.,NY, 2003, Page A.6

INDIAN INSTITUTE OF TECHNOLOGY KANPUR
Department of Chemical Engineering
Unit Operation Lab

Experiments Name: Finned Tube Heat Exchanger

1. OBJECTIVE:

To study the performance of a Finned Tube Heat Exchanger.

2. AIM:

To calculate LMTD, Heat transfer rate and Overall heat transfer coefficient.

3. INTRODUCTION:

In most of the industrial applications it is frequently required to heat up or cool down a surrounding fluid via heat transfer. The heat which is conducted through a solid body must frequently be removed by some convection process. For example, the heat lost by conduction through a furnace wall must be dissipated to the surroundings through convection. In heat exchanger applications, a finned tube arrangement might be used to remove heat from a hot fluid.

4. THEORY:

Finned tube heat exchangers are also known as extended surface heat exchangers in which outside area of tube is extended by fins and thereby, the outside area in contact with fluid has much larger than the inside area. The fluid having the lower heat transfer coefficient is brought into contact with extended surface and flows outside the tube while other fluid, having high heat transfer coefficient, flows through the tubes.
Overall Heat Transfer Coefficient can be calculated by the formulae:

$$U_o = \frac{Q_{avg}}{A_o \, \Delta T_m}$$

$$U_i = \frac{Q_{avg}}{A_i \, \Delta T_m}$$

5. DESCRIPTION:

Present set up consist of a horizontal finned tube double pipe heat exchanger. Hot water flows through the inner tube while cold water through annular space between inner tube and outer tube. Equipment can be operated in parallel or counter- current mode by changing the direction of the flow of cold water. Proper valve arrangement is provided to change the mode of operation. Water bath, made of SS, is provided with heater and a temperature sensor for hot water. Temperature of water in bath is maintained by Digital Temperature Controller (DTC). Hot and cold water flow rates are measured by separate rotameters. Temperature of hot and cold water is measured by digital temperature indicator provided with multi channel switch.

Technical Details:

Outer Pipe:	Material Stainless Steel, Inner Diameter 78 mm, Length 550 mm.
Inner Pipe:	Material Stainless Steel, Inner Diameter 28 mm, Outer Diameter 34 mm, Length 500 mm.

6. UTILITIES REQUIRED:

1. Electricity Supply: Single Phase, 220 VAC, 50Hz, 32 Amps MCB with earth connection.
2. Water Supply: Continuous @ 5 LPM at 1 Bar.
3. Proper arrangement for draining required.
4. Floor Area Required: 1.75 m x 1 m.

7. EXPERIMENTAL PROCEDURE:

Starting procedure:

1. Close all the valves provided on the set up.
2. Open the lid of hot water tank, fill the tank with water and put the lid back to its position.
3. Ensure that switches given on the panel are at OFF position.
4. Connect electric supply to the set up.
5. Set the desired water temperature in the DTC by operating the increment or decrement and set button of DTC.

6. Open by pass valve and Switch ON the pump.
7. Switch ON the heater and wait till desired temperature is achieved.
8. Connect cooling water supply to the set up.
9. Connect both the outlet (parallel / counter) of cooling water to drain.
10. Open the inlet & outlet valve for cold water as per desired mode (parallel/counter flow).
11. Allow cold water to flow through heat exchanger and adjust the flow rate by Rotameter and control valve.
12. Allow hot water to flow through heat exchanger and adjust the flow rate by Rotameter, control valve and by pass valve.
13. At steady state (constant temperature) record the temperatures & flow rate of hot and cold water.
14. Repeat the experiment for different flow rate of hot & cold water.
15. Repeat the experiment for different bath temperature.
16. Repeat the experiment for other mode (counter/parallel flow).

Closing procedure:

1. When experiment is over switch OFF heaters.
2. Switch OFF pump.
3. Switch OFF Power Supply to Panel.
4. Stop cooling water supply.
5. Drain hot water tank by the drain valve provided.

8. OBSERVATION & CALCULATION:

DATA:

D_o = 0.034 m

D_i = 0.028 m

L = 0.5 m

Y = 0.020 m

N_f = 6

OBSERVATION TABLE:

S. No.	Mode Parallel / Counter	F_h (LPH)	T_1 (^oC)	T_2 (^oC)	F_c (LPH)	T_3 (^oC)	T_4 / T_5 (^oC)
1.							
2.							

CALCULATIONS:

Find the properties of water (C_{ph}, ρ_h) at $T_h = \frac{T_1 + T_2}{2}$ and (C_{pc}, ρ_c) at $T_c = \frac{T_3 + T_4}{2}$ *or* $\frac{T_3 + T_5}{2}$ (as per mode selected) from data book.

C_{ph} = ------- J /kg ^oC

C_{pc} = ------- J /kg ^oC

ρ_h = ------- kg/m^3

ρ_c = ------- kg/m^3

$M_h = \frac{F_h \times \rho_h}{3600 \times 1000}$, kg/s = ---------- kg/s

$Q_h = M_h C_{ph}(T_1 - T_2)$, W = ---------- W

$M_c = \frac{F_c \times \rho_c}{3600 \times 1000}$, kg/s = ---------- kg/s

$Q_c = M_c C_{pc}(T_4 - T_3)$, W (for parallel flow) = ---------- W

$Q_c = M_c C_{pc}(T_5 - T_3)$, W (for counter flow) = ---------- W

$Q = \frac{Q_h + Q_c}{2}$, W = ---------- W

$\Delta T_1 = T_1 - T_3$, ^oC (for parallel flow) = ---------- ^oC

$\Delta T_1 = T_1 - T_5$, ^oC (for counter flow) = ---------- ^oC

$\Delta T_2 = T_2 - T_4$, ^oC (for parallel flow) = ---------- ^oC

$\Delta T_2 = T_2 - T_3$, ^oC (for counter flow) = ---------- ^oC

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}},\ ^oC \quad = \quad \text{---------- } ^oC$$

$$A_o = L(\pi D_o + 2N_F Y),\ m^2 \quad = \quad \text{---------- } m^2$$

$$A_i = \pi \times D_i \times L,\ m^2 \quad = \quad \text{---------- } m^2$$

$$U_i = \frac{Q}{A_i \Delta T_m},\ W/m^2\ ^oC \quad = \quad \text{---------- } W/m^2\ ^oC$$

$$U_o = \frac{Q}{A_o \Delta T_m},\ W/m^2\ ^oC \quad = \quad \text{---------- } W/m^2\ ^oC$$

9. NOMENCLATURE:

A_i	=	Inside heat transfer area, m^2
A_o	=	Outside heat transfer area, m^2
C_{pc}	=	Specific heat of cold water, kJ/kg ^oC
C_{ph}	=	Specific heat of hot water, kJ/kg ^oC
D_o	=	Outer diameter of tube, m
D_i	=	Inner diameter of tube, m
F_h	=	Hot water flow rate, LPH
F_c	=	Cold water flow rate, LPH
L	=	Fin length, m
M_h	=	Mass flow rate of the hot water, kg/sec
M_c	=	Mass flow rate of the cold water, kg/sec
N_F	=	No. of fins per tube.
Q_{avg}	=	Average heat transfer, W
Q_c	=	Heat taken by cold water, W
Q_h	=	Heat lost by hot water, W
T_h	=	Mean temperature of hot water, ^oC
T_c	=	Mean temperature of cold water, ^oC
T_1	=	Inlet temperature of the hot water, ^oC
T_2	=	Outlet temperature of the hot water, ^oC
T_3	=	Inlet temperature of the cold water, ^oC
T_4	=	Outlet temperature of the cold water for parallel flow, ^oC
T_5	=	Outlet temperature of the cold water for counter flow, ^oC

ΔT_m = Log mean temperature difference, ^oC

U_i = Inside overall heat transfer coefficient, $W/m^2\ ^oC$

U_o = Outside overall heat transfer coefficient, $W/m^2\ ^oC$

Y = Fin height, m

ρ_c = Density of cold water at mean temp, kg/m^3

ρ_h = Density of hot water at mean temp, kg/m^3

10. PRECAUTIONS & MAINTENANCE INSTRUCTIONS:

10.5 Never run the apparatus if power supply is less than 180 volts and above 230 volts.

10.6 Never switch ON mains power supply before ensuring that all the ON/OFF switches given on the panel are at OFF position.

10.7 Operator selector switch off temperature indicator gently.

10.8 Always keep the apparatus free from dust.

11. TROUBLESHOOTING:

1. If electric panel is not showing the input on the mains light, check the main supply.

12. REFERENCES:

1. Holman, J.P., **"Heat Transfer",** 9th ed., McGraw Hill, NY, 2008, Page 43-44, 525-526, 528-531.
2. McCabe, Smith, J.C., Harriott, P., **"Unit Operations of Chemical Engineering",** 7th ed. McGraw Hill, NY, 2005, Page 327-329, 331-333.

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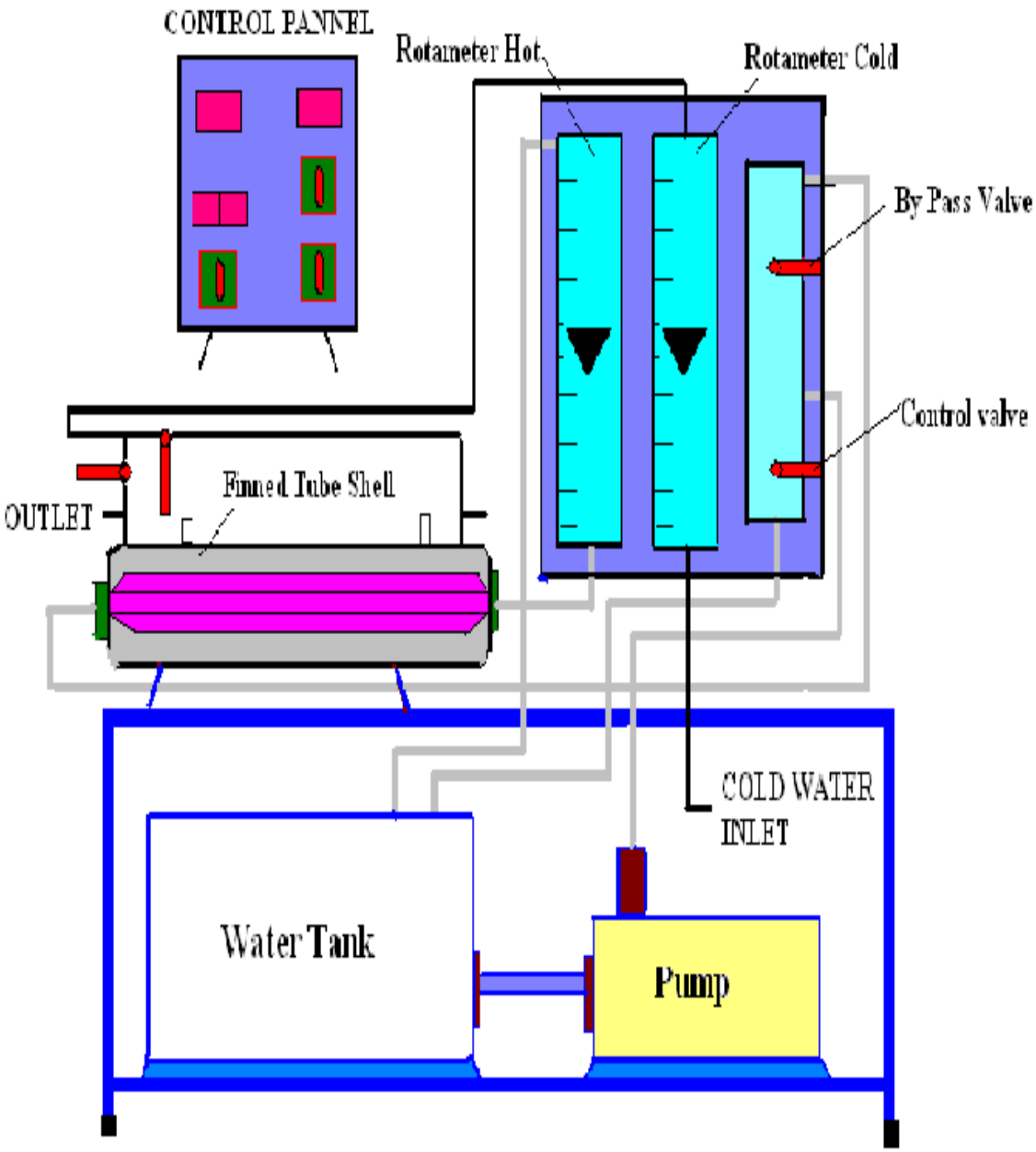

FINNED TUBE HEAT EXCHANGER

INDIAN INSTITUTE OF TECHNOLOGY KANPUR
Department of Chemical Engineering
Unit Operation Lab

Experiment Name: PARALLEL FLOW/COUNTER FLOW HEAT EXCHANGER

1. OBJECTIVE:
To study the heat transfer phenomena in Parallel / Counter flow arrangements.

2. AIM:

To calculate rate of heat transfer, LMTD and overall heat transfer coefficient for both type of heat exchanger.

