KING FAISAL UNIVERSITY

College Of Engineering

DEPARTMENT OF CHEMICAL ENGINEERING

ChE 306: Chemical Engineering Lab I

"Lab Manual"

Major Topics covered and schedule in weeks:

Topic	Week #	Courses Covered
Introduction to chemical engineering labs and lab's safety.	1	Introduction
Experiment 1: Flow measurements.	2	ChE 204
Experiment 2: Fluidized bed.	3	ChE 204
Experiment 3 Friction loss in pipes and fittings.	4	ChE 204
Experiment 4: Series and parallel pumps.	5	ChE 204
Experiment 5: Linear heat conduction.	6	ChE 302
Experiment 6: Convective heat transfer.	7	ChE 302
Experiment 7: Boiling heat transfer	8	ChE 302
Experiment 8: Shell and tube Heat exchanger	9	ChE 302
Experiment 9: Batch settling.	10	ChE 303
Experiment 10: Size reduction and screening.	11	ChE 303
Experiment 11: Filter press.	12	ChE 303
Design of an experiment part 1	13	ChE 204, 302, 303
Design of an experiment part 2	14	ChE 204, 302, 303
Final Exam	15	

Specific Outcomes of Instruction (Lab Learning Outcomes):

1. Conduct experiments in the areas of fluid, heat transfer and separation processes.**(6,7)**
2. Demonstrate and practice different modes of heat transfer including conduction, convection and radiation.**(1,6)**
3. Analyze and interpret experimental data with theories learned in previous courses **(1,6)**
4. Work effectively in a team environment**. (5)**
5. Understand and apply the safety guidelines and regulations in the workplace (**4**)

Student Outcomes (SO) Addressed by the Lab:

z	Outcome Description General Engineering Student Outcomes	Contribution
1.	an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics	H
2.	an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors	
3.	an ability to communicate effectively with a range of audiences	L
4.	an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts	L
5.	an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives	M
6.	an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions	H
7.	an ability to acquire and apply new knowledge as needed, using appropriate learning strategies	L

Table of Contents

Experiment 1: Flow Measurements

I. Objective:

- To determine the flowrate of liquids using a Venturi meter, an orifice plate/nozzle meter and a Rotameter.

II. Test Standard

Standing-start-and-finish method
ASTM D2458 : Standard Method of flow measurement of water by the venturi meter tube

III. Theory:

Bernoulli's Equation Demonstration

Bernoulli's Theorem states that "The total head of flowing liquid between two points remains constant assuming there are no loss due to friction and no gain due to application of external work between the two points".
The total head (H_t) of a flowing liquid is made up of Elevation head (H_z), Pressure head (H_s) and Velocity head (H_v) and according to Bernoulli's theorem, the total head is constant between any two points along the streamline of a flowing fluid.

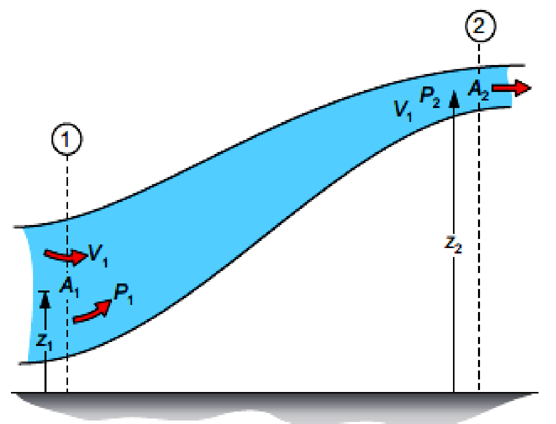


Figure 1 :The Steady Flow energy equation

$$H_t = \frac{P}{\rho g} + \frac{V^2}{2g} + Z \quad \text{.................................} \quad [1]$$

Where: H_t is the total head (m), V is the average velocity (m/s), P is the pressure (Pa), Z is the elevation (m), ρ is the density (Kg/m^3) and g is the gravitational acceleration (m/s^2). Thus between point 1 and 2 for example (Figure 1)

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + Z_2 + h_L (Head\ loss) \quad \text{..} \quad [2]$$

If the Bernoulli's tube is horizontal, then $Z_1 = Z_2$ and if loss between point 1 and 2 is negligible then the equation becomes

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + Z_2 \quad \text{...} \quad [3]$$

Or $\frac{P_1}{\rho g} - \frac{P_2}{\rho g} = \frac{V_2^2}{2g} - \frac{V_1^2}{2g}$ ………………………………………………………………… [4]

If point 1 and point 2 are of different diameters, then V_1 and V_2 are different. It is demonstrated by the difference in manometer water level reading between point 1 and 2.

Therefore

$$\frac{V_2^2}{2g} - \frac{V_1^2}{2g} = h_1 - h_2 \quad \ldots\ldots\ldots\ldots [5]$$

From continuity

$$A_1V_1 = A_2V_2 \quad \rightarrow \quad V_1 = \frac{A_2V_2}{A_1} \quad \ldots\ldots\ldots\ldots [6]$$

Sub. equation 6 into equation 5 and rearrange

$$V_2 = \sqrt{\frac{2g(h_1 - h_2)}{1 - \left(\frac{A_2}{A_1}\right)^2}} \quad \ldots\ldots\ldots\ldots [7]$$

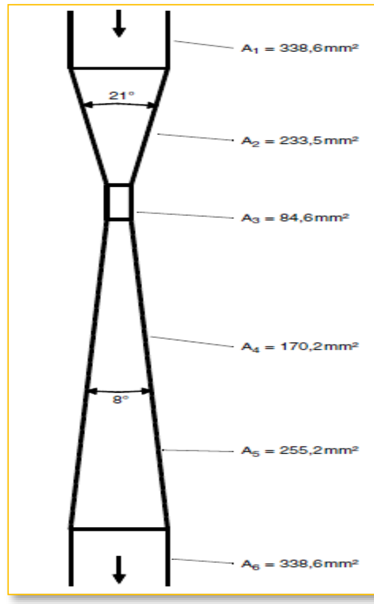


Figure 1 cross sections of Venturi

<u>Venturi (Between points A and B)</u>

$$V_B = \sqrt{\frac{2g(h_A - h_B)}{1 - \left(\frac{A_B}{A_A}\right)^2}} \quad \ldots\ldots\ldots\ldots [8]$$

Where $A_B < A_A$.

Theoretical volumetric flow rate is :

$$Q_{th} = A_BV_B \quad , \quad A_B\sqrt{\frac{2g(h_A - h_B)}{1 - \left(\frac{A_B}{A_A}\right)^2}} \quad \ldots\ldots\ldots\ldots [9]$$

The discharge coefficient is defined as the ratio of actual volume flow rate to theoretical volume flow rate: Coefficient of discharge,

$C_d = Q_{actual}/Q_{theoretical}$

Then,

$Q_{act} = C_d\, Q_{th}$

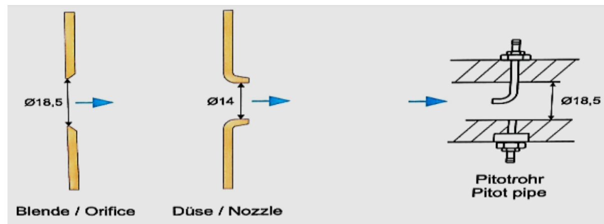
$$Q_{act} = C_d\, A_B\sqrt{\frac{2g(h_A - h_B)}{1 - \left(\frac{A_B}{A_A}\right)^2}} \quad \ldots\ldots\ldots\ldots [10]$$

<u>Orifice/nozzle (Between points A and P)</u>

For orifice Coefficient of discharge introduced in equation due to high head losses

$$V_o = \sqrt{\frac{2g(h_A - h_p)}{1-\left(\frac{A_P}{A_A}\right)^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [11]$$

$$Q_{act} = \mathbf{K} A_p \sqrt{\frac{2g(h_A - h_p)}{1-\left(\frac{A_p}{A_A}\right)^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [12]$$



Where:

K : Coefficient of discharge ≈ 0.6 for orifice

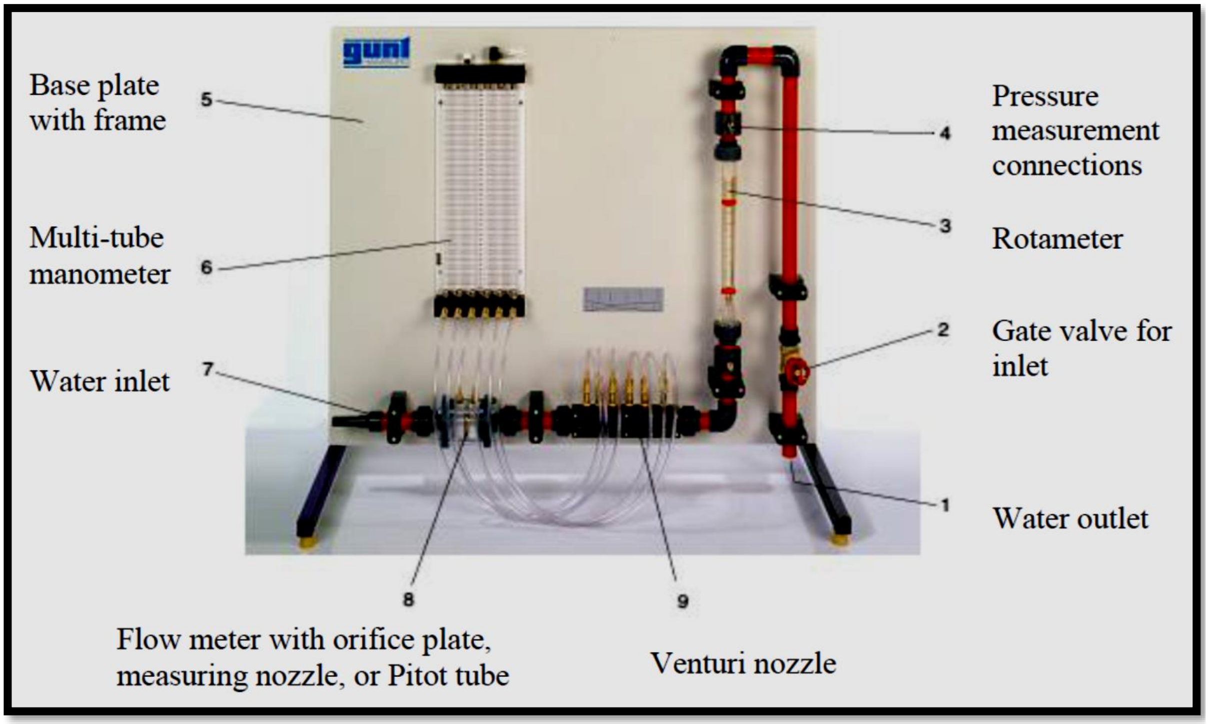
And ≈ 0.9 for nozzle.

A_p : Area of meter's opening.

Figure 2 orifice, nozzle and Pitot tube

IV. Apparatus:

Figure 3 shows the Flow Measurement apparatus. Water from the Hydraulic Bench enters the equipment through an orifice/nozzle meter then it passes to a Venturi meter, which consists of a gradually converging section with six pressure-measuring points connected with manometers. The unit has six manometers and ten pressure-measuring connections. At the end, water passes through a rotameter to measure flow directly.



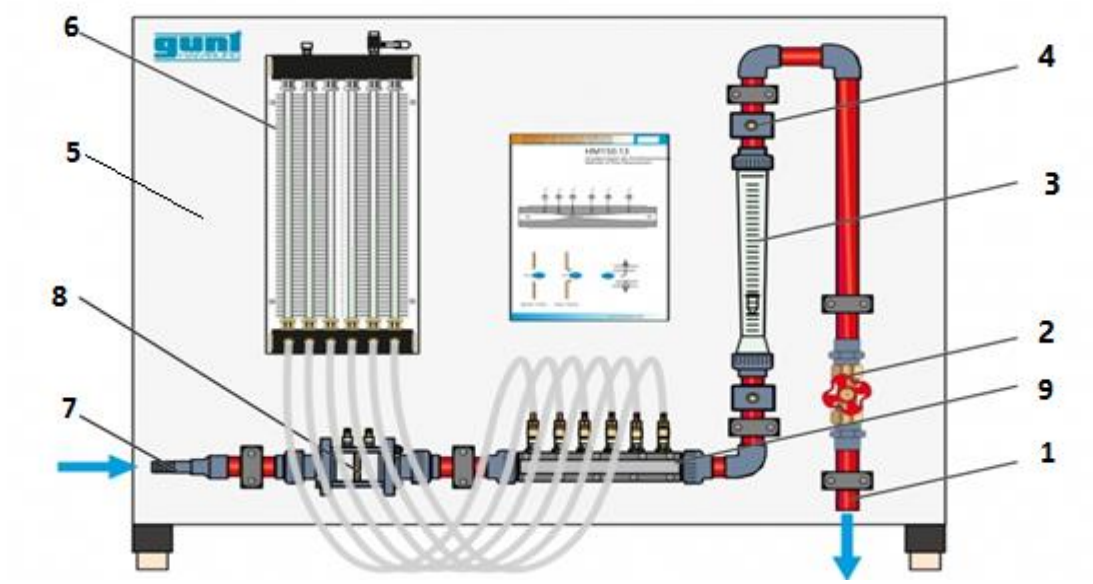


Figure 3 Flow measurement apparatus.