To compare the performance of Parallel and Counter flow heat exchanger.

3. INTRODUCTION:

Heat Exchanger is a device in which heat is transferred from one fluid to another. The necessity for doing this arises in a multitude of industrial applications. Common examples of heat exchangers are the radiator of a car, the condenser at the back of a domestic refrigerator and the steam boiler of a thermal power plant.

Heat Exchangers are classified in three categories:

1) Transfer Type.
2) Storage Type.
3) Direct Contact Type

4. THEORY:

A transfer type of heat exchanger is one on which both fluids pass simultaneously through the device and heat is transferred through separating walls. In practice most of the heat exchangers used are transfer type ones.

The transfer type exchangers are further classified according to flow arrangement as -

1. Parallel flow in which fluids flow in the same direction.
2. Counter flow in which they flow in opposite direction and
3. Cross flow in which they flow at right angles to each other.

A simple example of transfer type of heat exchanger in the form of a tube type arrangement in which one of the fluids is flowing through the inner tube and the other through the annulus surroundings it. The heat transfer takes place across the walls of the inner tube.

5. DESCRIPTION:

The apparatus consists of a tube in tube type concentric tube heat exchanger. The hot fluid is hot water which is obtained from an insulated water bath using a magnetic drive pump and it flow through the inner tube while the cold fluid is cold water flowing through the annuals. The hot water flows always in one direction and the flow rate of which is controlled by means of a valve. The cold water can be admitted at one of the end enabling the heat exchanger to run as a parallel flow apparatus or a counter flow apparatus. This is done by valve operations. For flow measurement Rotameters are provided at inlet of cold water and outlet of hot water line. A magnetic drive pump is used to circulate the hot water from a recycled type water tank, which is fitted with heaters and Digital Temperature Controller.

Technical Detail:

Outer Pipe	Inner Diameter 28 mm, Length 1.6 m.
Inner Pipe	Inner Diameter 9.5 mm, Outer Diameter 12.7 mm, Length 1.6 m.

6. UTILITIES REQUIRED:

1. Electricity Supply: Single Phase, 220 VAC, 50Hz, 5-15Amp socket with earth connection.
2. Water Supply: Continuous @ 5 LPM at 1 Bar.
3. Drain Required.
4. Floor Area Required: 2 m x 0.5 m

7. EXPERIMENTAL PROCEDURE:

Starting procedure:

1. Close all the valves provided on the set up.
2. Open the lid of hot water tank, fill the tank with water and put the lid back to its position.
3. Ensure that switches given on the panel are at OFF position.
4. Connect electric supply to the set up.
5. Set the desired water temperature in the DTC by operating the increment or decrement and set button of DTC.
6. Open by pass valve and Switch ON the pump.
7. Switch ON the heater and wait till desired temperature achieves.

8. Connect cooling water supply to the set up.
9. Connect both the outlet (parallel / counter) of cooling water to drain.
10. Open the inlet & outlet valve for cold water as per desired mode (parallel/counter flow).
11. Allow cold water to flow through heat exchanger and adjust the flow rate by Rotameter and control valve.
12. Allow hot water to flow through heat exchanger and adjust the flow rate by Rotameter, control valve and by pass valve.
13. At steady state (constant temperature) record the temperatures & flow rate of hot and cold water.
14. Repeat the experiment for different flow rate of hot & cold water.
15. Repeat the experiment for different bath temperature.
16. Repeat the experiment for other mode (counter/parallel flow).

Closing procedure:

1. When experiment is over switch OFF heaters.
2. Switch OFF pump.
3. Switch OFF Power Supply to Panel.
4. Stop cooling water supply.
5. Drain hot water tank by the drain valve provided.

8. OBSERVATION & CALCULATION:

DATA:

D_i = 0.0095 m

D_o = 0.0127 m

L = 1.6 m

OBSERVATION TABLE:

S. No.	Mode Parallel / Counter	F_h LPH	T_1 °C	T_2 °C	F_c LPH	T_3 °C	T_4 / T_5 °C
1.							
2.							

CALCULATIONS:

Find the properties of water (C_{ph}, ρ_h) at $T_h = \frac{T_1 + T_2}{2}$ and (C_{pc}, ρ_c) at $T_c = \frac{T_3 + T_4}{2}$ *or* $\frac{T_3 + T_5}{2}$ (as per mode selected) from data book.

C_{ph} = ---------- kJ/kg ^oC

C_{pc} = ---------- kJ/kg ^oC

ρ_h = ---------- kg/m^3

ρ_c = ---------- kg/m^3

$M_h = \frac{F_h \times \rho_h}{3600 \times 1000}$, kg/s = ---------- kg/s

$Q_h = M_h C_{ph}(T_1 - T_2)$, W = ---------- W

$M_c = \frac{F_c \times \rho_c}{3600 \times 1000}$, kg/s = ---------- kg/s

$Q_c = M_c C_{pc}(T_4 - T_3)$, W (for parallel flow) = ---------- W

$Q_c = M_c C_{pc}(T_5 - T_3)$, W (for counter flow) = ---------- W

$Q = \frac{Q_h + Q_c}{2}$, W = ---------- W

$\Delta T_1 = T_1 - T_3$, ^{o}C (for parallel flow) = ---------- ^{o}C

$\Delta T_1 = T_1 - T_5$, ^{o}C (for counter flow) = ---------- ^{o}C

$\Delta T_2 = T_2 - T_4$, ^{o}C (for parallel flow) = ---------- ^{o}C

$\Delta T_2 = T_2 - T_3$, ^{o}C (for counter flow) = ---------- ^{o}C

$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}}$, ^{o}C = ---------- ^{o}C

$A_i = \pi D_i L$, m^2 = ---------- m^2

$A_o = \pi D_o L$, m^2 = ---------- m^2

$U_i = \frac{Q}{A_i \Delta T_m}$, W/$m^2$ ^{o}C = ---------- W/m^2 ^{o}C

$U_o = \frac{Q}{A_o \Delta T_m}$, W/m^2 ^{o}C = ---------- W/m^2 ^{o}C

9. NOMENCLATURE:

A_i	=	Inside heat transfer area, m^2
A_o	=	Outside heat transfer area, m^2
C_{ph}	=	Specific heat of hot fluid at mean temperature, kJ/kg ^{o}C
C_{pc}	=	Specific heat of cold fluid at mean temperature, kJ/kg ^{o}C
D_o	=	Outer diameter of tube, m
D_i	=	Inner diameter of tube, m
F_h	=	Flow rate of hot water, LPH
F_c	=	Flow rate of cold water, LPH
L	=	Length of tube, m
M_h	=	Mass flow rate of the hot water, kg/s
M_c	=	Mass flow rate of the cold water, kg/s
Q	=	Average heat transfer from the system, W
Q_c	=	Heat gained by the cold water, W
Q_h	=	Heat loss by the hot water, W
T_h	=	Mean temperature of hot water, ^{o}C
T_c	=	Mean temperature of cold water, ^{o}C
T_1	=	Inlet temperature of the hot water, ^{o}C
T_2	=	Outlet temperature of the hot water, ^{o}C
T_3	=	Inlet temperature of the cold water, ^{o}C
T_4	=	Outlet temperature of the cold water for parallel flow, ^{o}C
T_5	=	Outlet temperature of the cold water for counter flow, ^{o}C
ΔT_m	=	Log mean temperature difference, ^{o}C
U_i	=	Inside overall heat transfer coefficient, W/ m^2 ^{o}C
U_o	=	Outside overall heat transfer coefficient, W/ m^2 ^{o}C
ρ_c	=	Density of cold water at mean temp, kg/m^3
ρ_h	=	Density of hot water at mean temp, kg/m^3

10. PRECAUTIONS & MAINTENANCE INSTRUCTIONS:

10.9 Never run the apparatus if power supply is less than 180volts and above than 230volts.

10.10 Never switch ON mains power supply before ensuring that all the ON/OFF switches given on the panel are at OFF position.

10.11 Operator selector switch off temperature indicator gently.

10.12 Always keep the apparatus free from dust.

11. TROUBLESHOOTING:

2. If electric panel is not showing the input on the mains light, check the main supply.

12. REFERENCES:

1. Holman, J.P., **"Heat Transfer"**, 9th ed., McGraw Hill, NY, 2008, Page 525-526, 528-531.
2. McCabe, Smith, J.C., Harriott, P., **"Unit Operations of Chemical Engineering"**, 7th ed. McGraw Hill, NY, 2005, Page 327-329, 331-333.

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INDIAN INSTITUTE OF TECHNOLOGY KANPUR
Department of Chemical Engineering
Unit Operation Lab

Experiment Name: - PLATE & FRAME FILTER PRESS

1. OBJECTIVE:

To study the operation of plate and frame filter press.

2. AIM:

To determine Specific cake resistance (α) and medium resistance (R).

3. INTRODUCTION

The separation of solids from a suspension in a liquid by means of porous medium or screen which retains the solids and allow the liquid to pass is termed filtration. In general the pores of the medium will be larger than the particles which are to be removed, and the filter will work efficiently only after an initial deposit has been trapped in the medium. Filtration is essentially a mechanical operation and is less demanding in energy than evaporation or drying. The most suitable filter for any given operation is the one which will fulfill the requirements at minimum overall cost. The most important factors in filter selection are the specific resistance of filter cake, the quantity to be filtered and the solid concentration.

4. THEORY:

Filtration involves the separation of solids from liquids by passing a suspension through a permeable medium, which retains the particles.