Rotameter reading

The measured flow rate value is always read at the upper edge of the float. The maximum flow measured by the rotameter is 1600 L/h.

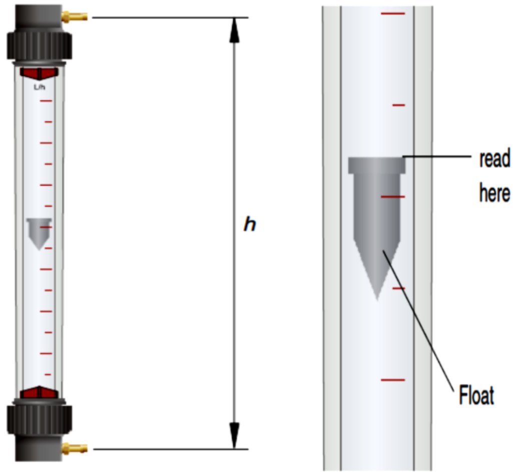
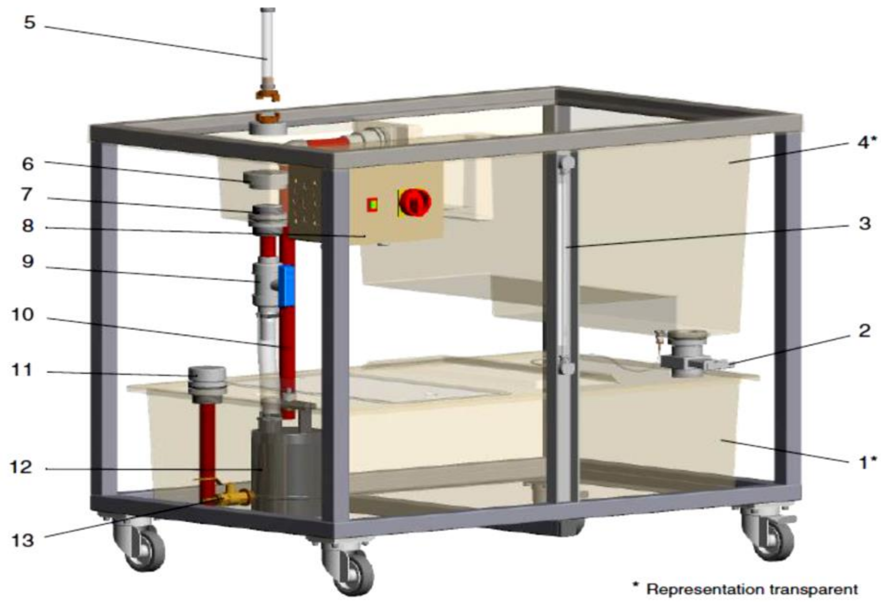


Figure 4 Reading the measurement of rotameter



Pos.	Item	Pos.	Item
1	Sump tank	8	Switch box
2	Sliding valve	9	Flow control valve
3	Remote sight gauge	9	Overflow pipe
4	Volumetric measuring tank with channel	10	Water supply connection for accessories with pump
5	Water supply connection for accessories without pump	11	Submersible motor driven pump
6	Diverting cap	12	Drain cock
7	Connecting piece for pump		

Figure 5 Basic bench

V. Procedure:

1. Make sure Orifice or Nozzle are fix (Venturi meter is permanently fixed).
2. Make sure manometer tubes are connected (H1 & H2) to the Orifice / Nozzle.
3. For the Venturi meter, make a tube connection H1 to H3.
4. Close inlet valve and control valve.
5. Switch on the main switch.
6. Switch on the pump.

TO GET RID OF THE AIR BUBBLE

7. Open the inlet valve slowly; also open the control valve slowly until maximum level (until water in the manometer overflow).

   I. Open the black valve (anticlockwise) on top of the manometer to release all bubble in the system;
   II. Close the black valve.

8. Close the control valve.
9. Switch off the pump and control the water level.
10. Slowly open the white valve until maximum level of 30-40 mm.
11. Switch on the pump again.
12. Open the control valve slowly until level of water in H1 reach maximum (390 mm) and manometer H at minimum level. Take all the reading (Multi-tube Manometer/ Rotameter).

ACTUAL Q FLOWRATE CALCULATION

13. Collect the water in a jar and at the same time, take the time taken for the maximum volume filled/collected or close the basin tank valve, take the time measured for example, 5 Liter.
14. Take 4 different flow rate, Q (Range above 200 L/min is the reference flow to all component).
15. Close the control valve and pump switch again.

VI. Experimental Work:

1. Fill the table given for all measuring meters.
2. Calculate flowrate by level tank $= \frac{Volume\ of\ water\ collected}{time}$
3. Calculate the discharge coefficient (C_d) of Venturi [Equations 9&10]
4. Calculate flowrate through orifice/nozzle [Equations 11&12]
4. Comment on the pressure drop in Rotameter (If available).
5. Calculate the differences between the flow values recorded compared to the actual flowrate (tank level) and draw them on one graph for straight comparison.
6. Plot the flow values recorded against the associated differential head.
7. Use the following equation to check your results of venture meter.

$$Q_{act} = k\sqrt{\Delta p} \quad \text{where } k = 132 \text{ and has the unit of } \frac{L}{h\,.\sqrt{mbar}}$$

Note: Δp must be used in mbar

		Test Number					
		1	2	3	4	5	6
Rotameter (L/min)							
Manometers Level (mm)	1						
	2						
	3						
	4						
	5						
	6						
Water (L)							
Time (s)							
Flowrate $\dot{V}$ (L/min)	Orifice/Nozzle						
	Rotameter						
	Actual Flow (Tank)						
	Venturi						
C_d	Venturi						

Discussion

1- Compare between the three methods of flow rate measurement in terms of a-accuracy, b-head loss, and c-ease of use (According to your experiment results and to the industrial applications).

2- What are the advantages and disadvantages of each instrument?

3- Mention other methods to measure the flowrate.

4- Demonstrate factors contributing to errors or inaccuracy in experimental data and propose recommendations to improve the results.

5- Explain the high-pressure drop in the orifice/nozzle meter.

(*Include a discussion on the result noting trends in measured data, and comparing measurements with theoretical predictions when possible. Include the physical interpretation of the result, the reasons on deviations of your findings from expected results, your recommendations on further experimentation for verifying your results and your findings.)*

Reference:

ROBERSON, J. A., ELGER, D. F., WILLIAMS, B. C., & CROWE, C. T. (2013). *Engineering fluid mechanics*.

Experiment 2: Packed And Fluidized Bed

I. Objective:

1- To measure the minimum velocity of fluidization.
2- To validate the Ergun equation for the pressure drop the bed of particles

II. Test Standard

ASTM D7743 - 12 :Standard Test Method for Measuring the Minimum Fluidization Velocities of Free Flowing Powders

III. Theory:

The minimum velocity at which a bed of particles fluidizes is a crucial parameter needed for the design of any fluidization operation. The details of the minimum velocity depend upon a number of factors, including the shape, size, density, and polydispersity of the particles. The density, for example, directly alters the net gravitational force acting on the particle, and hence the minimum drag force, or velocity, needed to lift a particle. The shape alters not only the relationship between the drag force and velocity, but also the packing properties of the fixed bed and the associated void spaces and velocity of fluid through them.

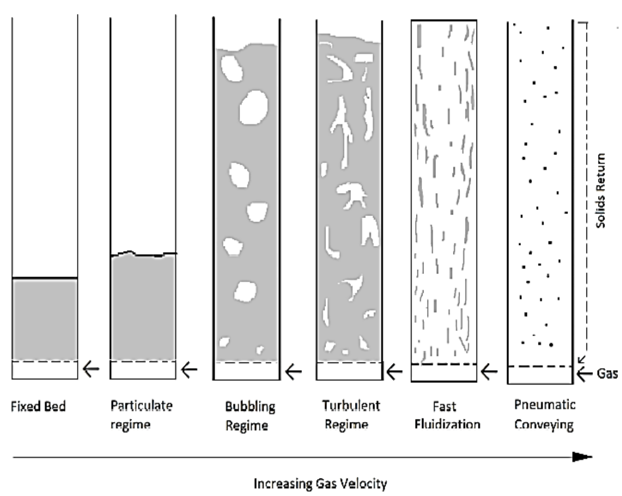


Figure 1 The regimes of fluidization

The theory for this experiment is covered in Chapter 7 of McCabe, Smith, and Harriott (M,S&H). To find the minimum fluidizing velocity, V_{mf}, experimental and theoretical approaches can be used. Methods for calculating the flow rate at which fluidization occurs are described first, as a review of fundamental ideas that govern the behavior of the bed of particles. Then, a procedure for estimating the minimum velocity from experimental measurements is described.

The flow of a fluid, either liquid or gas, through a static packed bed can be described in a quantitative manner by defining a bed friction factor, f_p, and a particle Reynolds number, $N_{Re,p}$, as follows:

$$f_p = \frac{\Delta p g_c \phi_s D_p \varepsilon^3}{\rho \bar{V}_o^2 L\,(1-\varepsilon)}$$ similar to equation 7.19 in M.S& H …………………(1)

Where :
ΔP = pressure drop across the bed
L = bed depth or length
g_c = conversion constant (= unity if SI units are used)
D_p = particle diameter
ρ = fluid density
ε = bed porosity or void fraction
$\bar{V}_o$ = superficial fluid velocity
ϕ_s = sphericity

For laminar flow, $(N_{Re,p} < 20)$, experimental data may be correlated by means of the Kozeny-Carman equation:(See McCabe and Smith 4th edition, pg.137)

$$f_p = \frac{150\,(1-\varepsilon)}{N_{Rep}\cdot\phi_s}$$ similar to equation 7.17 in M.S& H …………………(2)

For highly turbulent flow where inertial forces predominate, $(N_{Re,p} > 1000)$, experimental results may instead be correlated in terms of the Blake-Plummer equation:

f_p= 1.75 similar to 7.20 M.S & H…………..…..…..………….. (3)

While both equations (2) and (3) have a sound theoretical basis, Ergun empirically found that the friction factor could be described for all values of the Reynolds number by simply adding the right hand sides of equations (2) and (3). Thus:

$$f_p = \frac{150\,(1-\varepsilon)}{N_{Rep}\cdot\phi_s} + 1.75$$ similar to equation 7.22 in M.S& H ……………….... (4)

Minimum fluidization velocity $\bar{V}_{oM}$

for the case of small particles and consequent, $N_{Re} < 1$:

$$\bar{V}_{oM} = \frac{g(\rho_p - \rho)\varepsilon_M^3 \phi_s^2 D_p{}^2}{150\mu(1-\varepsilon_M)} \quad \ldots\ldots (5)$$

This equation is the basis for some empirical equations found in the literature. The terms can be rearranged as follows:

$$\bar{V}_{oM} = \frac{\varepsilon_M^3 \phi_s^2}{150(1-\varepsilon_M)} \frac{g\,(\rho_p - \rho)\ D_p{}^2}{\mu} \quad \ldots\ldots (6)$$

The first factor contains the sphericity of the particles and the bed porosity at the point of incipient fluidization. Neither of these factors is usually known with a high degree of accuracy. If spheres are assumed $(\phi_s = 1)$ and a reasonable value of voidage, say $\varepsilon_M = 0.4$, then the first factor is 0.00071. The factor is quite sensitive to ε_M. For example, if $\varepsilon_M = 0.413$, then the factor is 0.0008.

One scientist has simply determined the first factor from his data and actually found 0.0008 to be the best value; that is, he reported the following correlation:

$$\bar{V}_{oM} = 0.0008\ \frac{g\,(\rho_p - \rho)\ D_p{}^2}{\mu} \quad \ldots\ldots (7)$$

Void fraction ε

The voids between particles of the bed plays an important role in fluidization. It also affect the calculation of the minimum fluidization velocity. The void fraction can defined by the relation:

$$\varepsilon = \frac{(V - V_p)}{V} \quad \ldots\ldots (8)$$

Where V is the volume of the bed and V_p is the volume of the particles.

$$\varepsilon = \frac{(V - (V_t - V_i))}{V} = 1 - \frac{(V_t - V_i)}{V} = 1 - \frac{\rho_a}{\rho_s} \quad \ldots\ldots (9)$$

$$\rho_s = \frac{(\rho_t - \rho_i)}{V_t - V_i} \quad \ldots\ldots (10)$$

$$\rho_a = \frac{(\rho_t - \rho_i)}{V} \quad \ldots\ldots (11)$$

where:

- Pi : mass of the test tube
- Vi : a known volume of water in the test tube

- P_t : total mass of this test tube = the total weight of this test tube after having added a volume of solid particles not tapped down
- V_t : the total volume of this test tube containing the liquid and the particles
- ρ_a : the apparent density of the solid.
- ρ_s :the real mass per unit volume of the solid.