FOR INCOMPRESSIBLE CAKE:

The basic filtration equation is:

$$\frac{dt}{dv} = \frac{\alpha * \mu * c}{2A^2 * \Delta P} * v + \frac{\mu * R}{A * \Delta P} \qquad \text{--------- (1)}$$

$$\frac{dt}{dv} = a_1 \frac{v}{2A^2 \Delta P} + b_1 \frac{1}{A \Delta P} \qquad \text{---------- (2)}$$

Where,

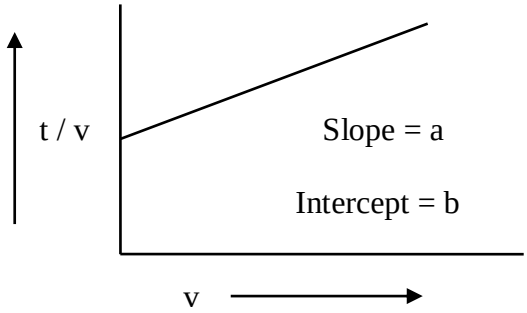
$a_1 = \alpha * \mu * c$ and $b_1 = \mu * R$.

a) Under constant pressure filtration condition, integration of the above equation yields:

$$\frac{t}{v} = av + b$$

Where, $a = \frac{a_1}{2A^2 \Delta P}$ and $b = \frac{b_1}{A \Delta P}$

Plot of t/v vs v yields constants a & b.



$a_1 = 2 * A^2 * \Delta P * a$ and $b_1 = A * \Delta P * b$

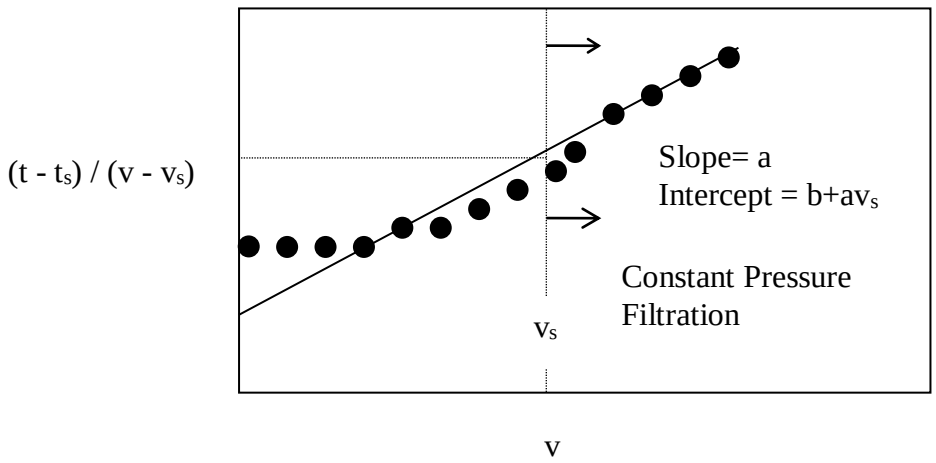
and so,

$$\alpha = \frac{a_1}{\mu * c} \text{ and } R = \frac{b_1}{\mu}$$

b) When true constant pressure filtration condition starts at t_s & v_s then the 1st equation can be written as:

$$\frac{t - t_s}{v - v_s} = \frac{\alpha * \mu * c}{2 * A^2 * \Delta P} * (v + v_s) + \frac{\mu * R}{A * \Delta P} \qquad \text{---------- (3)}$$

Using equation (3), plot of $\frac{t - t_s}{v - v_s}$ (sec / m^3) vs. v (m^3) yields:



Constant α and R can be calculated as:

$$\alpha = \frac{2 * A^2 * \Delta P * a}{\mu * c} \qquad \text{---------- (4)}$$

$$R = \frac{A * \Delta P * b}{\mu} \qquad \text{---------- (5)}$$

5. DESCRIPTION:

The set up consists of 7 plates and 6 frames. Frames are covered with filter cloth. Feed is fed by gear pump at the top and filtrate collected at the bottom from each plate by operating the cock. After removing cake, washing and cleaning can be done by water provided by overhead tank. Inlet and outlet pressures are measured by pressure gauges. Rate of filtrate removals is measured by calibrated tank provided.

6. UTILITIES REQUIRED:

1. Electricity Supply: Single phase, 220 V AC, 50 Hz, 5-15 amp socket with earth connection.
2. Water Supply (Initial fill)
3. Drain required.
4. $CaCO_3$: 10 kg.

7. EXPERIMENTAL PROCEDURE:

1. Prepare slurry of $CaCO_3$ in water (5%).
2. Filter the prepared solution and fed it in the feed tank.
3. Switch on the agitator of the feed tank.
4. Fix the plate and frames on the press.
5. Connect the outlet of the filter press to the filtrate tank.
6. Start the pump and allow feed to enter the press.
7. Record the Inlet slurry pressure, P_i and Outlet slurry pressure, P_o.
8. Collect the filtrate in the receiver. Record the amount of filtrate collected v in time t.
9. Run the filtration till there is appreciable fall in rate of filtrate collection.

8. OBSERVATION & CALCULATION:

DATA:

N_F = 6

A_c = ----- m^2.

A_{F1} = ----- m^2

μ at 20°C = 0.001 Ns/m^2

g = 9.81 m/sec^2

OBSERVATION:

c = ---------- kg/m^3

OBSERVATION TABLE:

S.No	t, sec	h, cm	P_i, kg/cm^2	P_o, kg/cm^2

CALCULATIONS:

$$v = \frac{A_c \times h}{100}$$

S.No.	t, sec	v, m^3	t/v (sec/m^3)

From the above table, plot the graph between v vs. t/v.

Then find out the slope & the intercept (i.e. a and b).

$\Delta P = P_i - P_o$ = ---------- N/m^2

$A = 2 \times N_F \times A_{F1}$, m^2 = ---------- m^2

$$\alpha = \frac{2 \times A^2 \times \Delta P \times a}{\mu \times c}, \text{ m/kg} = \text{---------- m/kg}$$

$$R = \frac{A \times \Delta P \times b}{\mu}$$, m^{-1} = ---------- m^{-1}

9. NOMENCLATURE:

a	=	Slope of the graph
A_{F1}	=	Area of one frame, m^2
A_C	=	Area of filtrate tank, m^2
A	=	Total Filtration Area, m^2
b	=	Intercept of the graph
c	=	Concentration of the slurry, kg/m^3
G	=	Acceleration due to gravity, m/sec^2
N_F	=	Number of frame
ΔP	=	Pressure drop, kg/cm^2
P_i	=	Inlet pressure, kg/cm^2
P_o	=	Outlet pressure, kg/cm^2
R	=	Medium Resistance, m^{-1}
t	=	Time, sec.
v	=	Volume of filtrate collected in time t, m^3
α	=	Specific Cake Resistance, m/kg
μ	=	Viscosity of the filtrate, Ns/m^2
h	=	Height of filtrate finished collected in time t, cm

10. PRECAUTIONS & MAINTENANCE INSTRUCTIONS:

1. Proper cleaning of plates and frames and its clothes is must.
2. Feed slurry is filtered before feeding it into the tank.
3. Plates & frames should be properly tightened.

11. TROUBLESHOOTING:

1. If the slurry is leaking more than enough detached the plate and frame, arrange it properly and tight it again.
2. If the slurry is not coming properly than check whether the holes of the clothes and frames are matching if not arrange it accordingly.

12. REFERENCES:

1. Coulson & Richardson, "Chemical Engineering Vol-2" 4th ed, Asian Books Pvt.Lt, ND,1991, Page 303-309
2. George Granger Brown, "Unit Operations", 1st ed, CBS Publishers & Distributors, ND, 1995, Page 231-233

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

Department of Chemical Engineering

Unit Operation Lab

Experiments Name: Cyclone Separator

OBJECTIVE:

To study the operation of a cyclone separator.

AIM:

1. To calculate the inlet gas velocity.
2. To calculate the collection efficiency of a given cyclone separator.

INTRODUCTION:

Cyclones are widely used principle type of gas-solids separators employing centrifugal force. These are basically simple constructions; can be made from a wide range of materials and designed for high temperature and pressure operation. Cyclones are also extensively used for separating solids from liquids, especially for purpose of classification.

THEORY:

Cyclone is the most widely used centrifugal separation equipment for separating dust or mist from gases. It is basically a settling device in which a strong centrifugal force, acting radially, is used in place of a relatively weak gravitational force acting vertically. It consists of a vertical cylinder with a conical bottom, a tangential inlet near the top, and an outlet for dust at the bottom of the cone. The incoming dust laden air travels in a spiral path around and down the cylindrical body of the cyclone. The centrifugal force developed in the vortex tends to move the particles radially towards the wall, and the particles that reach the wall slide down into the cone and are collected.

DESCRIPTION:

The setup consists of I.D. blower connected to discharge side of cyclone separator and a pneumatic conveying system. A flow meter with manometer is provided to measure flow of air. Pressure gauge and regulator is provided to control air supply to feed

chamber. Collector is provided to collect solid particles. Flow control valve and by pass valve are provided for control the flow.

UTILITIES REQUIRED:

1. Electricity Supply: Single phase, 220 V AC, 50 Hz, 5-15 Amp combined socket with earth connection.
2. Floor Area Required: 2 m x 1 m.
3. Electronics Weighing Balance capacity 2 kg, least count 1 gm.
4. Raw material for feed (Coal powder, talcum powder – 0.5 kg)

EXPERIMENTAL PROCEDURE:

STARTING PROCEDURE:

1. Prepare feedstock of Coal powder or talcum powder with constant average particle size.
2. Note down the weight (W) and particle size of the feed.
3. Switch ON the power supply.
4. Connect air supply.
5. Feed the dust particles in feeding chamber.
6. Start the cyclone separator.
7. Set desired pressure with the help of pressure gauge and regulator.
8. Fix the flow rate of air by adjusting the flow control valve and by pass valve.
9. Note down the manometer reading.
10. Collect the particles from bottom.
11. Measure the weight of particles collected from the bottom of cyclone (W_c).
12. Repeat the experiment for different particle size.
13. Repeat the experiment for different flow rate of air.
14. Repeat the experiment for different air pressures.

CLOSING PROCEDURE:

When the experiment is over switch OFF the power supply.

OBSERVATION & CALCULATION:

DATA:	
Acceleration due to gravity (g)	= 9.81 m/sec^2
Diameter of pipe for pitot tube (d)	= 0.042 m
Density of manometric fluid (ρ_m)	= 1000 kg/m^3
Density of air (ρ_a)	= 1.21 kg/m^3
Coefficient of pitot tube (C_v)	= 0.98

OBSERVATION TABLE:

S.No	S (mm)	h_1 (cm)	h_2 (cm)	W (kg)	W_c (kg)

CALCULATIONS:

$$\Delta H = \left(\frac{h_1 - h_2}{100}\right)\left(\frac{\rho_m}{\rho_a} - 1\right) \text{ (m of } H_2O)$$

$$A = \frac{\pi}{4} d^2 \ (m^2)$$

$$V = C_V \sqrt{2g\Delta H} \ (m/sec)$$

$$Q = VA \ (m^3/sec)$$

$$\eta = \frac{W_c}{W} \times 100 \ (\%)$$

NOMENCLATURE:

Nom	Column Heading	Units	Type
A	Cross sectional area of pipe	m^2	Calculated
C_V	Coefficient of pitot tube	unitless	Given
d	Diameter of the pipe for pitot tube	m	Given
g	Acceleration due to gravity	m/sec^2	Given
h_1,h_2	Reading of manometer	cm	Measured
Q	Flow rate of air	m^3/sec	Calculated
S	Size of the particle	mm	Measured
V	Inlet gas velocity of air	m/sec	Calculated
W	Weight of particles fed to the cyclone	kg	Measured
W_c	Weight of particles collected at the bottom of the cyclone	kg	Measured
ΔH	Head loss	m of H_2O	Calculated
ρ_a	Density of air	kg/m^3	Given
ρ_m	Density of manometric fluid	kg/m^3	Given
η	Collection efficiency	%	Calculated

PRECAUTION & MAINTENANCE INSTRUCTIONS:

1. Never run the apparatus if power supply is less than 180 volts and more than 230 volts.
2. Always use the dry particles.