Useful link : https://www.wikihow.com/Calculate-Porosity

Pressure drop and $\bar{V}_{oM}$

Fixed bed can is converted to fluidized bed with increasing the velocity according to the following curve:

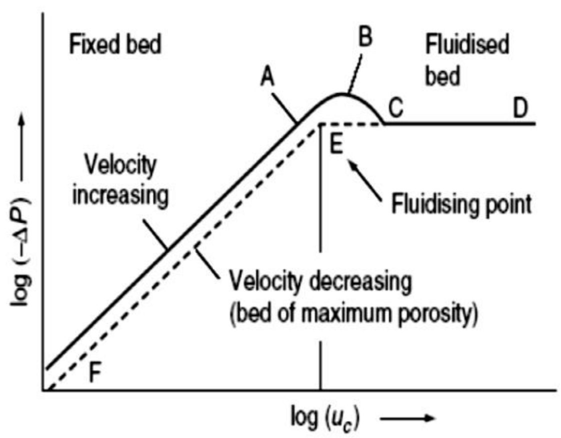


Figure 2 Pressure drop over fixed and fluidized bed (Richardson, 2012)

IV. Apparatus:

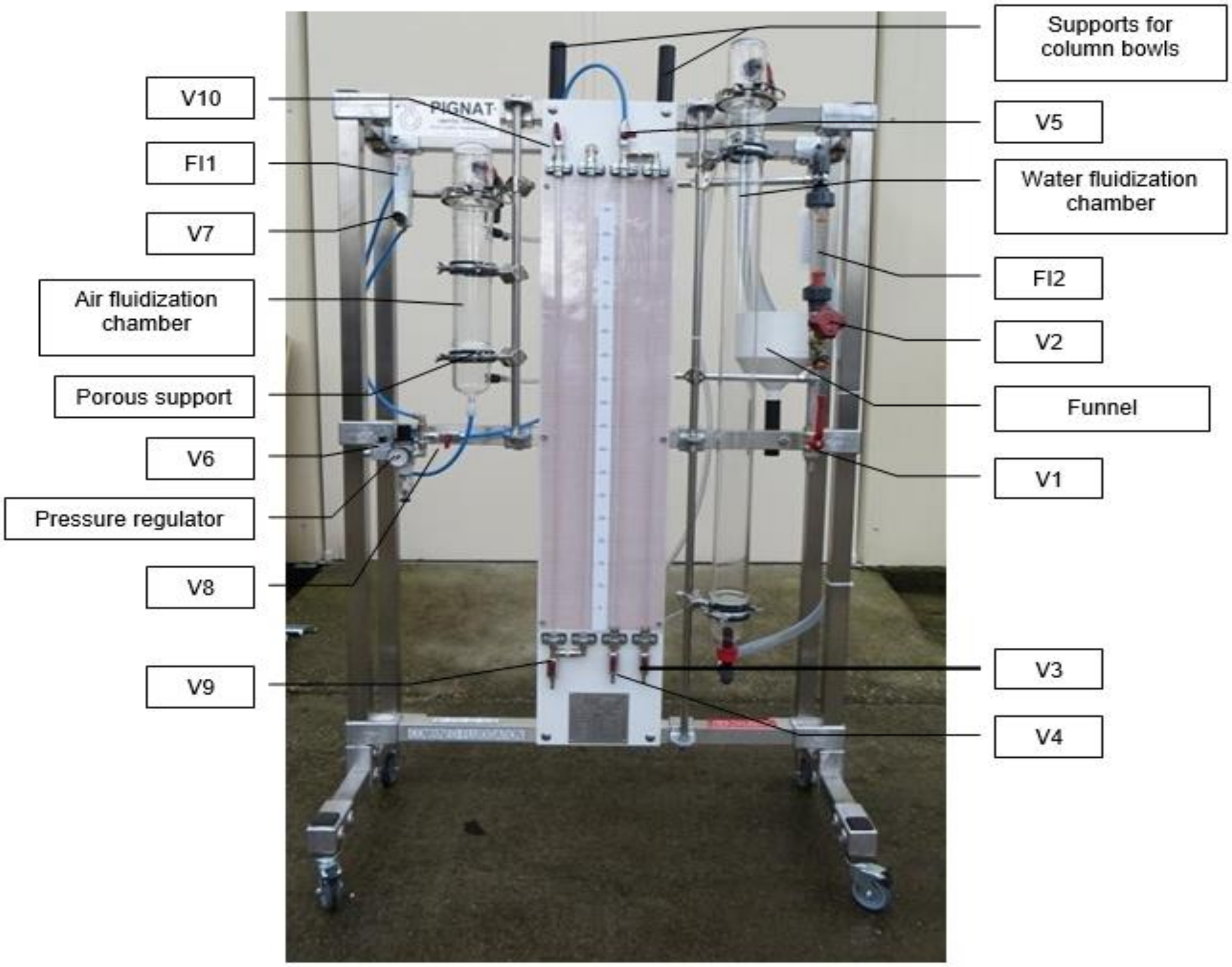


Figure 3 The experimental apparatus

V1	cut-off valve for the water feed to the installation.
V2	water flow rate control valve.
V3	emptying valve for the differential manometer ΔP_2.
V4	emptying valve for the differential manometer ΔP_2.
V5	isolating/venting valve for the differential manometer ΔP_2.
V6	cut-off valve for the compressed air feed to the installation.
V7	air flow rate control valve.
V8	compressed air feeding valve of the differential manometer ΔP_2.
V9	emptying valve for the differential manometer ΔP_1.
V10	filling valve for the differential manometer ΔP_1.
FI_1	measurement of the air flowrate by rotameter (0 to 100L/h)
FI_2	measurement of the water flow rate by rotameter (100 to 1000L/h)
ΔP_1	differential manometer of the liquid-solid fluidization column
ΔP_2	differential manometer of the gas-solid fluidization column

Table 1 Key for the labels on the experimental equipment shown in Figure 2

V. Procedure:

A. Gas-solid fluidization:

- Fill the fluidization vessel with dry alumina obtaining a height of solid of about 10 cm.
- Open valves V6 then V7 to fluidize the bed, and then close valve V7 in such a way as to correctly deposit the solid.
- Progressively open valve V7 and note down:
  - The air flowrate
  - The pressure losses of the whole of the "glass vessel/fritted glass distributor/bed" assembly
  - The height of the particle bed
- Continue these measurements until the maximum airflow rate.
- Continue these measurements while progressively closing V7.

B. Liquid-solid fluidization:

- Fill the fluidization vessel with glass beads obtaining a height of solid of about 20 cm.
- Open valves V1 then V2 to fluidize the bed, and then close valve V2 in such a way as to correctly deposit the solid.
- Progressively open valve V2 and note down:
  - The water flow rate
  - The pressure losses of the whole of the "glass vessel/glass distributor/bed" assembly
  - The height of the particle bed
- Continue these measurements until the maximum water flow rate.
- Continue these measurements while progressively closing V2.

C. Void Fraction ε :

Prepare a sample with known mass follow the steps below:

- Measure the mass of the test tube Mi
- Prepare a known volume of water in the test tube Vi
- Measure (M_t) which is the total mass of this test tube = the total weight of this test tube after having added a volume of solid particles not tapped down
- Measure V_t which is the total volume of this test tube containing the liquid and the particles.
- Use equations 8 and 9 to calculate void fraction ε.

Useful link : https://www.wikihow.com/Calculate-Porosity

VI. Experimental Work:

<u>Fluidization of the Alumina bed</u>

Initial height of the bed: cm.

Qv (l/h)	Um (m/s)	ΔH (cm)	ΔP_{tot} (Pa)	Z (cm)	ΔP_{Empty}	ln Um	ln ΔP	Observations

Discussion

1. Plot the measured pressure drop versus the volumetric flow rate.
2. Calculate Reynolds number for eachrun.
3. Calculate the value of the pressure drop at point where fluidization begins.
4. From your results, calculate experimental V_{0M} in m/s for each of your runs and beds.
5. Use the theoretical equation given to predict theoretical V_{0M}
6. Compare your findings with the theoretical results critically.
7. Demonstrate factors contributing to errors or inaccuracy in experimental data and propose recommendations to improve the results.

(*Include a discussion on the result noting trends in measured data, and comparing measurements with theoretical predictions when possible. Include the physical interpretation of the result, the reasons on deviations of your findings from expected results, your recommendations on further experimentation for verifying your results and your findings.)*

Technical Data

Solid:

Alumina Corindon Blanche F120, diameter 106μm
Density: ρ_s = 3950 kg.m^{-3}
Average porosity: ε = 0.5
Glass beds, Ø 3 mm and Ø 6 mm

Air fluidization vessel:

Internal diameter: 60 mm Maximum
capacity: 0.8 liters Porosity of
support: 100 to 160 µm

Water fluidization vessel:

Internal diameter: 60 mm Maximum

capacity: 2.8 liters Slot plate

Height of glass bed: from 10 to 36 cm
Height of alumina bed: from 5 to 18 cm

Reference:

MCCABE, W. L., & SMITH, J. C. (2004). *Unit operations of chemical engineering*. New York, McGraw-Hill.

Experiment 3: Series and Parallel Pumps

I. Objectives:

3- To study performance of a single centrifugal pump.
4- To study performance of two pumps where connected in parallel or series.

II. Test Standard

- API standard 610
- Manufacturer Standard

III. Theory:

Pumps are used to transfer fluid in a system, either at the same level or to a new height. The flow rate depends on the height to which the fluid is pumped, and the relationship between "head" and flow rate is called the "pump characteristic". This has to be determined experimentally for a single pump and two similar pumps connected in Series and Parallel.

The increase in head H between the inlet and outlet of a pump is a function of the flow rate and rotational speed N. This relationship is expressed graphically and called the "pump characteristic", as shown in Figure 1.

Head, H, is a height measured in meters of water, but an alternative convention is to use the pressure rise across the pump, Δp (N/m^2 or bar).

Δp and H are related to each other by:

Δp = ρgH

And

Mass flow rate through pump, $\dot{m} = \rho\dot{Q}$(kg/s)

Hydraulic power generated,

$P_H = \dot{m}gH = \rho g\dot{Q}H$ (W)……………….(1)

Mechanical power P_m input to pump = $2.\pi.n.t$ (Watt)

n: pump speed in RPS

t: Motor torque N.m

Overall pump efficiency

$$\eta = \frac{P_H}{P_m} = \frac{\rho g\dot{Q}H}{2\pi.n.t} \dots\dots\dots\dots\dots (2)$$

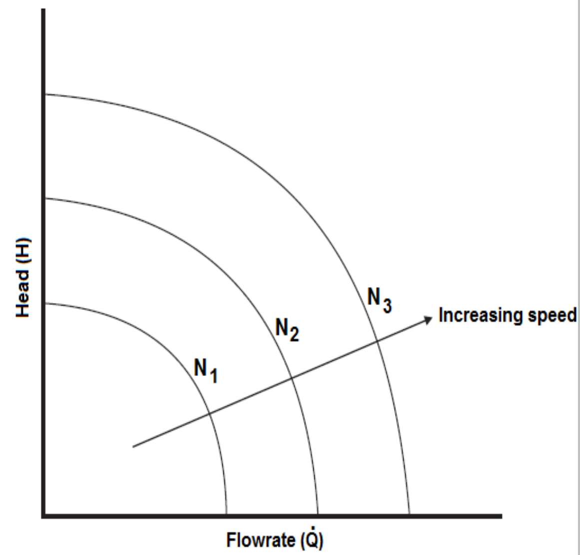


Figure 1 Pump characteristics

Some text books work in terms of Δp, others in terms of H. The two sets of equations look similar, but differ by the presence of ρg. Never confuse the two systems.

Two pumps in series

A schematic representation of two pumps in series is shown in Figure 2. Ignoring any losses that occur between the two pumps, the flow rate through both is the same, but the overall pressure rise is the sum of the two individual values. If both pumps are identical then the pressure rise is doubled for a given flow rate. Figure 3 shows the pressure/flowcharacteristics for two pumps in series.

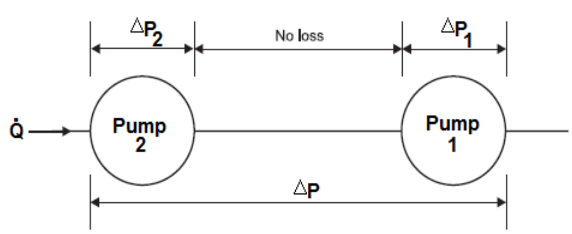


Figure 2 Schematic showing two pumps in series

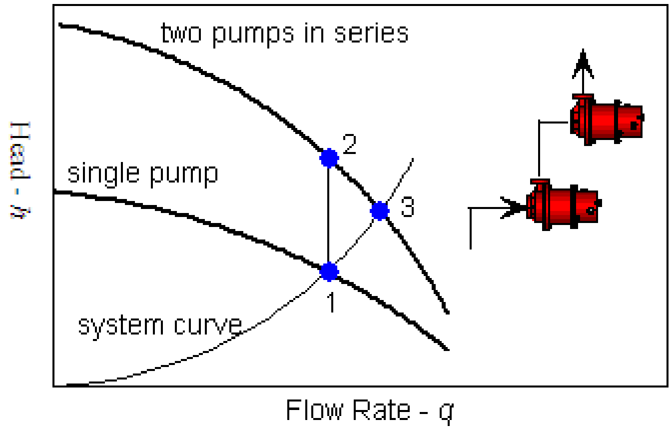


Figure 3 head - flow characteristics for pumps in series

__Two pumps in parallel__

A schematic representation of two pumps in parallel is shown in Figure 4. Ignoring any losses between the two pumps, the pressure rise across each pump is the same and is the total pressure rise. The overall flow rate is the sum of the two individual values, as shown in Figure 5. If both pumps are identical, then the total flow rate is twice that of each single pump.

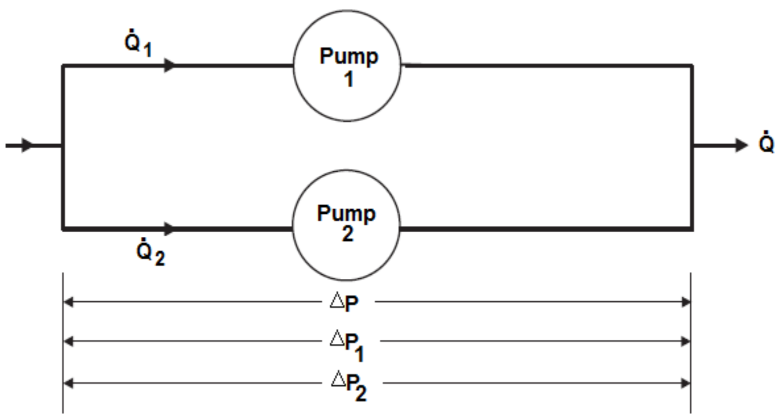


Figure 4 Schematic showing two pumps in parallel

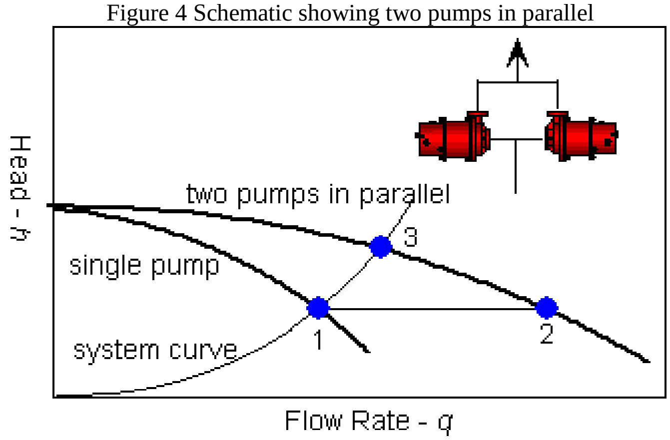


Figure 5 head - flow characteristics for pumps in parallel

The actual pressure/flow characteristic is a curve of the form $\Delta P = A - B\dot{Q}^2$where A and B are constants which depend on the system. It is therefore useful to plot curves of Δp against$\dot{Q}^2$ (Figure 6), which should be straight lines.

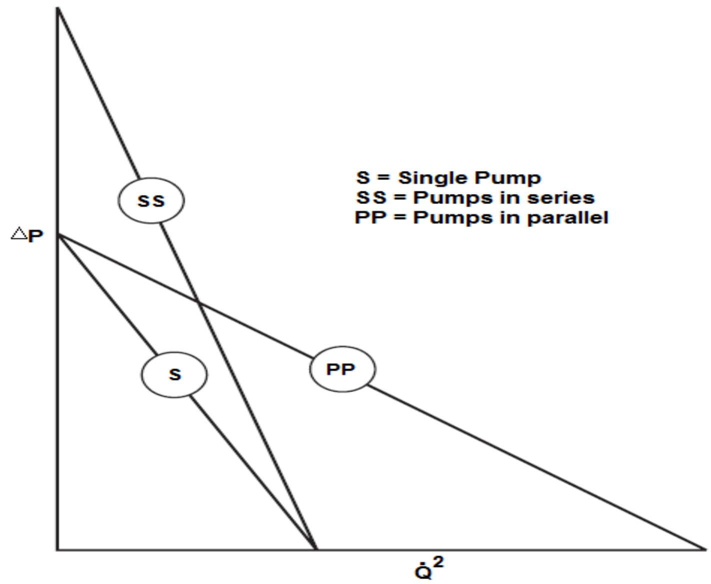


Figure 6 Curves of Δp versus $\dot{Q}^2$

IV. Apparatus:

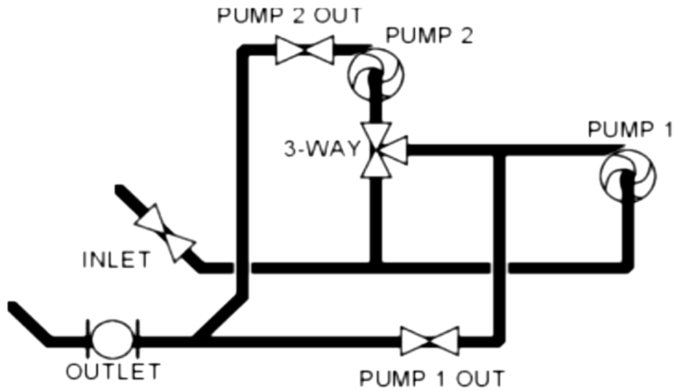
The apparatus consists of a tank and pipe work which delivers water to and from two identical centrifugal pumps. The unit is fitted with electronic sensors which measure the process variables. Signals from these sensors are sent to a computer via an interface device, and the unit is supplied with data logging software as standard.

The speed of one of the pumps may be varied to allow the collection of performance data over a range of parameters. Outlet pressures may be varied to control the flow rate. Flow through the system may be set to allow single pump operation, series pump operation or parallel pump operation.

<u>Setting the flow path</u>

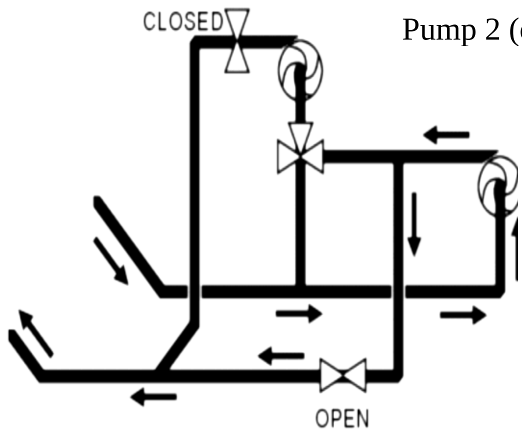
The system may be configured to drive flow using single, series or parallel pumps.

The system valves are as shown:



Valves should be set to configure the system as in figures 11, 12 and 13. The software should also beset to the corresponding flow path to ensure that the correct calculations are performed.

Figure 11 The Series and Parallel Pump Test Set



Pump 2 (off)

Figure 12 Setting the three valves – pump 1 only

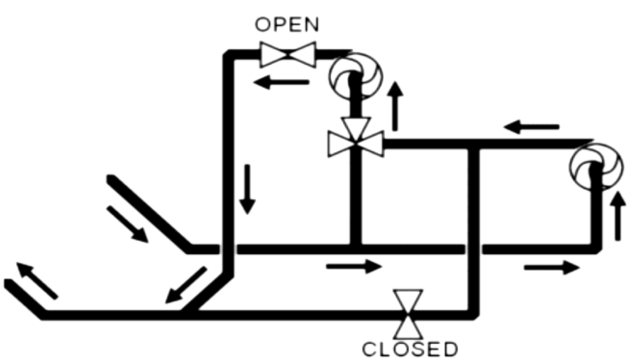


Figure 13 *Setting the three valves – pumps in parallel*

The software allows control of the pump frequency and logging of data from all sensors. The software also performs calculations on the data obtained, and may be construct the graphs of the results automatically or the data obtained may be imported into a spread-sheet (Excel) and the graphs may be plotted manually. The exercises may be performed in separate tests and these results may be combined into a single session without shutting down the equipment and produced a single spread-sheet and graphs. The mimic diagram screen of the software is shown below.

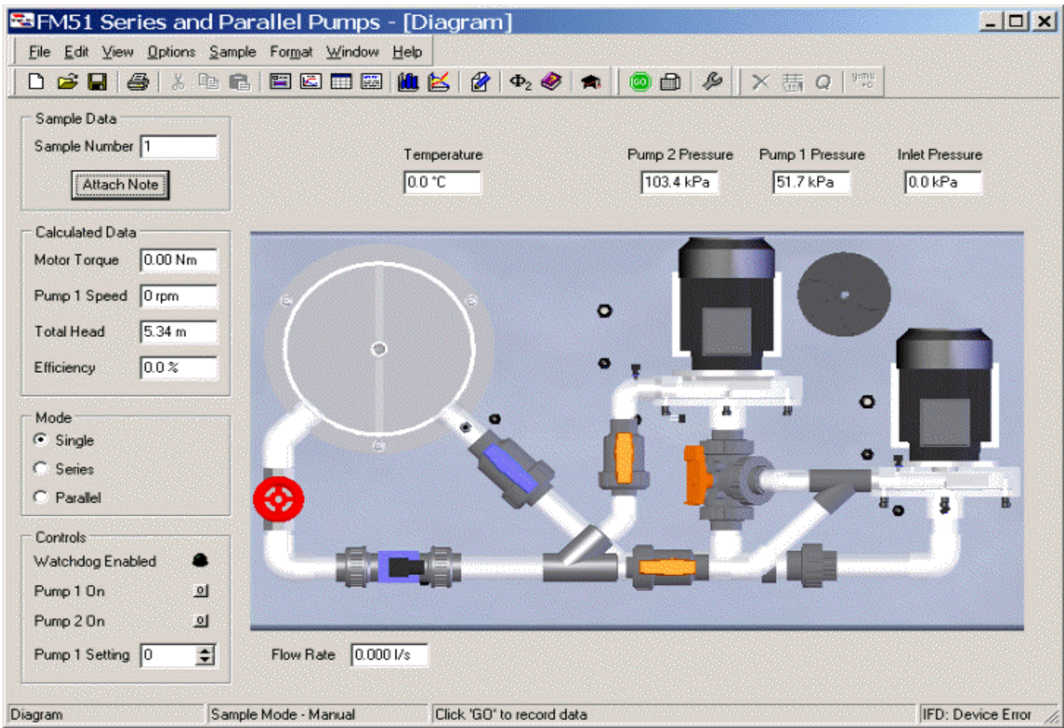


Figure 14 Software interface.

V. Procedure:

1) Set the valves for a particular pump test (refer to Figures 12 to 14 if necessary).
2) In the software, on the mimic diagram, set the 'Mode' to 'Single or series or parallel' by selecting the appropriate mode button.
3) Run the software. Check that 'IFD: OK' is displayed in the bottom right cornerof the screen and that there are values displayed in all the sensor display boxes on the mimic diagram.
4) Set the pump to 100%.
5) Allow water to circulate until all air has been flushed from the system.
6) Select the  icon to record the sensor readings and pump settings on the results table of the software.
7) Open the gate valve to give a low flow rate. Allow sufficient time for the sensor readings to stabilize, then select the icon  to record the next set of data.
8) Open the gate valve in small increments, allowing the sensor readings to stabilize then recording the sensor and pump data each time.

9) Using the arrow buttons on the software display, reduce the pump speed to 0%. Select 'Save' or 'Save As…' from the 'File' menu and save the results with a suitable file name (e.g. the date and the exercise).

VI. Experimental Work:

1- The mass flow rate Q_{total} [kg/s]

$$Q_{P1} = Q_{P2} = Q_{total} \quad for\ series$$

$$Q_{P1} + Q_{P2} = Q_{total} \quad \rightarrow \quad Q_{P1} = Q_{P2} = \frac{1}{2} Q_{total} \qquad for\ Parallel$$

2- Fill the given tables and show your calculations.

3- On a base of flow rate, plot a graph of total head gain for the single pump and

- for two pumps connected in series
- for two pumps connected in parallel

4- Calculate the difference between

- The total head gain for single and series pumps.
- The total flow rate for single and parallel pumps.

5- Plot graphs of pressure rise against flow rate and (flow rate)^2.

6- Plot graphs of Efficiency against flow rate.

Table 4: Apparatus data

Name	Symbol	Unit	Definition
Inlet diameter	d_{in}	m	Diameter of inlet pipe d_{in} = 0.0235
Outlet Diameter	d_{out}	m	Diameter of outlet pipe d_{out} = 0.0175
Change in Elevation Head	He	m	Vertical distance between inlet and outlet He = 0.075m
Change in Static Head	Hs	m	$\frac{p_{out} - p_{in}}{\rho g}$
Change in Velocity Head	Hv	m	$\frac{V_{out}^2 - V_{in}^2}{2g}$
Change in total Head	Ht	m	He + Hs +Hv

Table 1: Single pump

Pump 1 Inlet Velocity [m/s]	Pump 1 Outlet Velocity [m/s]	Pump 1 Total Head [m]	Combined Total Head [m]	Pump 1 Hydraulic Power [W]	Total Hydraulic Power [W]	Pump 1 Mechanical Power [W]	Pump 1 Efficiency E1 [%]	Overall Efficiency Egr [%]

Table 2 : Pumps on series

Pump 1 Total Head [m]	Pump 2 Total Head [m]	Combined Total Head [m]	Pump 1 Hydraulic Power [W]	Pump 2 Hydraulic Power [W]	Total Hydraulic Power [W]	Pump 1 Mechanical Power [W]	Pump 1 Efficiency E1 [%]	Pump 2 Efficiency E2 [%]	Overall Efficiency Egr [%]

Table 3: Pumps on series

Pump 1 Total Head [m]	Pump 2 Total Head [m]	Combined Total Head [m]	Pump 1 Hydraulic Power [W]	Pump 2 Hydraulic Power [W]	Total Hydraulic Power [W]	Pump 1 Mechanical Power [W]	Pump 1 Efficiency E1 [%]	Pump 2 Efficiency E2 [%]	Overall Efficiency Egr [%]

Discussion

1- What are the sources of error in this experiment?
2- Compare your graphs with what is expected theoretically.
3- Comment on all results and figures.
4- State the applications of both series and parallel connections
5- From your results, what is the main difference between connecting pumps on parallel or on series.