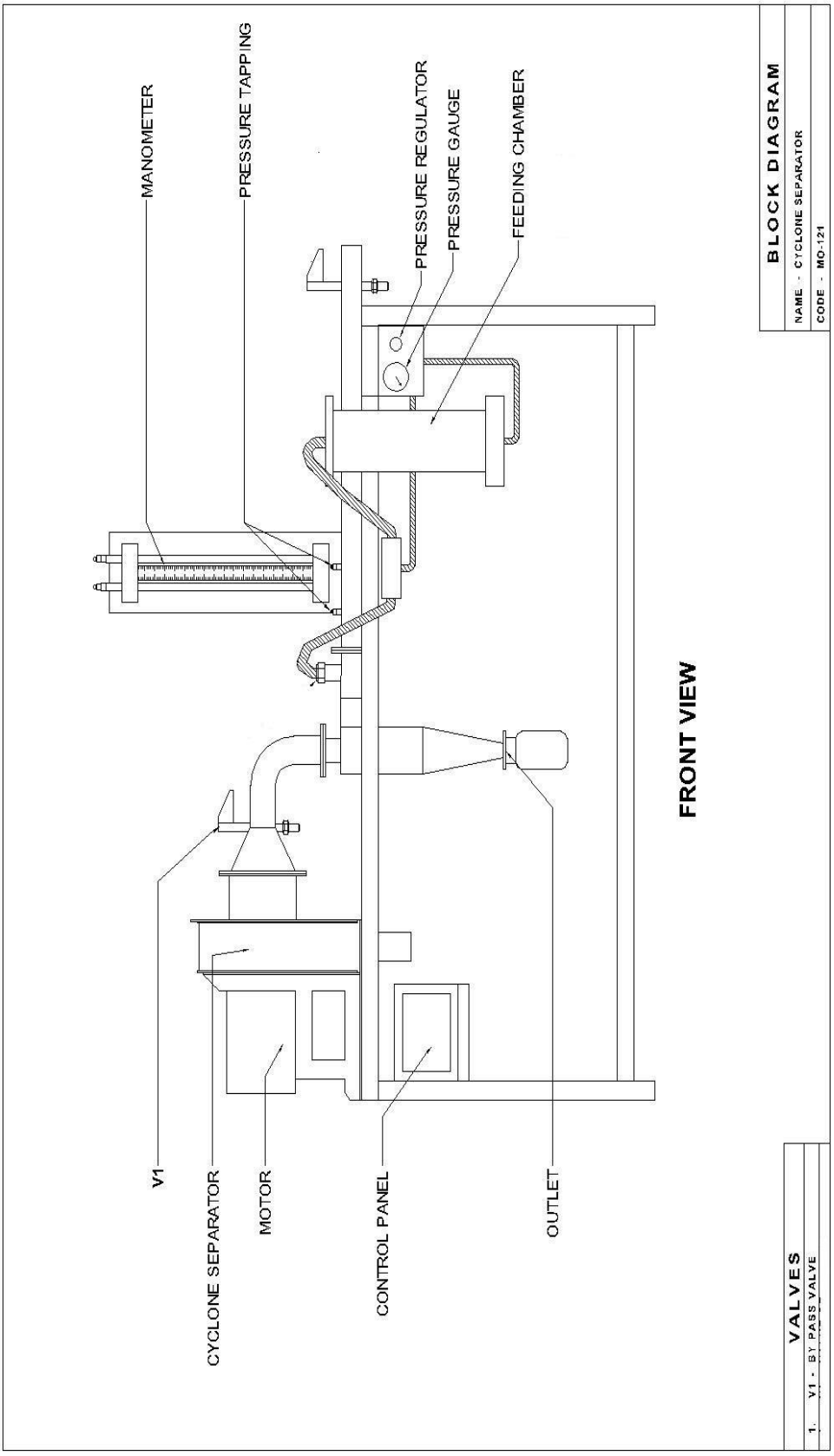
TROUBLESHOOTING:

If the motor shaft is not moving but electric power is showing ON then switch OFF the power supply and move the motor shaft manually. When it moves freely, then start it again.

REFERENCES:

McCabe, Warren L. Smith, Julian C. Harriott, Peter (2005). *Unit Operations of Chemical Engineering.* 7th Ed. NY: McGraw-Hill. pp 1066-1069.

BLOCK DIAGRAM:



INDIAN INSTITUTE OF TECHNOLOGY KANPUR

Department of Chemical Engineering

Unit Operation Lab

Experiments Name: Batch Distillation

1. **Scope:**
When a liquid is to be separated into its components batch distillationis especiall y useful for small amount of material . A given batch distillation unitmay be used to process many different mixtures. When there are several compounds (N) in the feed, one batch column will suffice to separate all of them whereas N-1 continuous stills will be required. When solids are present, batch distillation is moreconvenient than the continuous one.

2. **Objective:**
(a) To observe the operation of batch distillation
(b) To determine the number o theoretical plates; to obtain an overall heat Balance.

3. **Theory & Formulae:**
In batch distillation, a batch of liquid is charged in the still and heated, and when vaporshave reached the condensing system a portion of the condensed distillate is returned as reflux. As top product take off is carried out , the material in the still becomes poorer in the more volatile component (s) ,hence as the distillation proceeds the reflux ratio must be increased to maintain the top-product quality, or sacrifice in sharpness of separation must be made.
If the column is operated with a given mixture at total reflux, the Fenske Underwood equation can be used to calculate theoretical plates for a binary separation.

$$N+1=\frac{\log\dfrac{x_p(1-x_s)}{x_s(1-x_p)}}{\log\alpha} \qquad (1)$$

Where, α = Relative volatility
N = Theoretical plates
x_p = Product concentration .
x_s = Final still concentration ,mole fraction.

If the column is operated at a fixed know reflux ratio, then the product concentration varies during the cycle. The variation of product concentration with amount of liquid remaining in the still is given by

$$\ln\frac{S_1}{S_2}=\int_{x_{s_2}}^{x_{s_1}}\frac{dx_s}{(x_p-x_s)} \qquad (2)$$

Where, S_1= initial batch charge, moles
S_2=residue in kettle at the end, moles

Relation betweenx_p&x_s can be obtained from X-Y diagram by plottingenriching section operating line of slope determines by the fixed (L/V)ratio, with the lower terminus starting with the initial still concentration and final line terminating with x_{s2}. Based upon the fixed no. of plates a relation between x_p&x_s can be calculated by the above procedure. Equations (2) can then be integrated to give curves showing product and still composition as functions of the percent of charge distilled.
(refer Perry's Chemical Engineering Handbook,6th edition pg.13-82 to 13-85)

4. Materials and Apparatus:

The binary system used in the distillation experiment is ethanol-water. Analysis is carried out by refractometer. The calibration curve of refractive index vs percent ethanol (0-100 %) must be obtained at room temperature before hand. The reflux ratio can be adjusted by timer. Other apparatus include sample bottles, thermometers or thermocouples.

5. Procedure:

5.1 Obtain the calibration curve for refractive index vs percent ethanol.
5.2 Charge a known amount of ethanol and water (50-50%) mixture in the still and start heating.
5.3 Operate under total reflux (keeping the timer off) until steady state is reached obtained distillate and bottoms (x_p, x_s) samples.
5.4 Take the necessary data – refractive index and specific gravityof reflux and residue, cooling water rate, reflux rate and temperatureof inlet and outlet water stream in order to be able to obtained a heat balance.
5.5 Record the weight (or volume) distilled vs time and record the weight of the still sample.
5.6 Operate under a known fixed reflux ratio (say 5:1). Obtain samples at various times and measure total amount of distillate collected.
5.7 Obtain RI and Specific Gravity of both Distillate collected and RI of bottoms.
5.8 Record the temperature of bottoms and distillate for heat balance.
5.8 Repeattherun at other known reflux ratio.

6. Results:

6.1 Plot calibration curve and equilibrium data for ethanol water system at 1.013 x 10^2 KN/m^2total pressure.
6.2 Find number of theoretical stages using Fenske-Underhood equation and compare with actual number of stages.
6.3 Set up material and energy balance equations.
6.4 Make a heat balance for the total reflux run and determine the % heat loss.
6.5 Plot moles of liquid remaining in the still vs distillate composition ($s_2$vsx_p) and compare with results obtained from equation (2).
6.6 Comment on the sieve plates in the column.
6.7 Obtain a material balance on the last run and determine the % ethanol loss. Account for all the ethanol.

7. Questions:

7.1 While setting up the equations, negligible column hold up is assumed. What happens if the hold up is not actually negligible?
7.2 Can a packed column be used instead of sieve plate or bubble plate column for any separation?
7.3 What must be done to maintain the distillate quality in a batch distillation column?
7.4 How will you set up the performance equation for the still if the assumption of constant rate of distillate is not valid?

8. References:

8.1 Fenske, Ind.Eng.Chem. 24, 482, (1932)

8.2 Smoker & Rose, Trans Am.Inst.Chem.Engrs. 36, 285 (1940)

8.3 M. Van Winkle, "Distillation", McGrow Hill Book Co. New York, (1967)

8.4 Perry's Chemical Engineering Handbook,6th edition, Editors:RobertH.Perry and Don Green.

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

Department of Chemical Engineering

Unit Operation Lab

Experiment Name: Natural convection Apparatus

1. Objective:

Study of convection heat transfer in natural convection.

2. Aim:

To find out the heat transfer co-efficient of vertical cylinder in natural convection.

3. Introduction:

Convection is defined as process of heat transfer by combined action of heat conduction and mixing motion. Convection heat transfer is further classified as Natural Convection and Forced Convection. If the mixing motion takes place due to density difference caused by temperature gradient, then the process of heat transfer is known as Natural or Free Convection. If the mixing motion is induced by some external means such as a pump or blower then the process of heat transfer is known as Forced Convection.

4. Theory:

Natural convection phenomenon is due to the temperature difference between the surface and the fluid and is not created by any external agency. The Setup is designed and fabricated to study the natural convection phenomenon from a vertical cylinder in terms of average heat transfer coefficient.

The average heat transfer coefficient is given by

$$h = \frac{Q_a}{A(T_s - T_a)}$$

5. Description:

The apparatus consists of a brass tube fitted in a rectangular duct in a vertical fashion. The duct is open at the top and bottom and forms an enclosure and serves the purpose of undisturbed surrounding. One side of it is made up of glass/acrylic for visualization. A heating element is kept in the vertical tube, which heats the tube surface. The heat is lost from the tube to the surrounding air by natural convection. Digital Temperature Indicator measures the temperature at the different points with the help of temperature sensors. The heat input to the heater is measured by Digital Ammeter and Digital voltmeter and can be varied by a dimmerstat.