(Include a discussion on the result noting trends in measured data, and comparing measurements with theoretical predictions when possible. Include the physical interpretation of the result, the reasons on deviations of your findings from expected results, your recommendations on further experimentation for verifying your results and your findings.)

IMPORTANT: Attach the calculations spreadsheet (excel) with your report.

References:

1- ROBERSON, J. A., ELGER, D. F., WILLIAMS, B. C., & CROWE, C. T. (2013). *Engineering fluid mechanics*.

2- www.engineeringtoolbox.com

Experiment 4: Friction Loss in pipes and fittings

I. Objectives:

1- To investigate the head loss in a straight pipe as a function of volume flow.
2- To determine the relationship between friction factor and Reynolds number for flow of water in a straight pipe.
3- To find the head loss due to friction in different fittings and valves.

II. Test Standard

- NA

III. Theory:

For an incompressible fluid flowing through a pipe from point (1) to point (2), figure 1. The following equations apply:

Continuity equation:

$$Q = A_1 V_1 = A_2 V_2$$

Bernoulli equation:

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + Z_2 + h_{L1-2}$$

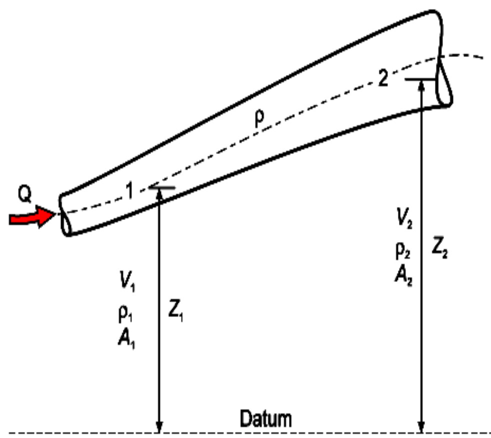


Figure 1 Flow in pipe

Where:

Q : Volumetric flow rate (m^3/s);
V : Mean velocity (m/s);
A : Cross sectional area (m^2);
Z : Height above datum (m);
P : Static pressure (N/m^2);
P : Density (kg/m^3);
g : Acceleration due to gravity (9.81 m/s^2).

h_L : is the head loss (m); which is the total energy lost due to friction between the liquid and the wall and the interaction of the liquid molecules.

The friction head (head loss) between two points can be expressed by:

$$h_L = \left(\frac{P_1}{\gamma} - \frac{P_2}{\gamma}\right) + \left(\frac{V_1^2}{2g} - \frac{V_2^2}{2g}\right) + (Z_1 - Z_2) \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

and the total energy of water at any point may be expressed as the total head at that point h_t *where :*

Total head (h_t) = Pressure head +velocity head + static head (elevation)

$$= h_p + h_v + h_s = \frac{P}{\gamma} + \frac{V^2}{2g} + Z \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Head Loss

The head loss in a pipe circuit falls into two categories:

a) Major Head loss (Pipe head loss): That due to fully developed flow conduits, and it is caused by shear loss.
b) Minor head loss (component head loss): That due to flow through devices such as valves, bends, and tees.

The overall head loss is a combination of both categories.

- **Head Loss in Straight Pipes [Major Loss]**

Fluid flow in a direction of decreasing pressure and the decrease in the pressure is caused by the frictional loss in a pipe. The friction loss in a pipe depends on the type of the flow (Laminar or turbulent) and the surface roughness of the pipe.

Laminar flow $Re \leq 2000$

Head loss h_f is given by Darcy – Weisbach equation

$$h_f = f\frac{L}{d}\frac{V^2}{2g} \quad Where\ f = \frac{64}{Re} \qquad Re = \frac{\rho V D}{\mu}$$

OR

$$h_f = \frac{32\mu L V}{\gamma D^2} \quad Where\ \frac{h_f}{L} \propto V$$

Where V is the average velocity and D is the pipe diameter and L is the pipe length and γ is the specific weight and μ is the dynamic viscosity.

Turbulent flow $Re \geq 3000$

Also head loss h_f is given by Darcy – Weisbach equation

$$h_f = f\frac{L}{d}\frac{V^2}{2g} \quad Where \quad \frac{h_f}{L} \propto V^2$$

$Where f$ is a function of Reynolds number ,Re ,and pipe roughness, $\frac{k_s}{D}$

f: friction factor

K_s: Roughness height

$\frac{K_s}{D}$: Relative roughness

- **Head Loss for Valves and Pipe Fittings [Minor loss]**

There is no established formula for friction of Valves and pipe fittings. However from experimental results:

$h_L = K\frac{V^2}{2g}$ Where K is a constant called fittings loss coefficient.

Considering Figure 2, apply Bernoulli's equation between 1 and 2:

$$\frac{P_1}{\gamma}+\frac{V_1^2}{2g}+Z_1=\frac{P_2}{\gamma}+\frac{V_2^2}{2g}+Z_2+h_L$$

But $V_1 = V_2 and Z_1 = Z_2$

So $h_L = \frac{P_1-P_2}{\gamma}$ …………………………………... (3)

For Piezometer tubes

$P_1-\gamma(x+y)=P\ and\ P_2-\gamma y=P\ therfore$

$P_1-\gamma(x+y)=P_2-\gamma y$

Rearrange the last equation to get

$\frac{P_1-P_2}{\gamma}=x$ ……………………………………….. (4)

From equations 1 and 2 we find that $h_L = x$

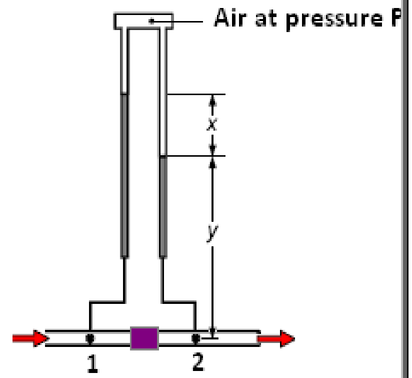


Figure 2 Pressurized piezometer tubes to measure pressure loss between two points

Considering Figure 3, apply Bernoulli's equation between 1 and 2:

$$\frac{P_1}{\gamma}+\frac{V_1^2}{2g}+Z_1=\frac{P_2}{\gamma}+\frac{V_2^2}{2g}+Z_2+h_L$$

But $V_1 = V_2 and Z_1 = Z_2$

So $h_L = \frac{P_1-P_2}{\gamma_{H_2O}}$ …………………………………... (5)

Consider the U-tube. Pressures in both limbs of U-tube are equal at level 0-0. Therefore equating pressure at 0-0:

$P_2-\gamma_{H_2O}(x+y)+\gamma_{Hg}x=P_1-\gamma_{H_2O}y$

Giving : $P_1-P_2=x\left(\gamma_{Hg}-\gamma_{H_2O}\right)$

Hence : $\frac{P_1-P_2}{\gamma_{H_2O}}=x(s-1)$ ……………………….(6)

Considering Equations 5 and 6 and taking the specific gravity of mercury as 13.6, then $h_L = 12.6x$

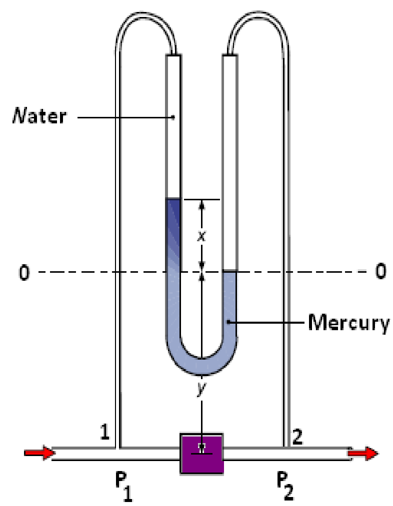


Figure 3 U-tube containing mercury used to measure pressure loss across valves

IV. Apparatus:

The apparatus setup is shown in figure 4. It consists of two separate hydraulic circuits; one painted dark blue, one painted light blue, each one containing a number of copper pipe system components. Both circuits are supplied with water from the same hydraulic bench. The components in each of the circuits are as detailed at figure 1 and table 1.

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

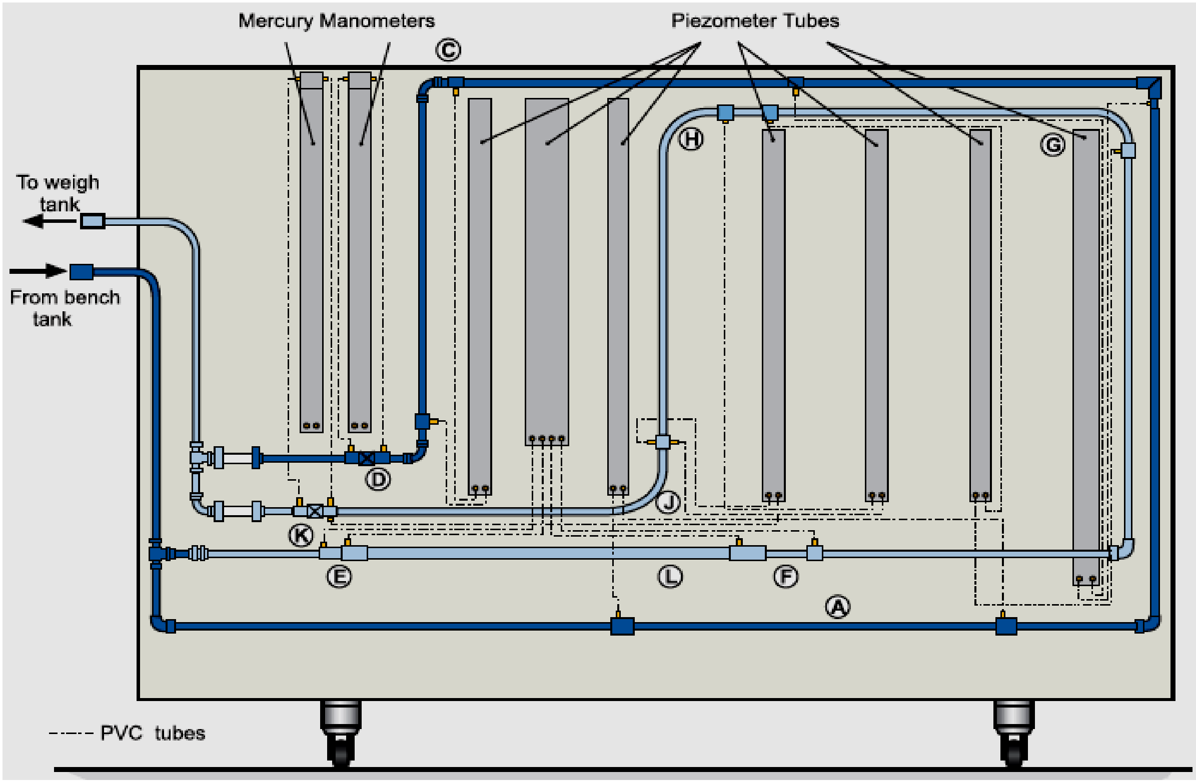


Figure 4 The setup of friction loss apparatus

Dark Blue Circuit	Light Blue Circuit
A) Straight pipe 13.7 mm bore(copper)	E) Sudden expansion - 13.6 mm / 26.2 mm
B) 90°Sharp bend (mitre)	F) Sudden contraction - 26.2 mm / 13.6 mm
C) Proprietary 90°elbow 12.7 mm diameter	G) Smooth 90°bend 50.8 mm radius
D) Gate valve	H) Smooth 90°bend 100 mm radius
Distance between pressure tappings for straight pipe and bend experiments = 0.914 m	J) Smooth 90°bend 152 mm radius
	K) Globe Valve
	L) Straight Pipe 26.4mm

Table 1 Components of the apparatus

Unit	Manometer tube	Unit	Manometer tube
12.7 mm 90º elbow	1	Contraction	9
	2		10
Straight pipe	3	152 mm bend	11
	4		12
Mitre bend	5	100 mm bend	13
	6		14
Expansion	7	50.8 mm bend	15
	8		16

Table 2 Identification of Manometer Tubes and Components

V. Procedure:

In this experiment, the dark blue circuit only is to be tested

1. Open fully the water control valve on the hydraulic bench.
2. Close fully the globe valve to isolate the Light Blue circuit.
3. Open the gate valve fully to obtain maximum flow through the Dark Blue circuit.
4. Start the pump on the hydraulic bench.
5. Wait until readings are settle down
6. Record the readings on the piezometer tubes and the U-tube.
7. Measure the time needed to collect a quantity of water in the weigh tank [10 L].
8. Repeat the above procedure for a total of six different flow rates, obtained by closing the control valve on the hydraulic bench.
9. With an accurate thermometer, record the water temperature in the sump tank of the bench at the beginning and at the end of the experiment. Consider the average value as the water temperature.
10. Close the gate valve.
11. Switch off the pump.

VI. Experimental Work:

Table 3 Experimental Results

Test number	**Time to collect 25 kg of water (s)**	**Piezometer tube readings (cm) water**						**U-tube (cm) Hg Gate valve**	
		1	2	3	4	5	6		
1									
2									
3									
4									
5									
6									

Table 4 Calculated Results for straight pipe

Test number	**Volume Flow rate Q (m^3/s)**	**Mean Velocity V (m/s)**	**Log V**	**Reynolds number Re**	**Laminar or Turbulent flow**	**Friction head loss h_f (m)**	**Log h_f**	**Friction Factor f**
1								
2								
3								
4								
5								
6								

Table 5 Calculated Results for 90° elbow 12.7 mm diameter.

Test number	**Volume Flow rate Q (m^3/s)**	**Mean Velocity (m/s)**	**Friction head loss h_f(m)**	**Minor loss coefficient K_{EXP}**	**Minor loss coefficient K_{THEO}**	**% Error**
1						
2						
3						
4						
5						
6						

Table 6: Calculated Results for 90°Sharp bend (mitre)

Test number	**Volume Flow rate Q (m^3/s)**	**Mean Velocity (m/s)**	**Friction head loss h_f(m)**	**Minor loss coefficient K_{EXP}**	**Minor loss coefficient K_{THEO}**	**% Error**
1						
2						
3						
4						
5						
6						

Table 7: Calculated Results for Gate valve

Test number	**Volume Flow rate Q (m^3/s)**	**Mean Velocity (m/s)**	**Friction head loss h_f(m)**	**Minor loss coefficient K_{EXP}**	**Minor loss coefficient K_{THEO}**	**% Error**
1						
2						
3						
4						
5						
6						

- ***Head Loss in Straight Pipes [Table 4]***

1. Volume flow rate of water Q $\qquad$ $\dot{Q} = \frac{volume of water}{time}\ [m^3/s]$

2. Mean velocity V $\qquad$ $V = \frac{\dot{Q}}{A}\ [m/s]$

3. Reynolds number *Re*
Classify flow as Laminar or turbulent $\qquad$ $Re = \frac{\rho V D}{\mu} = \frac{VD}{\nu}$

4. Friction Head Loss h_f $h_f = h_3 - h_4 = \Delta h$

5. Friction factor f Darcy – Weisbach equation

6. Plot a graph of the head loss versus the average velocity and identify the laminar and turbulent zones on the graph.
7. Confirm that the graph is a straight line for the laminar flow zone and $\boldsymbol{h_L \sim V^n}$ for the turbulent flow.
8. Plot a graph of ***log*** $\boldsymbol{h_f}$ [y-axis] versus ***logV*** [x-axis] and confirm that the graph is a straight line and find the exponent n from the slope of this graph.

➢ ***Head Loss in fittings (Elbow, Mitre bend, Gate valve) [Tables 5, 6, and 7]***

1. Volume flow rate of water$Q$ $\dot{Q} = \frac{volume of water}{time} [m^3/s]$

2. Mean velocity V $V = \frac{\dot{Q}}{A} [m/s]$

3. Friction Head Loss h_f $h_f = \Delta h$ for related manometers

4. Minor loss coefficient K_{Exp} $h_f = K \frac{V^2}{2g}$

5. Find K_{Theo} from literature [Appendix and find % error
6. Plot a graph of $\boldsymbol{h_f}$ [y-axis] versus $\frac{V^2}{2g}$ [x-axis] and confirm that the graph is a straight line and find the slope of this graph. What the slope represents?. Comment on your curve and slope

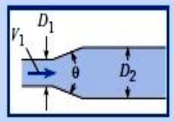
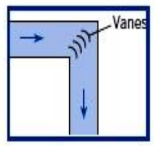
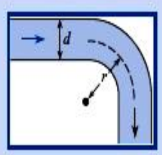
<u>Discussion</u>

1. Compare all experimental results with what expected theoretically.
2. Comment on the percentage error and discuss any source of error in the experiment.
3. State the importance of this experiment and mention some related applications.
4. Discuss the head losses in 90^o Mitre and Elbow.
5. Plot the relation between head loss h_L and volumetric flow rate Q^n and find n for straight pipe.
6. Obtain the K value of the gate valve when it is fully open and compare it with table 7.
7. Plot *f* [y-axis] versus *Re* [x-axis] for straight pipe. Compare it with Moody's charts.

Note: You should have 7 plots in your report.

Reference:

ROBERSON, J. A., ELGER, D. F., WILLIAMS, B. C., & CROWE, C. T. (2013). *Engineering fluid mechanics*.

Description	Sketch	Additional Data	K	Source
Expansion $h_L = K_E V_1^2/2g$		D_1/D_2 K_E $\theta = 20°$	K_E $\theta = 180°$	(9)
		0.00	1.00	
		0.20 0.30	0.87	
		0.40 0.25	0.70	
		0.60 0.15	0.41	
		0.80 0.10	0.15	
90° miter bend		Without vanes	$K_b = 1.1$	(15)
		With vanes	$K_b = 0.2$	(15)
90° smooth bend		r/d		(16) and (9)
		1 $K_b = 0.35$		
		2 0.19		
		4 0.16		
		6 0.21		
		8 0.28		
		10 0.32		
Threaded pipe fittings	Globe valve—wide open		$K_v = 10.0$	(15)
	Angle valve—wide open		$K_v = 5.0$	
	Gate valve—wide open		$K_v = 0.2$	
	Gate valve—half open		$K_v = 5.6$	
	Return bend		$K_b = 2.2$	
	Tee			
	Straight-through flow		$K_t = 0.4$	
	Side-outlet flow		$K_t = 1.8$	
	90° elbow		$K_b = 0.9$	
	45° elbow		$K_b = 0.4$	

[†]Reprinted by permission of the American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, Georgia, from the 1981 *ASHRAE Handbook—Fundamentals*.

ROBERSON, J. A., ELGER, D. F., WILLIAMS, B. C., & CROWE, C. T. (2013). *Engineering fluid mechanics*.

Experiment 5: Linear Heat Conduction

I. Objectives:

1- To understand the heat transfer concept through homogeneous solid material section
2- To determine the thermal conductivity for the flow of heat through common metals.

II. Test Standard

- **ASTM E1225 – 20** : Standard Test Method for Thermal Conductivity of Solids Using the Guarded-Comparative-Longitudinal Heat Flow Technique

III. Theory:

If heated and cooled surfaces are clamped tightly together and are in good thermal contact, then the two sections can be considered as a continuous homogenous sample of uniform cross section and material.

According to Fourier's law of heat conduction:

If a plane section of thickness Δx and constant area A maintains a temperature difference ΔT then the heat transfer rate per unit time $\dot{Q}$ by conduction through the wall is found to be:

$$\dot{Q} \propto A\frac{\Delta T}{\Delta X}$$

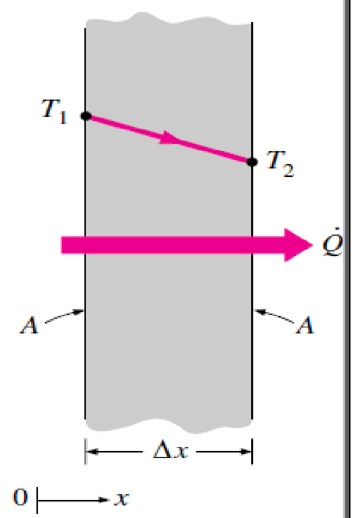


Figure 1 Heat conduction

If the Material of the wall is homogeneous and has a thermal conductivity K then :

$$\dot{Q} = -kA\frac{\Delta T}{\Delta X}$$

The negative sign follows thermodynamic convention in that heat transfer is normally considered positive in the direction of the temperature fall.

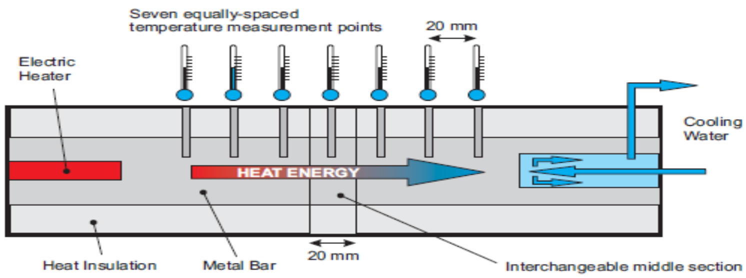


Figure 2 heat conduction section.

According to figure 2 :

Heat transfer rate from the heater can be calculated from:

$$\dot{Q} = V \times I \qquad \text{(watt)}$$

Temperature difference at the heated section between T1 and T3:

$$\Delta T_{hot} = \Delta T_{1-3} = \Delta T_1 - \Delta T_3$$

Similarly the temperature difference in the cooled section between T5 and T7:

$$\Delta T_{cold} = \Delta T_{5-7} = \Delta T_5 - \Delta T_7$$

Hot and Cold Face Temperatures

The temperatures of the hot and cold faces can be calculated from the following equations:

$$T_{cold\ face} = T_5 + \frac{(T_5 - T_6)}{2} \qquad T_{hot\ face} = T_3 - \frac{(T_2 - T_3)}{2} \qquad \ldots\ldots\ldots\ldots (1)$$

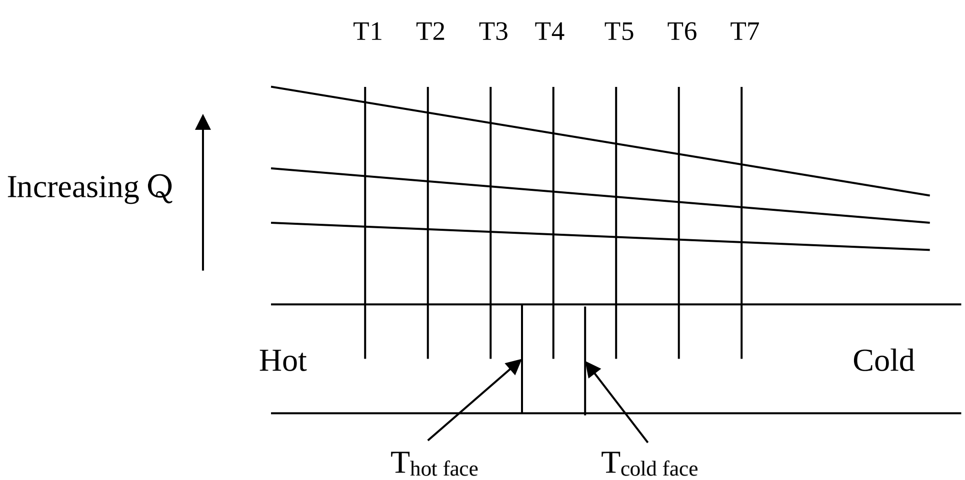


Figure 3 Hot and cold face temperatures

The distance between any two temperature measuring points is 20 mm as shown in figure 2.

Hence, the temperature gradient along heated and cooled sections may be calculated from:

$$Heated\ Section = \frac{\Delta T_{1-3}}{\Delta X_{1-3}}$$

$$Cooled\ Section = \frac{\Delta T_{5-7}}{\Delta X_{5-7}}$$

$$Intermediate\ \ Section = \frac{\Delta T_{H-C}}{\Delta X_{int.}}$$

Thermal Resistance Concept

$$\dot{Q}_{cond} = kA\,\frac{T_1 - T_2}{L}$$

$$\dot{Q}_{cond} = \frac{T_1 - T_2}{R}$$

$\boldsymbol{R = \frac{L}{KA}}$ = Thermal Resistance of the Wall against heat conduction.

$$R_{total} = \frac{1}{U} = \frac{\Delta x_{hot}}{K_{hot}} + \frac{\Delta x_{int}}{K_{int}} + \frac{\Delta x_{cold}}{K_{cold}} \quad \ldots\ldots\ldots\ldots.\ (2)$$

$$U = \frac{Q}{A(T1 - T7)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(3)$$

where U is the overall heat transfer coefficient (W/m.k)

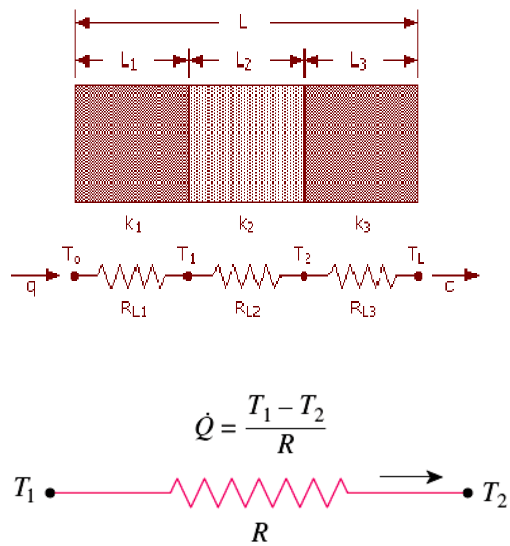


Figure 4 composite material

IV. Apparatus:

The Linear Heat Conduction' consist of:

- **A heating section**

It is manufactured from 30 mm diameter cylindrical brass (CZ 121) bar with a cartridge type electric heating element installed at one end.