6. Utilities Required:

6.1 Electricity Supply: Single Phase, 220 V AC, 50 Hz, 5-15Amp socket with earth connection.

6.2 Floor Area Required: 1 m x 1 m.

7. Experimental Procedure:

7.1 Starting procedure:

7.1.1 Ensure that Mains ON/OFF switch given on the panel is at OFF position & dimmer stat is at zero position.

7.1.2 Connect electric supply to the set up.

7.1.3 Switch ON the Mains ON / OFF switch.

7.1.4 Set the heater input by the dimmer stat, voltmeter in the range 40 to 100 V.

7.1.5 After 1.5 hrs. note down the reading of voltmeter, ammeter and temperatures in the observation table after every 10 minutes interval until change in observed value in consecutive readings of temperatures is less than ± 0.2 ^oC

7.2 Closing procedure:

7.2.1 After experiment is over set the dimmer stat to zero position.

7.2.2 Switch OFF the Mains ON/OFF switches.

7.2.3 Switch OFF electric supply to the set up.

8. Observations and Calculations:

DATA:

L = 0.5 m
d = 0.038 m

OBSERVATION TABLE:

S. No.	V volts	I amp	T_1 ^oC	T_2 ^oC	T_3 ^oC	T_4 ^oC	T_5 ^oC	T_6 ^oC	T_7 ^oC	T_8 ^oC

CALCULATIONS:

$Q = V \times I$, W = ---------- W

$A = \pi dL$, m^2 = ---------- m^2

$T_s = \frac{T_1 + T_2 + T_3 + T_4 + T_5 + T_6 + T_7}{7}$,°C = ---------- °C

$h = \frac{Q}{A(T_s - T_a)}$, W/m^2 °C, (Ta = T_8) = ---------- W/m^2 °C

9. Nomenclature:

A	=	Heat transfer area, m^2
d	=	Diameter of cylinder, m
h	=	Heat transfer coefficient, W/m^2 °C
I	=	Ammeter reading, amp
L	=	Length of cylinder, m
Q	=	Amount of heat transfer, W
T_s	=	Average surface temperature,°C
T_a	=	Temperature of air,°C
T_1 to T_7	=	Surface temperature of test section, ^{o}C
V	=	Voltmeter reading, volts

10. Precaution and maintenance Instructions:

10.13 Never run the apparatus if power supply is less than 180 volts and above than 230 volts.

10.14 Never switch ON mains power supply before ensuring that all the ON/OFF switches given on the panel are at OFF position.

10.15 Operate selector switch off temperature indicator gently.

10.16 Always keep the apparatus free from dust.

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11. Troubleshooting:

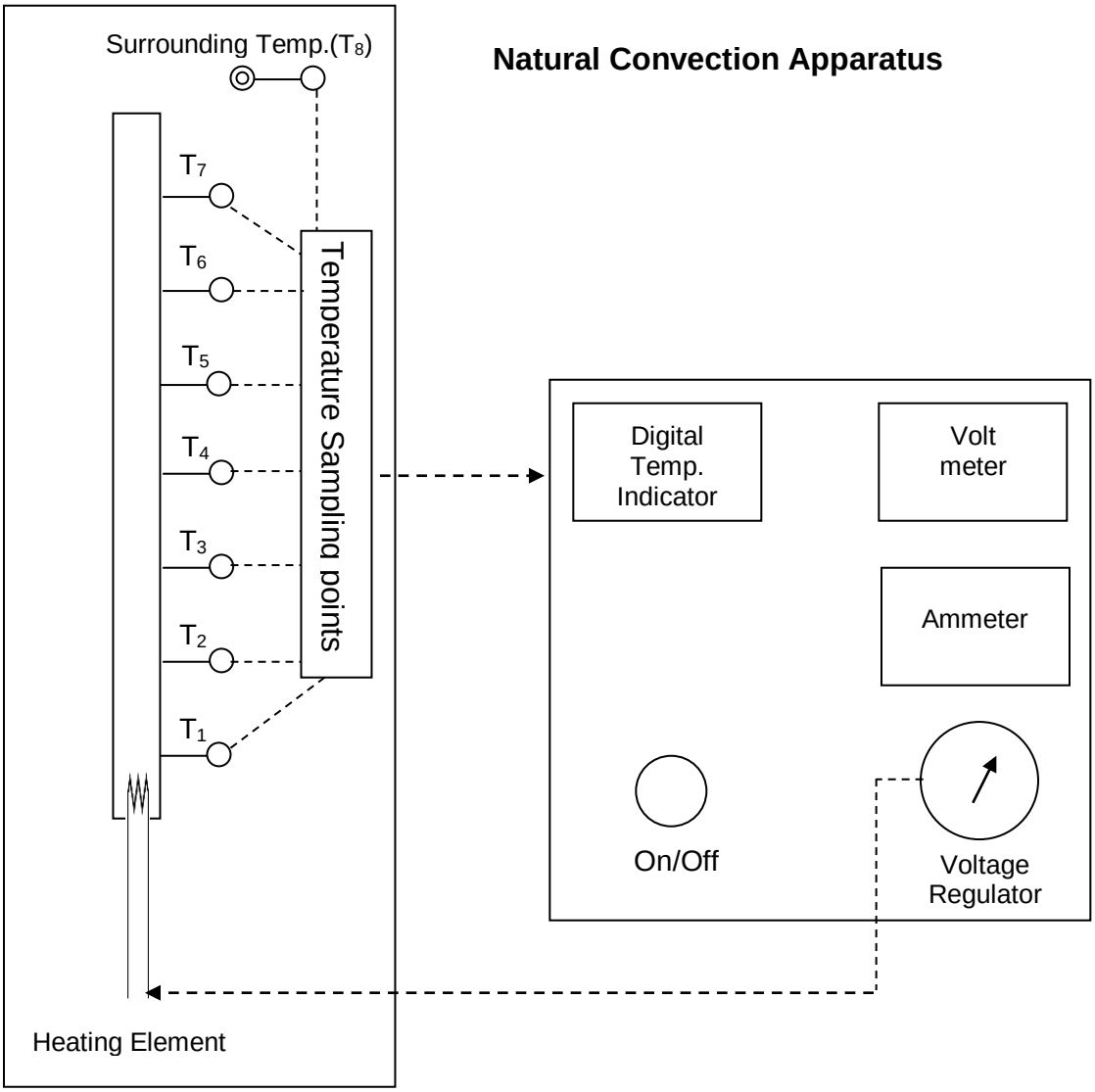
11.1 If electric panel is not showing the input on the mains light, check the main supply.

11.2 Voltmeter showing the voltage given to heater but ammeter does not show reading, check the connection of heater in control panel.

12. References:

12.1 McCabe, W.L., Smith, J.C., Harriott, P., **"Unit Operations of Chemical Engineering"**, 7th ed., McGraw Hill, NY, 2005, Page 296.

12.2 Y.A. Cengel, **"Heat & Mass Transfer"**, McGraw Hill, ND, 2008, Page 25-26.


Natural Convection Apparatus
Surrounding Temp.(T_8)
T_7
T_6
T_5
T_4
T_3
T_2
T_1
Temperature Sampling points
Heating Element
Digital Temp. Indicator
Volt meter
Ammeter
On/Off
Voltage Regulator

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

Department of Chemical Engineering

Unit Operation Lab

Experiment Name: Thermal Conductivity of Insulating Slab

1. **Objective:**
   Study of heat transfer through insulating slab
   Study of variation of thermal conductivity of the material with temperature

2. **Aim:**
   To find out the thermal conductivity of insulating material in the form of slab

3. **Principle and Formulae:**
   When a temperature gradient exists in a body, there is an energy transfer from the high temperature region to the low temperature region. Energy is transferred by conduction and heat transfer rate per unit area is proportional to the normal temperature gradient:

$$\frac{q}{A} \alpha \frac{\Delta T}{\Delta X}$$

When the proportionality constant is inserted,

$$q = -kA\frac{\Delta T}{\Delta X}$$

Where q is the heat transfer rate and $\Delta T / \Delta X$ is the temperature gradient in the direction of heat flow. The positive constant k is called thermal conductivity of the material.

For the measurement of thermal conductivity (k) what is required is to have a one dimensional heat flow through the flat specimen, an arrangement for maintaining its faces at constant temperature and some metering method to measure heat flow through a known area. To eliminate the distortion caused by edge losses in unidirectional heat flow, the central plate is surrounded by a guard ring, which is separately heated. Temperatures are measured by calibrated temperature sensors either attached to the plates or to the specimens at the hot and cold faces. Two specimens are used to ensure that all the heat comes out through the specimen only. Knowing the heat input to the central plate heater, the temperature difference across the specimen, its thickness and the metering area, one can calculate K of the specimen by the following formula:

$$K = \frac{q}{2A}\left(\frac{L}{T_h - T_C}\right) \text{ W/mK}$$

4. Equipment/ Apparatus Description

The apparatus consists of main central heater and ring guard heater, sandwiched between the specimens. Cooling plates are provided on the either side of the specimen. Two identical specimens are clamped between heater ensures unidirectional heat flow through specimen. The whole assembly is kept in chamber and insulated by ceramic wool insulation around the set-up.

5. Utilities Required

5.1 Electricity Supply: Single Phase, 220 VAC, 50Hz, 5-15 Amp socket with earth connection.
5.2 Water supply: Continuous @ 2 LPM at 1 Bar.
5.3 Drain.
5.4 Bench area required: 1 m X 1 m.

6. Experimental Procedure

6.1 Starting procedure:

6.1.1 Connect continuous water supply to the inlet of water chamber.
6.1.2 Connect water outlet of chamber to drain.
6.1.3 Ensure that main ON/OFF switch given on the panel is at OFF position & dimmer stat is at zero position.
6.1.4 Connect electric supply to the set-up.
6.1.5 Switch on the main ON/OFF switch.
6.1.6 Set the central heater input by the dimmer stat, voltmeter in the range 40 to 100 V
6.1.7 Set guarded heater input by dimmer stat, voltmeter, 5 V above than central heater.
6.1.8 After 1.5 hrs note down the reading of voltmeter, ampere meter and temperature sensors in the observation table
6.1.9 Than after every 10 minutes interval till record change in consecutive readings reading of temperature sensors in the observation table (more than $\pm 1^{o}C$).

6.2 Closing Procedure**:**

6.2.1 After experiment is over set the dimmer stat to zero position.
6.2.2 Switch OFF the Main ON/OFF switch.
6.2.3 Switch OFF electric supply to the set-up and remove the board socket.
6.2.4 Stop flow of water by closing the valve provided as well as the mail source valve.

7. Observation and Calculation

DATA
d = 0.18 m
x = 0.012 m

OBSERVATION TABLE:

Sl. No	Central Heater				Guarded Heater				Cooling Plate	
	V_C	I_C	T_1	T_2	V_G	I_G	T_3	T_4	T_5	T_6
1,										
2.										
3.										

CALCULATIONS:

$Q = V_C \times I_C$, W = …… W

$A = \frac{\pi}{4} d^2$, m^2 = …… m^2

$T_h = \frac{(T_1 + T_2)}{2}$, ^oC = ……^oC

$T_c = \frac{(T_5 + T_6)}{2}$, ^oC = ……^oC

$k = \frac{Q \times x}{2A(T_h - T_c)}$, W/m^oC =……..W/m^oC

8. Nomenclature

A	=	Area of the specimen
d	=	Diameter of specimen
I_C	=	Central Heater Current, amp
I_G	=	Guarded Heater Current, amp
K	=	Thermal Conductivity of slab, W/m^oC
Q	=	Heat flow rate in the specimen, W
T_h	=	Hot Plate Temperature, ^oC
T_c	=	Cold Plate Temperature, ^oC
T_1,T_2	=	Temperature of upper heater slab, ^oC
T_3,T_4	=	Temperature of the side guarded heater, ^oC
T_5,T_6	=	Surface temperature of the cooling plate, ^oC
V_C	=	Central heater voltage, Volts
V_G	=	Guarded heater voltage, Volts
x	=	Thickness of specimen. m

9. Safety measures and precautions

9.1 Never run the apparatus if power supply is less than 180 volts and more than 230 volts

9.2 Never switch ON mains power supply before ensuring that all the ON/OFF switches given on the panel are at OFF position.