- **A cooling section**

It is manufactured from 30 mm diameter cylindrical brass bar to match the heating section and cooled at one end by water passing through galleries in the section.

- **6 thermocouples specimen**

Three thermocouples (T1, T2 and T3) are positioned along the heated section at uniform intervals of 20 mm to measure the temperature gradient along the section.
Three thermocouples (T5, T6 and T7) are positioned along the cooling section at uniform intervals of 20 mm to measure the temperature gradient along the section.

- **Intermediate specimen**

20 mm thick metal section of the same diameter as the heating and cooling sections (30 mm diameter) and fitted with one thermocouples (T4).

Figure 5 Heat conduction unit with VDAS-F hardware

V. Procedure:

1. Turn the voltage controller anti-clockwise to set the AC voltage to minimum.
2. Ensure the cooling water is flowing and then set the heater power to 30W.
3. Monitor temperatures T1, T2, T3, T4, T5, T6 and T7 and wait for the temperatures to stabilize and then record them.
4. When the temperatures are stabilized record:T1-T7.
5. For comparison, repeat the test at one or more heater powers greater than 30W.
6. Repeat procedure1, but use different metals in the middle section.
7. After each change, allow sufficient time to achieve steady state conditions (Up to 10 min).
8. When completed, if no further experiments are to be conducted reduce the heater power to zero and shut down the system.

VI. Experimental Work:

Table 1 Experimental measurements pat 1 Middle section Material: brass (CZ 121)

Sample	T_1 °C	T_2 °C	T_3 °C	T_4 °C	T_5 °C	T_6 °C	T_7 °C	Power (w)
1								
2								
3								
Distance from T1	0							

Table 4: Experimental Calculations for brass

Sample No.	$\dot{Q}$	ΔT_{1-3} Hot	ΔT_{5-7} Cold	ΔT_{H-C} Int.	ΔX_{1-3} Hot	ΔX_{5-7} Cold	ΔX_{int} Int.	k_{1-3hot}	k_{int}	$k_{5-7cold}$
units	Watts	K	K	K	m	m	m	W/m.K	W/m.K	W/m.K
1										
2										
3										

Table 5 Experimental measurements part 2 Middle section Material:

Sample	T_1 °C	T_2 °C	T_3 °C	T_4 °C	T_5 °C	T_6 °C	T_7 °C	Power (w)
1								
2								
3								
Distance from T1	0							

Table 6: Experimental Calculations for material 2

Sample No.	$\dot{Q}$	ΔT_{1-3} Hot	ΔT_{5-7} Cold	ΔT_{H-C} Int.	ΔX_{1-3} Hot	ΔX_{5-7} Cold	ΔX_{int} Int.	k_{1-3hot}	k_{int}	$k_{5-7cold}$
units	Watts	K	K	K	m	m	m	W/m.K	W/m.K	W/m.K
1										
2										
3										

Discussion

1. Plot the temperature profile along the entire length of the bar and determine the slope, dT/dx. (one plot for each part)
2. Calculate the thermal conductivity $K_{overall}$ of the brass bar. Compare it with the typical value given in references. Can you explain any cause of any errors?
3. What do you notice about the gradient of the charts for each heater power setting?

4. For the second material(Experiment part 2), find the thermal resistance R_{total} for bar (equations 2 & 3), then use the thermal resistance to find the k_{int} value for the middle section material.
5. Discuss the characteristics of your plots and compare them to what you would expect based on the theory. Is Fourier's Law satisfied? Also comment on the validity of the assumptions made and heat loss from the equipment on your results.

Reference:

INCROPERA, F. P., & DEWITT, D. P. (2002). *Fundamentals of heat and mass transfer*. New York, J. Wiley.

Experiment 1: Free and forced convection

I. Objectives:

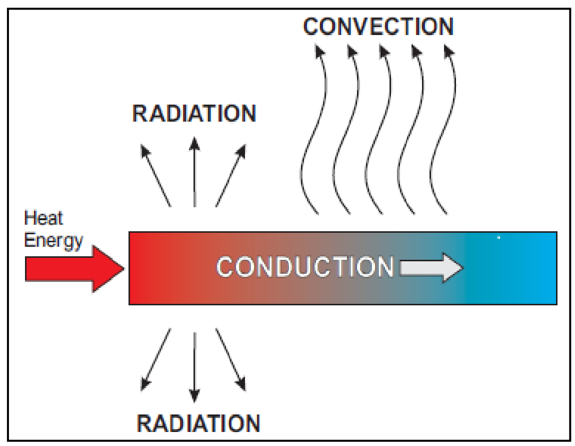
1- To demonstrate the relationship between power input and surface temperature in free convection.

2- To demonstrate the relationship between velocity and surface temperature in forced convection

II. Test Standard

- NA

III. Theory:



If a surface, at a temperature above than of its surroundings is located in stationary air at the same temperature as the surroundings then heat will be transferred from the surface to the air and surroundings. This transfer of heat will be a combination of natural convection to the air (air heated by contact with the surface becomes less dense and rises) and radiation to the surroundings. **Convection** is the mechanism of heat transfer through a fluid in the presence of bulk fluid motion. Convection is classified as natural (or free) and forced convection depending on how the fluid motion is initiated. In natural convection, any fluid motion is caused by natural means such as the buoyancy effect, i.e. the rise of warmer fluid and fall the cooler fluid. Whereas in forced convection, the fluid is forced to flow over a surface or in a tube by external means such as a pump or fan.

Figure 5 Modes of heat transfer

The heat transfer rate to the fluid, $\dot{Q}$, can be calculated using the fist law of thermodynamics for the heated fluid:

$$\dot{Q} = \dot{m}\, \Delta h \quad \text{………………………………………………….. (1)}$$

where Δh is the enthalpy variation of the fluid in the duct and $\dot{m}$ is the mass flow rate which is calculated as:

$$\dot{m} = \rho\, u\, A \quad \text{…………………………………………...…… (2)}$$

where **ρ** is the air density, **u** is the averaged velocity and **A** is cross sectional area of the duct. The air density can be fond from thermodynamics tables. Using perfect gas assumption for the air, Eq. (1) becomes:

$$\dot{Q} = \dot{m}\, C_p\, \Delta T \quad \text{…………………………………………………. (3)}$$

The temperature difference Δ**T** is calculated from the difference between the average inlet and outlet temperatures. The specific heat capacity of the air C_p is also dependent on the air temperature and should be found from thermodynamics tables. Since the temperature is varying in the duct length, the value of C_p should be evaluated in the averaged temperature of air in the duct, T_M

$$T_M = \frac{T_{in} - T_{out}}{2} \quad \text{...…………………………………………. (4)}$$

The amount of power that is consumed by the heaters, **P**, can be considered as a measure of the amount of heat released. The factor for efficiency **η** provides information on the losses which occur during heat transfer. This factor indicates the portion of the input energy that is transferred to the fluid. This can be written as follows:

$$\eta = \frac{\dot{Q}}{P} \quad \text{...…………………………………………….………. (5)}$$

The efficiency shows all losses which result from convection and radiation to the surroundings and not to the fluid.

The average heat transfer coefficient of the system, $\bar{h}$ [W /m^2 K], can be calculated as :

$$\bar{h} = \frac{\dot{Q}}{A\, \Delta T_{lm}} \quad \text{...…………………………………………...… (6)}$$

where $\dot{Q}$ is the heat transfer rate, A is the area of the heated surface, and ΔT_{lm} is the log-mean temperature difference defined as,

$$\Delta T_{lm} = \frac{T_{L\,out} - T_{L\,in}}{\frac{T_S - T_{L\,in}}{T_S - T_{L\,out}}} \quad \text{…………………………………..…(7)}$$

where T_L is the air temperature and T_s is the hot surface temperature. Therefore, the heat transfer coefficient, $\bar{h}$ can be evaluated from Eqns. (3), (6), and (7).

The heat transfer depends not only on the temperature difference and the surface material of the heater, but is also influenced by the flow regime, i.e., laminar or turbulent flow. Reynolds number is a criterion for defining whether a flow is turbulent or laminar. For a flow over a flat plate the transition between these two regimes occurs at approximately $Re = 5 \times 10^5$. However, there are other values for pipes and fins. The Reynolds number is defined as:

$$Re = \frac{u\,L}{\nu} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

where L_c is characteristic length scale which is the plate length for flat surfaces and **ν** is the kinematic viscosity of the fluid. The kinematic viscosity of the air is temperature dependant and can be taken from thermodynamics tables at T_M **.** The Nusselt number is dimensionless and is used in measuring heat transfer rates:

$$Nu = \frac{h\,L_c}{k} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

where **k** is thermal conductivity. The Nusselt number can be calculated once the heat transfer coefficient, **h** is known.

Using the values obtained from Eq. (10 and 11) it is possible to check the accuracy of experiments for flat plate heater.

<u>Free convection: vertical plate</u>

The simple empirical correlations for the average Nusselt number Nu in natural convection are of the form

$$Nu = \frac{h\,L_c}{k} = c(R_a)^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(10)$$

$$R_a = (Gr\,Pr) = \left(\frac{g\beta(T_s - T_a)D^3}{v^2}\right).Pr \quad \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

$$\beta = \frac{1}{T_{film}}$$

where :

$$T_{film} = \frac{(T_s + T_a)}{2}$$

The values of the constants C and n depend on the geometry of the surface and the flow regime, which is characterized by the range of the Rayleigh number. The value of n is usually for laminar flow and for turbulent flow. The value of the constant C is normally less than 1. Simple relations for the average Nusselt number for various geometries are given in Table C.

When the average Nusselt number and thus the average convection coefficient is known, the rate of heat transfer by natural convection from a solid surface at a uniform temperature Ts to the surrounding fluid is expressed by Newton's law of cooling as

$\dot{Q}_{cconv} = hA_s\,(T_s - T_a)$……………………………………………..(12)

Forced convection: vertical plate

The experimental data for heat transfer is often represented conveniently with reasonable accuracy by a simple power-law relation of the form

$\boldsymbol{Nu = C\,Re^m Pr^n}$ ……………………………………….………......(15)

where m and n are constant exponents, and the value of the constant C depends on geometry and flow.The following equations offers a further way of determining the Nusselt number for a parallel flow over a smooth surface (plate):

$Nu = \frac{h\,L_c}{k} = 0.664\ Rr^{0.5}\ Pr^{0.33}$ (Laminar) ………..……....…(13) $Re < 5 \times 10^5$

$Nu = \frac{h\,L_c}{k} = 0.037\ Rr^{0.5}\ Pr^{0.33}$ (Turbulent) ……….………(14) $Re > 5 \times 10^5$

Radiation

For radiation component, the overall heat transfer coefficient may be determined from

$$h_r = \varepsilon F \sigma \frac{(T_s^4 - T_a^4)}{(T_s - T_a)}$$

Where σ = Stefan Boltzmann Constant = 5.67 x 10^{-8} w\mk

ε = emissivity if surface = 0.95

F = view or shape factor that depends upon the surrounding geometry relative to the heat emitting body = 1

IV. Apparatus:

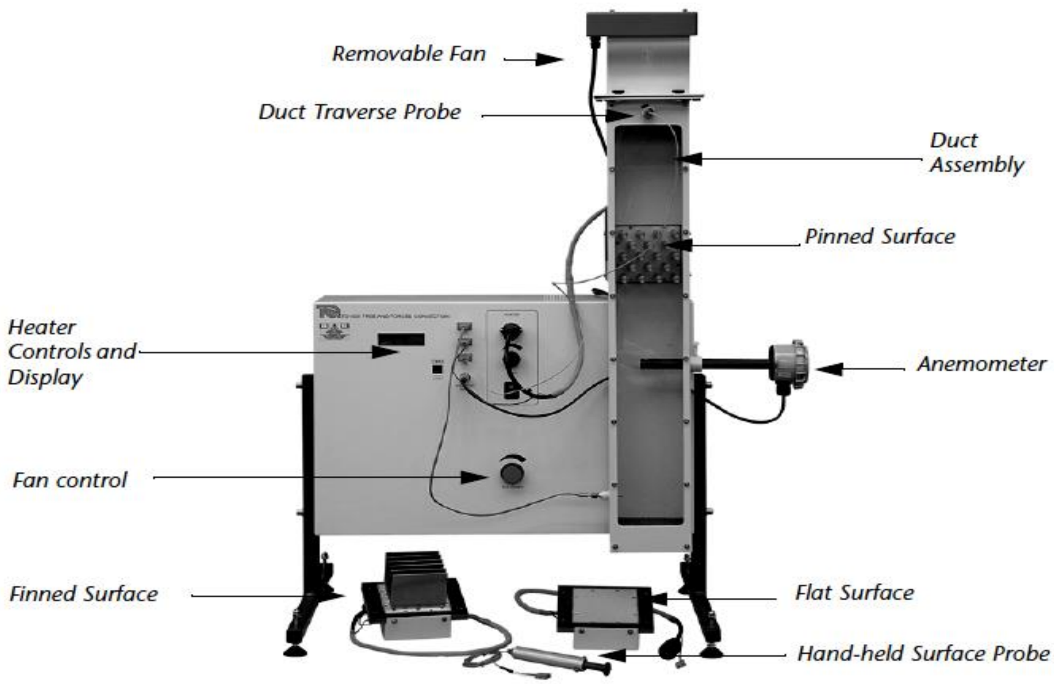


Figure 2 The Free and Forced Convection Apparatus (TD1005)

V. Procedure:

Part 1: Free convection

Determination of the heat transfer from a vertical plate in natural convection over a range of power input and corresponding surface temperature.