9.3 Operate selector switches gently

9.4 Don’t operate the apparatus on uncovered feet.

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

Department of Chemical Engineering

Unit Operation Lab

Experiment Name: Vapor in Air Diffusion

1. OBJECTIVE:

Study of the effect of temperature on the diffusion coefficient.

2. AIM:

To determine the diffusion coefficient of an organic vapor (i.e. CCl_4) in air.

3. INTRODUCTION:

Diffusion is concerned with the movement of individual molecules through a substance by virtue of their thermal energy. The phenomenon of molecular diffusion ultimately leads to a completely uniform concentration of substances throughout a solution which may initially have been non uniform.

So this equipment is very helpful in determining the diffusion coefficient of an organic vapour. We can also study the effect of temperature on diffusion coefficient.

4. THEORY:

If two gases are inter-diffusing with continual supply of fresh gas and removal of the products of diffusion, this diffusion reaches an equilibrium state with constant concentration gradients. This is known as steady state diffusion. If also there is no total flow in either direction the rates of diffusion of A and B, N_A and N_B are equal but have opposite sign.

According to Dalton's law the total concentration of the two components C_A and C_B is constant

$$\frac{dC_A}{dx} = -\frac{dC_B}{dx}$$

Then using the integrated form of the Fick Diffusion equation with appropriate

$$N_A = \frac{D}{RTx}(P_{A1} - P_{A2}) = N_B \frac{D}{RTx}(P_{B2} - P_{B1})$$

Where P_{A1} and P_{A2} are the partial pressures of A at the boundaries of the zone of diffusion and x is the distance over which diffusion occurs.

In case where gas A is diffusing through stagnant gas, B (non-diffusing) the flow carries both components in proportions to their partial pressure

$$\frac{N_A P_A}{P} + \frac{N_B P_B}{P}$$

The total transfer of A is the sum of this proportion of the flow and the transfer by diffusion

$$N_A = N_A \frac{P_A}{P} - \frac{D}{RT}\frac{dp_A}{dx}$$

$$\mathrm{N_A} = \mathrm{N_A}\ (1 - \mathrm{P_B}/\mathrm{RT}) + \frac{D}{RT}\frac{dp_B}{dx}$$

$$N_A \int_0^x dx = \frac{DP}{RT} \int_{PB1}^{PB2} \frac{dp_B}{p_B}$$

And

$$N_A = \frac{DP}{RTx} \ln \frac{p_{B2}}{p_{B1}}$$

This is the expression used for the experimental determination of vapour diffusion coefficients in gases by evaporation from a liquid surface in a narrow bore tube and measuring the fall of level of this surface. The distance of the liquid surface below the open end of the tube is measured before and after evaporation over a definite period. If the variation in level is small then arithmetic mean of these two readings is taken as the value of x. In case there is appreciable change of level, the value of x is determined by integration between the initial and final readings of level.

The rate of evaporation is thus given by:

$$N_A = \frac{DP}{RTx} \ln \frac{P_{B2}}{P_{B1}} = \frac{\rho_1}{M}\frac{dx}{d\theta}$$

Integration of this expression yields:

$$\frac{DP}{RT} \ln\left(\frac{P_{B2}}{P_{B1}}\right) \frac{M}{\rho_1} \int_0^\theta d\theta = \int_{x_1}^{x_2} x\,dx$$

$$\frac{DP}{RT}\ln\left(\frac{P_{B2}}{P_{B1}}\right)\frac{M\theta}{\rho_1}=\frac{x_2^2-x_1^2}{2}$$

Therefore,

$$D=\frac{RT}{P\ln\frac{P_{B2}}{P_{B1}}}\left(\frac{\rho_1}{M}\right)\frac{x_2{}^2-x_1{}^2}{2\theta}$$

Other form this equation that is convenient to use is:

$$D_{AB}=\frac{\rho_A\left[x^{\,2}-x_o{}^2\right]RTp_{BM}}{2P(p_{A1}-p_{A2})M_A\theta} \qquad \text{---------- (1)}$$

In terms of concentration terms the expression for D is:

$$(x^2-x_o{}^2)=\frac{2\theta M_A D_{AB}C_AC_T}{\rho_L C_{BM}} \qquad \text{---------- (2)}$$

$$C_{BM}=\frac{C_{B1}-C_{B2}}{\ln\frac{C_{B1}}{C_{B2}}}$$

Usually, x_o will not be measured accurately nor is the effective distance for diffusion, x, at time θ. Accurate values of $(x - x_o)$ are available, however, and hence:

Rewriting Eq.2 as:

$$\frac{\theta}{x-x_o}=\frac{\rho_l C_{Bm}}{2M_A D_{AB}C_AC_T}(x-x_o)+\frac{\rho_l C_{Bm}}{M_A D_{AB}C_AC_T}x_o \qquad \text{---------- (3)}$$

A graph between $\theta / (x - x_o)$ against $(x - x_o)$ should yield a straight line with slope

$$S=\frac{\rho_l C_{Bm}}{2M_A D_{AB}C_AC_T} \qquad \text{---------- (4)}$$

$$D_{AB}=\frac{\rho_l C_{Bm}}{2M_A C_AC_T S} \qquad \text{---------- (5)}$$

To determine total concentration

$C_T=\frac{P}{RT}$ k mole/m^3 at operating temperature of T K

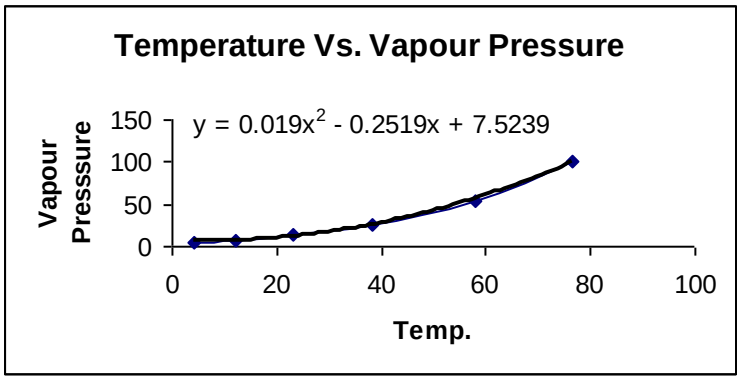
Then

$$C_A=\left[\frac{(V.P.)_A}{P}\right]\times C_T$$

C_{B1} shall be equal to C_T and

$$C_{B2} = C_T \times \left[\frac{P - (V.P)_A}{P} \right], \text{ k mol/m}^3$$

Evaluation of Vapor Pressure of CCl_4



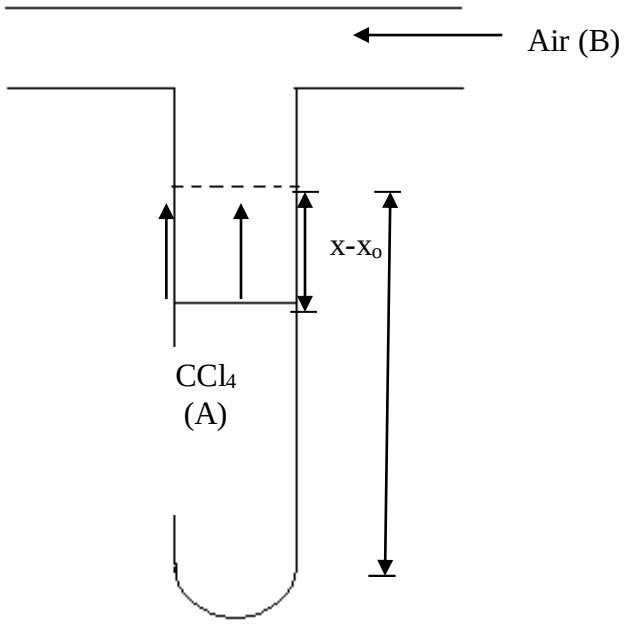
So Relation between temperature & Vapor pressure from this curve

$VP = 0.019 \times T^2 - 0.2519 \times T + 7.5239$ (Obtained from Perry's hand book)

Effect of temperature and pressure on co-efficient of diffusion, D is expressed as:

$D = \text{const.} \; T^{1.5} / P$ ---------- (6)

D can be determined by drawing a curve of DP Vs. T.



5. DESCRIPTION:

The equipment consists of a T tube made of glass, placed in a constant temperature water bath. Temperature of the bath is controlled by the DTC. Air pump is used to supply the air, passed through the T tube. Volatile component is filled in the T tube and air passed over it by the pump and change in the level is seen by the sliding microscope.

Technical Detail

T Tube Inner Diameter 11 mm.

6. UTILITIES REQUIRED:

1. Electricity Supply: Single Phase, 220 V AC, 50 Hz, 5-15 Amp. Socket with earth connection.
2. Floor Area Required: 1 m x 0.75 m
3. Required Chemicals & Laboratory Glassware.

7. EXPERIMENTAL PROCEDURE:

1. Clean the apparatus and make it free from dust.
2. Fill $3/4^{th}$ water bath with water.
3. Set the water bath temperature at the desired level (up to 60 ^{o}C) and wait till the bath attains the set temperature. Note the steady temperature of the bath.
4. Fill the T-tube with CCl_4 up to within two centimeters of the top of capillary leg. Note down the initial diffusion height of liquid in the capillary.
5. Make the connection with the Air or vacuum pump and allow a gentle current of air to flow over the capillary.
6. Record the height of liquid (x) in the capillary after every 15 min.
7. Repeat the steps 1 through 5 for different water bath temperatures.
8. Use different organic liquids like: ethanol, toluene, acetone, hexane etc. and tabulate the results and discuss.

8. OBSERVATION & CALCULATION:

DATA:

P = ---------- kN/m^2

R = ---------- k N m/k mol K

ρ_1 = ---------- kg/m^3

M_A = ---------- kg/ k mol

T = --------- K

OBSERVATION:

x_o = ---------- cm

OBSERVATION TABLE:

S.No.	θ, sec	x, cm

CALCULATIONS:

(x_o-x), cm	$\theta/(x_o-x)$, sec/cm

Plot of (x_o-x) vs. $\theta/(x_o-x)$ from the graph find the slope S

$VP = 0.019 \times T^2 - 0.2519 \times T + 7.5239$, k N m^2 = ---------- k N m^2

$C_T = \frac{P}{RT}$, k mole/m^3 = ---------- k mole/m^3

$C_A = \left[\frac{VP}{P}\right] \times C_T$, k mole/m^3 = ---------- k mole/m^3

S = ---------- sec/cm^2 = --------- *10^{-04}sec/m^2

$C_{B1} = C_T$, k mole/m ^{3} = ---------- k mole/m^3

$C_{B2} = C_{B1} \times \frac{(P - VP)}{P}$, k mole/m ^{3} = ---------- k mole/m^3

$C_{BM} = \frac{C_{B1} - C_{B2}}{\ln \frac{C_{B1}}{C_{B2}}}$, k mole/m^3 = ---------- k mole/m^3

$D_{AB} = \frac{\rho_1 C_{Bm}}{2 M_A C_A C_T S}$, m^2/sec = ---------- m^2/sec

9. NOMENCLATURE:

C_A	=	Molar concentrations of A, k mole/m^3
C_B	=	Molar concentrations of B, k mole/m^3
C_T	=	Total molar concentration, k mole/m^3
C_{BM}	=	Log mean concentration of CCl_4, k mole/m^3
D_{AB}	=	Diffusion coefficient, m^2/s
M_A	=	Molecular weight of CCl_4 (component A), kg/k mol
P	=	Total Pressure, k N/m^2
R	=	Gas Law Constant, k N m/k mol K
T	=	Operating temp, K
VP	=	Vapour pressure of the evaporating liquid, k N/ m^2
x	=	Final height from top end of the tube after time θ, cm
x_o	=	Initial height from top end of the tube, cm
$x_o - x$	=	Drop in liquid (CCl_4) level in time θ, cm
θ	=	Time of evaporation, sec
ρ_1	=	Density of CCl_4, kg/m^3
S	=	slope of graph sec/cm

10. Error Analysis:

$$D_{AB} = \frac{\rho_1 C_{BM}}{2M_A C_A C_T S}$$

$\Delta D_{AB}/D = \Delta\rho/\rho + \Delta C_{BM}/C_{BM} + \Delta M_A/M_A + \Delta C_A/C_A + \Delta C_T/C_T + \Delta S/S$

$\Delta\rho/\rho = 0$

$\Delta M_A/M_A = 0$

$\Delta S/S = 0$

$\Delta C_T/C_T = \Delta T/T$

$\Delta C_A/C_A = \Delta T/T + \Delta P^o/P^o$

$$\Delta C_{BM}/C_{BM} = \frac{\Delta C_{B1}}{C_{B1} - C_{B2}} + \frac{\Delta C_{B2}}{C_{B1} - C_{B2}} + \frac{\Delta C_{B1}}{C_{B1} \ln \frac{C_{B1}}{C_{B2}}} + \frac{\Delta C_{B2}}{C_{B2} \ln \frac{C_{B1}}{C_{B2}}}$$

11. Precautions & Maintenance Instructions:

1. Carbon tetrachloride (CCl_4) should be colorless.
2. Don't switch on the heater before filling the water in the bath.
3. Microscope focus should be clear if not adjust that.

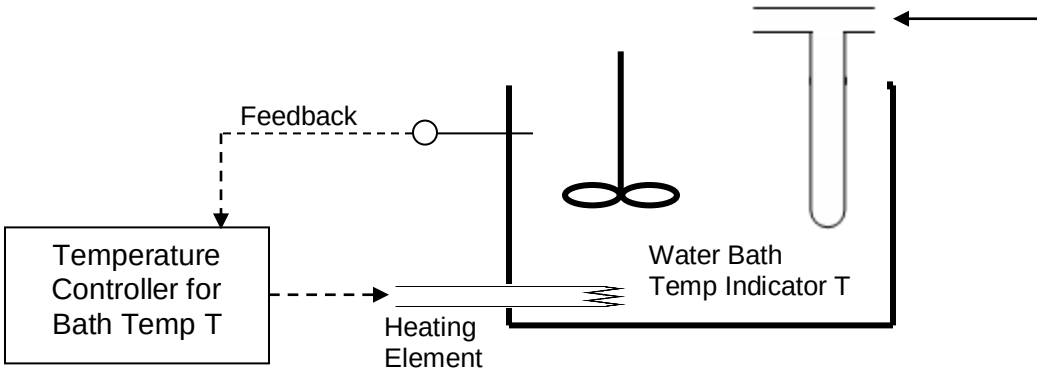
11. Troubleshooting:

1. If the temperature is not increasing after switch on the heater, check the connection of Heater in the panel.
2. If the meniscus is not clear adjust the focus of the lens.
3. If the movement of the microscope is not smooth put some lubricating oil on it.

12. References:

1. McCabe, Smith, **"Unit Operations of Chemical Engineering"**, 7th ed, McGraw-Hill, NY, 2005, Page 528, 531-532.
2. Binay K.Dutta, **"Principles of Mass Transfer and Separation Processes"**, Prentice Hall of India Pvt Ltd., ND, 2007, Page 11-15.

Air Diffusion Apparatus



INDIAN INSTITUTE OF TECHNOLOGY KANPUR

Department of Chemical Engineering

Unit Operation Lab

Experiment Name: BALL MILL (VARIABLE SPEED)

1. OBJECTIVE:

To study the operation of a ball mill..

2. AIM:

To determine the efficiency of a ball mill for grinding a material of known Wi.

To find the critical speed of ball mill nc

3. INTRODUCTION:

Generally the ball mills are known as the secondary size reduction equipment.The ball mill is made in a great many types and sizes and can be used on a greater variety of soft materials than any other type of machine. The feed must be non-abrasive with a hardness of 1.5 or lessA Ball Mill consists of a cylindrical shell slowly turning about a horizontal axis and filled to about 1/4th of its volume with solid grinding medium (i.e. metallic balls etc.). When the Ball Mill is rotated, the grinding elements (balls) are carried to the side of the shell nearly to the top, from where; they fall on the particles under gravity. In a Ball Mill most of the size reduction is done by impact. The energy expanded in lifting the grinding units are utilizes in reducing the size of the particles. Ball Mill can accept a feed size of 12mm or less and deliver a product size in the range of 50μm. The speed of Ball Mill varies between 60 to 70 r.p.m. As the product size become fines, the capacity of a mill reduces the energy requirement increases.

4. THEORY:

A ball mill consists of a cylindrical shell slowly turning about a horizontal axis and filled with solid grinding medium (Metallic Balls, Wooden balls or rubber balls).

CRITICAL SPEED OF A BALL MILL (n_c):

$$n_c = \frac{1}{2\pi} \times \sqrt{\frac{g}{R-r}} \qquad \text{---------- (1)}$$

Where n_c = Critical Rotational Speed

R = Radius of the ball mill

r = Radius of the ball

For effective operation of the mill, the mill should be operated at 65 to 80 % of critical Speed. As the product size becomes finer, the capacity of a mill reduces and the energy requirement increases. As the speed of the mill exceeds n_c (i.e. mill is centrifuging the size reduction capacity decreases.)

BOND CRUSHING LAW AND WORK INDEX:

A more realistic method of estimating the power required for crushing and grinding is

$$\frac{P}{m} = \frac{K_b}{\sqrt{D_p}} \qquad \text{---------- (2)}$$

Where K_b is a constant which depends on the type of machine and on the material being crushed, D_p is in millimeters, P in kilowatts and m in tons per hour.

W_i is defined as the gross energy requirements in kilo watt hours per ton of feed needed to reduce a very large feed. This definition leads to a relation between K_b and W_i.

$$K_b = 0.3162 * W_i \qquad \text{---------- (3)}$$

If 80 percent of the feed passes a mesh size of D_{pa} mm and 80 percent of the product a mesh of D_{pb} mm, it follows from eq (1) & (2).

$$\frac{P}{m} = 0.3162 \times W_i \left(\frac{1}{\sqrt{D_{Pb}}} - \frac{1}{\sqrt{D_{Pa}}} \right)$$

$$P = m \times 0.3162 \times W_i \left(\frac{1}{\sqrt{D_{Pb}}} - \frac{1}{\sqrt{D_{Pa}}} \right) \qquad \text{---------- (4)}$$

5. DESCRIPTION:

The present laboratory Ball Mill is designed to crush particles to very fine (powder) particles. It can handle variety of material. The compact and rugged construction can handle general laboratory or small pilot plant requirements. The shell is fabricated from thick steel and balls are also of special steel. An opening and tightening arrangement is provided in the center of the shell to feed and to take off the material. Balls are provided along with the material.

6. UTITLITIESREQUIRED:

1. Electricity Supply: Single phase, 220 V AC, 50 Hz, 5-15 amp socket with earth connection
2. Floor Area Required 1.5 m x 1 m.
3. Raw Material for Feed (size 5-8 mm).
4. Set of Sieves with Sieve Shaker for analysis.

7. EXPERIMENTALPRODCEDURE:

1. Prepare a uniform sized feed of material to be crushed (5mm to 8mm approx).
2. Fill the shell with the balls provided.
3. Ensure that all Switches given on the Panel are at OFF position.
4. Now switch on the Main Power Supply.
5. Switch ON the MCB and then starter to run the machine.
6. Calculate the power consume to run the machine at no load condition by determining the time for 10 or 20 pulses on the energy meter.
7. Switch OFF the starter and then MCB.
8. Fill the Feed in the ball mill.
9. Switch ON the MCB and then starter to run the machine.
10. Calculate the power consume to run the machine at loaded condition by determining the time for 10 or 20 pulses on the energy meter.
11. Run the mill for specific time and calculate the size distribution of the product
12. Repeat the above steps for different RPM.

8. OBSERVATION&CALCULATION:

DATA:

D_{pa} = ----------, mm

D_{pb} = ----------, mm

r = 0.0075 m

R = 0.08

g = 9.81 m/s^2

EMC = 3200 Pulses/kWh

Work Indexes for some common minerals

Material	Specific Gravity	W_i
BAUXITE	2.20	8.78
CEMENT CLINKER	3.15	13.45
COAL	1.40	13.00
COKE	1.31	15.13
GRAVEL	2.66	16.06
GYPSUM ROCK	2.69	6.73
LIME STONE	2.66	12.74
QUARTZ	2.65	13.57

OBSERVATION:

W_f= ----------, kg

t_c= ----------, min

OBSERVATIONTABLE:

P_{NL}		P_L	
P	t_p	P	t_p

Distribution of Particle Size of Crushed Product

Type of Tray (Mesh No.)	Size of the mesh (mm)	Amount of Product on Tray (gm)
Total Weight of Product Recovered		

CALCULATIONS:

$$n_c = \frac{1}{2\pi} \times \sqrt{\frac{g}{R-r}}, \text{ s}^{-1} = \text{----------s}^{-1}$$

$$P_{NL} = \frac{P \times 3600}{t_p \times EMC}, \text{kW} = \text{----------kW}$$

$$P_L = \frac{P \times 3600}{t_p \times EMC}, \text{kW} = \text{----------kW}$$

$$P_{act} = P_L - P_{NL}, \text{kW} = \text{----------} \text{ kW}$$

$$P_{cal} = m \times K_b \times \left[\frac{1}{\sqrt{D_{Pb}}} - \frac{1}{\sqrt{D_{Pa}}} \right], \text{kW} = \text{----------kW}$$

$$K_b = 0.3162 \times W_i = \text{----------}$$

$$m = \frac{W_f}{t_c} \times \frac{60}{1000}, \text{ tons/h} = \text{----------tons/h}$$

$$\eta = \frac{P_{act}}{P_{cal}} \times 100 = \text{----------}$$

9. NOMENCLATURE:

D_{pa} = Average feed size, mm

D_{pb} = Average product size, mm

EMC = Energy Meter Constant, Pulses/ kWh

g = Acceleration due to gravity, m/s^2

K_b = Bond's constant.

m = Feed rate, tons/ h

n_c = Critical speed of ball mill, s^{-1}

P = No. of pulses.

P_L = Power consume by machine at loaded condition, kW

P_{NL} = Power consume by machine at no load condition, kW

P_{act} = Actual power required for crushing, kW

P_{cal} = Calculated power required for crushing, kW

R = Radius of the ball mill, m

r = Radius of the ball, m

t_p= Time for P pulses, min

t_c = Time for crushing, min

W_i = Work index of material, kWh/ton

W_f = Weight of feed taken, kg

η= Crushing efficiency.

10.PRECAUTIONS&MAINTENANCE INSTRUCTIONS:

1. Never run the apparatus if power supply is less than 180 volts and above 230 volts
2. Revolution counter should be zero before start.
3. Coupling fixing pin should be fixed after attached the ball mill coupling.
4. Don't attached or detached the coupling during the experiment.

11.TROUBLESHOOTING:

1. If the motor is not working check electric connection.

12. REFERENCES:

1. McCabe, Smith "Unit Operations of Chemical Engineering"7thed, McGraw-Hill, NY, 2005, Page 985-986, 992-993.
2. Coulson & Richardson, "Chemical Engineering Vol-2"4thed, Asian Books Pvt. Ltd, ND,1991, Page 83-86.

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

Department of Chemical Engineering

Unit Operation Lab

Experiments Name: RTD STUDIES IN CSTR & PACKED BED REACTOR

1. OBJECTIVES:

a). To experimentaly measure the resisdance time distribution (RTD) of a CSTR and a Packed Bed.

b). To model the non-ideality of the CSTR using the tank- in- series model .

c) . To model the non-ideality of the packed bed using the dispersion model.

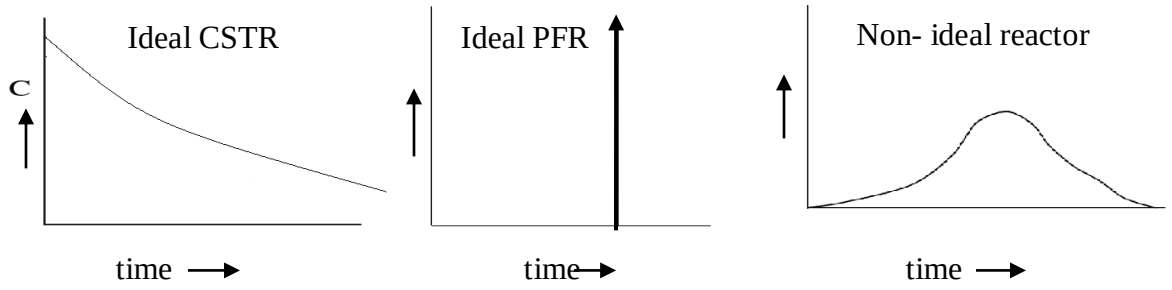
2. INTRODUCTION

Real reactors do not satisfy the ideal flow patterns, i.e. complete mixing (ideal CSTR) or no mixing (plug flow reactor).Except for an ideal PFR , different flow elements spend different times in the reactor , i.e. there is distribution of residence times in the reactor.Deviation from ideality may be due to the channeling of fluid through the vessel ,recycling of fluid within a vessel or due to the presence of stagnant regions in the vessel.

3. THEORY

The RTD of a reactor is the characteristic of the mixing that occurs in the reactor , and can be deternind experimentally by injecting an inert tracer into the reactor at t=0 and measuring the tracer concentration,C, in the efflunt stream as a function of time. The two common modes of injecting the tracer are either to give a pulse or step input

The typical response for the pulse input for different type of reactors is shown below:



The RTD function, E(t) , is defined such that E(t)dt gives the fraction of material that has a residence time between t and t+dt . Thus, by definition

$$\int_0^\infty E(t)dt = 1 \qquad (1)$$

It can be shown that for a pulse input

$$E(t) = \frac{C(t)}{\int_0^\infty C(t)dt} \qquad (2)$$

where C is the tracer concentration measured at the reactor outlet.

For an ideal CSTR , $E(t) = \frac{1}{\tau} e^{-t/\tau}$ or in dimensionless coordinates $E(\theta) = e^{-\theta}$

where $\theta = t/\tau$ and $E(\theta) = \tau E$.

The mean residence time , t_m, can be calculated as

$$t_m = \frac{\int_0^\infty tE(t)dt}{\int_0^\infty E(t)dt} = \int_0^\infty t\ E\ dt \qquad (3)$$

It can be shown that for a closed system (i.e. fluid enters and leaves by plug flow)

$$t_m = \tau = \frac{V}{Q} \qquad (4)$$

where τ is the space time , V is the volume of the reactor and Q is the volumetric flow rate.

The RTDs are usually compared by taking moments. The first moment is the mean residence time .The second moment (taken about the mean) is called the variance (σ^2) and can be calculated as

$$\sigma^2 = \int_0^\infty (t - t_m)^2 E(t)dt \qquad (5)$$

$$= \int_0^\infty t^2 E(t)dt - t_m^2 \qquad (6)$$

The variance measures the spread of the RTD .

4. Modeling of Non-Ideal Reactors

Different types of models have been proposed for modeling the non–ideality in chemical reactors. The most commonly used are the tank- in - series model and the dispersion model. Both of these are one parameter models .

Tank-in-series model : In this model, the actual reactor is taken to be equivalent to a number of equal volume ideal CSTRs in series. The total volume of all the reactors is equal to the total volume of the non-ideal reactor.

It can be shown that for N reactor in series:

$$E(t) = \frac{t^{N-1} e^{-t/\tau_i}}{(N-1)!\ \tau_i^N}, \qquad (7)$$

$$\tau_i = \tau / N, \quad V = NV_i$$

and

$$\sigma^2 = \frac{\tau^2}{N} \qquad (8)$$

Thus, form the experimentally measured RTD, N can be calculated. It should be noted that N has to be an integer.

Dispersion Model:

This model is usually used for the modeling of tubular or packed bed reactors for which the flow does not deviate too much from an ideal PFR . In this model , it is assumed that all the non-idealities can be accounted for by a dispersion term superimposed on the bulk flow . The axial dispersion coefficient, D_L , is used to characterize the degree of back mixing during the flow . D_L is assumed to be independent on the axial position.

For a closed- closed system, it can be shown that.

$$t_m = \tau \qquad (9)$$

and

$$\frac{\sigma^2}{t_m^2} = \frac{2}{Pe_r} - \frac{2}{(Pe_r)^2}(1 - e^{-Pe_r}) \qquad (10)$$

$$Pe_r = \frac{uL}{\varepsilon D_L} \qquad (11)$$

where L is the length of the reactor , *u* is the superficial linear velocity ,ε is the bed voidage, and Pe_r is the reactor Peclet number and represent the ratio of rate of transport by convection to the rate of transport by dispersion.

The fluid Peclet number, Pe_f ,is defined using the characteristic length that determines the fluid's mechanical behavior. For the packed bed, the characteristics length is the particle diameter, d_p and for empty tubes it is the tube diameter, d_t . For a packed bed

$$Pe_r = \frac{u\, d_p}{\varepsilon\, D_L} \qquad (12)$$

where u/ε is the interstitial velocity of the fluid.

The usual values of Pe_r and Pe_f for the packed bed are nearly 10^3 and 10^1 respectively. From the definitions

$$Pe_r = Pe_f \frac{L}{d_p} \quad \text{for packed beds} \qquad (13a)$$

and

$$Pe_r = Pe_f \frac{L}{d_t} \quad \text{for empty tubes} \qquad (13b)$$

Open – open system : When a tracer is injected into a packed bed at a location more than two or three particle diameters downstream from the entrance and measured some distance upstream from the exit , the system is analogous to an open-open system.

For such a system

$$t_m = \left(1 + \frac{2}{Pe_r}\right)\tau \qquad (14)$$

and

$$\frac{\sigma^2}{t_m^2} = \frac{2}{Pe_r} + \frac{8}{Pe_r^2} \qquad (15)$$

We can determining Pe_r by determining t_m and σ^2 from the experimental data and then use equation (15) to calculate Pe_r .We can also calculate t_m and then use equation (14) as a check, but this is usually less accurate . Once Pe_r is known D_L can be estimated.

5. DESCRIPTION:

The setup consists of one sump tank to which water is fed. Water is supplied to the overhead tank by pump. Two reactors (CSTR, Packed bed) are provided for RTD study which can be used one at a time. Water is supplied from overhead tank to any of the reactor at particular flow rate maintained by the Rotameter. A pipette is used for dozing the tracer into the C.S.T.R. while a special arrangement is provided to inject tracer at the lower end of reactor, using a syringe for packed bed. Samples can be taken periodically from the top outlet of reactor.

TECHNICAL DETAIL:

Reactor : CSTR (Material SS, Volume 2.4 ltrs).

Packed Bed (Material Glass, Packing Rasching Rings ID 6, OD 10 length 10 mm)

6. UTILITIES REQUIRED:

1. Electricity Supply: Single Phase, 220 V AC, 50 Hz, 5-15 Amps Socket with earth connection.
2. Water Supply (Initial Fill).
3. Floor Drain Required.
4. 5 conical flask
5. Burette

6. Pipette
7. Measuring cylinder
8. CHEMICALS: QUANTITY:

N/10 NaOH	200 ml
Concentrated HCl	100 ml
Phenolphthalein indicator	Few drops

7. EXPERMINTAL PROCEDURE:

1. Fill the sump tank with water.
2. Switch ON the pump.
3. Start the supply of water to the reactor (CSTR or Packed Bed) at particular flow rate with the help of Rotameter.
4. Input a concentrated HCl into the system (10 ml or 20 ml) with the help of pipette (tracer signal as a pulse).
5. At regular time intervals (say 15 sec for high water rate, 30 sec for low water rate), collect the samples at the outlet in beakers/measuring cylinder (about 20 ml) until all tracer leaves the vessel.
6. Analyze these samples with N/10 NaOH using phenolphthalein as indicator.
7. Repeat the experiment for different flow rates (before changing the flow rate, drain the reactor first).

8. OBSERVATION & CALCULATION:

DATA:

V_1 = -------- ml

N_1 = -------- g moles/L

V_2 = -------- ml

OBSERVATION TABLE:

S.No.	t, min	V_2, ml	Q, LPH

CALCULATIONS:

$$C_i = \frac{V_1 N_1}{V_2} \times 98$$ = ---------- moles/L

$$t_m = \frac{\sum t_i C_i}{\sum C_i},$$ = ---------- min

$$\tau = \frac{V_R * 60}{Q},$$ = ---------- min

$$\sigma^2 = \left(\frac{\sum t_i^2 C_i}{\sum C_i} \right) - t_m^2$$ = ---------- min^2

$$E_i = \frac{C_i}{\sum C_i \Delta t}$$

A) Plot the RTD [i.e. E(t)] curves for both the reactors .

B) For the CSTR from the experimentally determined σ^2, find N for the tank-in–series model.

C) For the packed bed reactor, from the experimentally determined t_m and σ^2 find Pe_r and D_L . Compare D_L with those available from correlations.

9. NOMENCLATURE:

C_i = Concentration of H_2SO_4 in sample, moles/L

D/uL = Dispersion number

E_θ = Exit age distribution at time θ

E_i = Exit age distribution at time i

N_1 = Normality of N/10HaOH, g moles/L

N_2 = Normality of H_2SO_4 in solution, g moles/L

t = time, min

Δt = Average time difference, min

V_2 = Volume of H_2SO_4 in sample, ml

V_1 = Volume of N/10 NaOH used for titration, ml

V_R = Volume of reactor, L

Q = Volumetric flow rate, LPH

θ = Reduced time, min

t_m = Mean residence time, min

τ = Space time ,min.

σ^2 = Variance.

10. PRECAUTIONS & MAINTENANCE INSTRUCTIONS:

1. Always use clean water and good quality chemicals and standard solution for titration.

2. Flow should not be disturbed during the experiments.

3. Handle the chemicals carefully.

11. TROUBLESHOOTING:

1. If there is any leakage tight that part or remove that and fix that again after wrapping Teflon tape.
2. If Rota meter fluctuating more than average tight control knob of that.

12. REFERENCES:

1. Octave Levenspiel, "Chemical reaction engineering,"3rd ed., John Wiley & Sons, NY, 2001, Page 260-265, 294-296.
2. H.Scott Fogler, "Elements of Chemical Reaction Engineering",4th edition,2006 Prentice-Hall of India, New Delhi, Chapter 13and14.