1. Remove the fan from the top of the duct (refer to your instructor)
2. Fit the required heat transfer surface.
3. For reference only, take readings of the surface and inlet temperatures with no power applied.
4. Switch on the heater and set power to 10 W.
5. Wait for the temperatures to stabilize and then record surface and inlet temperatures.
6. Repeat for several more heater powers as shown in the results table, stopping before the surface reaches 90°C.
7. Switch off the heater and allow the surface to cool down to near ambient temperature.
8. If asked, repeat the experiment for the other heat transfer surface (Pinned or Finned).

Part 2: Forced convection

Determination of the effect of forced convection on the heat transfer from a plate at varying air velocities.

1. Fit the fan to the top of the duct.

2. Fit either the finned or pinned heat transfer surface as recommended by your instructor.
3. Set the fan to give an air velocity of 1 $m.s^{-1}$.
4. Set the heater power to 50 W.
5. Wait for the temperatures to stabilize.
6. Record the surface and inlet temperatures.
7. Repeat for increased air velocities of approximately 1.5, 2.0, 2.5 and 3.0 $m.s^{-1}$.
8. If asked, repeat for the other surface.

VI. Experimental Work:

Part 1,Table 1 : Free convection readings

Heat Transfer Surface: Flat /Pinned /Finned				
Power (W)	T_2 Surface T_S (°C)	T_1 Duct Inlet (ambiant)T_{IN}(°C)	T_{out} Duct outlet (ambiant)T_{IN}(°C)	Difference T_S-T_{IN}(°C)
0				
10				
20				
30				
50				
60				
70				
80				
90				

Part 1, Table 2 : Free convection calculations

Sample	Q_{input}	h_r	h_c	Q_r	Q_c	Q_c/Q_{input}
	W	W\m²k	W\m²k	W	W	-
1						
2						
3						
4						
5						

Part 2,Table 1 : Forced convection readings

Heat Transfer Surface: Flat /Pinned /Finned				
Air velocity U ($m.s^{-1}$)	T_2 Surface T_S (°C)	T_1 Duct Inlet (ambiant)T_{IN}(°C)	T_{out} Duct outlet (ambiant)T_{IN}(°C)	Difference T_S-T_{IN}(°C)
1.5				

Part 2,Table 2 : Forced convection calculations

Sample	Q_{input}	P_r	υ	K	Re	Nu	h_c	Q_c	Efficiency η
	W	-	m^2/s	W/m.k	-	-	W/m^2k	W	-
1									
2									
3									
4									
5									

Discussion

Part 1: Free convection

1. Calculate the mass flow rate of the air and the heat transfer rate.
2. Calculate the efficiency (η) of the heat transfer, which is the measure of what fraction of energy input is transferred to the fluid (η).
3. Calculate the log-mean temperature difference and the average heat transfer coefficient.
4. Calculate Ra and the corresponding Nu and the average heat transfer coefficient.
5. Compare the measured heat transfer coefficient with the theoretical value.

Part 2: Forced convection

1. Calculate the efficiency (η).
2. Calculate the log-mean temperature difference and the average heat transfer coefficient
3. Calculate Re and the corresponding Nu and the average heat transfer coefficient.
4. Compare the measured heat transfer coefficient with the theoretical value.
5. Create a chart of T_s - T_{in} (vertical axis) against velocity.
6. Draw the relation between U and T_s .

Reference:

ÇENGEL, Y. A. (2002). *Heat transfer: a practical approach*. Boston, Mass, WBC McGraw-Hill.

Appendix 1

Table A

Item	Details
Duct	Nominal internal cross section:128mmx75mm= 0.0096 m^2 Approximate length: 850mm Nominal air velocity: Greater than 3.8 m/s with flat plate. Normal experiment velocity:3.5m.s^{-1} or less. Probe positions (away from heat transfer surface): 7.5 mm,19.5 mm,31.5 mm, 43.5 mm, 55.5 mm and 67.5 mm
Heater output and display	Maximum power approximately 100W Displayed resolution 0.1 W
Flat Plate	Net Dimensions:160 mmx140 mm x 55 mm and 810 g Plate material l:3mmthickAluminum Total surface area:106 mm x 106 mm=0.0112m^2 K-type thermocouple on back side of plate surface.
Finned Surface	Net Dimensions:160mmx140mmx125mm and 1227 g Flat plate with six fins at right angles to the plate. Plate material:3mmthickAluminum106mmx106mm
	Fin material: Stainless Steel Fin dimensions : 90mm x 73 mm x 1.5 mm thick. Totalsurfacearea:0.092m^2 (including ends of fins) K-type thermocouple on backside of plate surface.
Pinned Surface	Net Dimensions:160mm x 140mm x 125mm and 1836 g Flat plate with 18 pin straight angles to the plate. Plate material:3mm thick Aluminum106 mm x 106 mm Pin material: Stainless Steel PinDimensions:12mmdiameterx73mm Totalsurfacearea:0.027m^2 (including ends of pins) K-type thermocouple on backside of plate surface.

Table B

Properties of air at 1 atm pressure

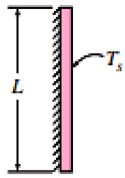
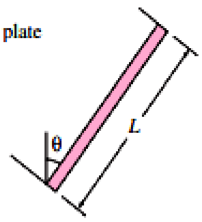
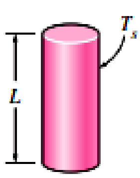
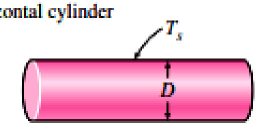
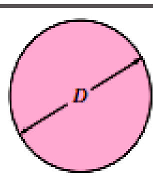
Temp. T, °C	Density ρ, kg/m³	Specific Heat c_p, J/kg·K	Thermal Conductivity k, W/m·K	Thermal Diffusivity α, m²/s	Dynamic Viscosity μ, kg/m·s	Kinematic Viscosity ν, m²/s	Prandtl Number Pr
−150	2.866	983	0.01171	4.158×10^{-6}	8.636×10^{-6}	3.013×10^{-6}	0.7246
−100	2.038	966	0.01582	8.036×10^{-6}	1.189×10^{-5}	5.837×10^{-6}	0.7263
−50	1.582	999	0.01979	1.252×10^{-5}	1.474×10^{-5}	9.319×10^{-6}	0.7440
−40	1.514	1002	0.02057	1.356×10^{-5}	1.527×10^{-5}	1.008×10^{-5}	0.7436
−30	1.451	1004	0.02134	1.465×10^{-5}	1.579×10^{-5}	1.087×10^{-5}	0.7425
−20	1.394	1005	0.02211	1.578×10^{-5}	1.630×10^{-5}	1.169×10^{-5}	0.7408
−10	1.341	1006	0.02288	1.696×10^{-5}	1.680×10^{-5}	1.252×10^{-5}	0.7387
0	1.292	1006	0.02364	1.818×10^{-5}	1.729×10^{-5}	1.338×10^{-5}	0.7362
5	1.269	1006	0.02401	1.880×10^{-5}	1.754×10^{-5}	1.382×10^{-5}	0.7350
10	1.246	1006	0.02439	1.944×10^{-5}	1.778×10^{-5}	1.426×10^{-5}	0.7336
15	1.225	1007	0.02476	2.009×10^{-5}	1.802×10^{-5}	1.470×10^{-5}	0.7323
20	1.204	1007	0.02514	2.074×10^{-5}	1.825×10^{-5}	1.516×10^{-5}	0.7309
25	1.184	1007	0.02551	2.141×10^{-5}	1.849×10^{-5}	1.562×10^{-5}	0.7296
30	1.164	1007	0.02588	2.208×10^{-5}	1.872×10^{-5}	1.608×10^{-5}	0.7282
35	1.145	1007	0.02625	2.277×10^{-5}	1.895×10^{-5}	1.655×10^{-5}	0.7268
40	1.127	1007	0.02662	2.346×10^{-5}	1.918×10^{-5}	1.702×10^{-5}	0.7255
45	1.109	1007	0.02699	2.416×10^{-5}	1.941×10^{-5}	1.750×10^{-5}	0.7241
50	1.092	1007	0.02735	2.487×10^{-5}	1.963×10^{-5}	1.798×10^{-5}	0.7228
60	1.059	1007	0.02808	2.632×10^{-5}	2.008×10^{-5}	1.896×10^{-5}	0.7202
70	1.028	1007	0.02881	2.780×10^{-5}	2.052×10^{-5}	1.995×10^{-5}	0.7177
80	0.9994	1008	0.02953	2.931×10^{-5}	2.096×10^{-5}	2.097×10^{-5}	0.7154
90	0.9718	1008	0.03024	3.086×10^{-5}	2.139×10^{-5}	2.201×10^{-5}	0.7132
100	0.9458	1009	0.03095	3.243×10^{-5}	2.181×10^{-5}	2.306×10^{-5}	0.7111
120	0.8977	1011	0.03235	3.565×10^{-5}	2.264×10^{-5}	2.522×10^{-5}	0.7073
140	0.8542	1013	0.03374	3.898×10^{-5}	2.345×10^{-5}	2.745×10^{-5}	0.7041
160	0.8148	1016	0.03511	4.241×10^{-5}	2.420×10^{-5}	2.975×10^{-5}	0.7014
180	0.7788	1019	0.03646	4.593×10^{-5}	2.504×10^{-5}	3.212×10^{-5}	0.6992
200	0.7459	1023	0.03779	4.954×10^{-5}	2.577×10^{-5}	3.455×10^{-5}	0.6974
250	0.6746	1033	0.04104	5.890×10^{-5}	2.760×10^{-5}	4.091×10^{-5}	0.6946
300	0.6158	1044	0.04418	6.871×10^{-5}	2.934×10^{-5}	4.765×10^{-5}	0.6935
350	0.5664	1056	0.04721	7.892×10^{-5}	3.101×10^{-5}	5.475×10^{-5}	0.6937
400	0.5243	1069	0.05015	8.951×10^{-5}	3.261×10^{-5}	6.219×10^{-5}	0.6948
450	0.4880	1081	0.05298	1.004×10^{-4}	3.415×10^{-5}	6.997×10^{-5}	0.6965
500	0.4565	1093	0.05572	1.117×10^{-4}	3.563×10^{-5}	7.806×10^{-5}	0.6986
600	0.4042	1115	0.06093	1.352×10^{-4}	3.846×10^{-5}	9.515×10^{-5}	0.7037
700	0.3627	1135	0.06581	1.598×10^{-4}	4.111×10^{-5}	1.133×10^{-4}	0.7092
800	0.3289	1153	0.07037	1.855×10^{-4}	4.362×10^{-5}	1.326×10^{-4}	0.7149
900	0.3008	1169	0.07465	2.122×10^{-4}	4.600×10^{-5}	1.529×10^{-4}	0.7206
1000	0.2772	1184	0.07868	2.398×10^{-4}	4.826×10^{-5}	1.741×10^{-4}	0.7260
1500	0.1990	1234	0.09599	3.908×10^{-4}	5.817×10^{-5}	2.922×10^{-4}	0.7478
2000	0.1553	1264	0.11113	5.664×10^{-4}	6.630×10^{-5}	4.270×10^{-4}	0.7539

Note: For ideal gases, the properties c_p, k, μ, and Pr are independent of pressure. The properties ρ, ν, and α at a pressure P (in atm) other than 1 atm are determined by multiplying the values of ρ at the given temperature by P and by dividing ν and α by P.

Source: Data generated from the EES software developed by S. A. Klein and F. L. Alvarado. Original sources: Keenan, Chao, Keyes, Gas Tables, Wiley, 1984; and Thermophysical Properties of Matter. Vol. 3: Thermal Conductivity, Y. S. Touloukian, P. E. Liley, S. C. Saxena, Vol. 11: Viscosity, Y. S. Touloukian, S. C. Saxena, and P. Hestermans, IFI/Plenun, NY, 1970, ISBN 0-306067020-8.

Table C

Empirical correlations for the average Nusselt number for natural convection over surfaces

Geometry	Characteristic length L_c	Range of Ra	Nu
Vertical plate 	L	10^4–10^9 10^9–10^{13} Entire range	$Nu = 0.59Ra_L^{1/4}$ (9-19) $Nu = 0.1Ra_L^{1/3}$ (9-20) $Nu = \left\{0.825 + \frac{0.387Ra_L^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}}\right\}^2$ (9-21) (complex but more accurate)
Inclined plate 	L		Use vertical plate equations for the upper surface of a cold plate and the lower surface of a hot plate Replace g by $g \cos\theta$ for $Ra < 10^9$
Horiontal plate (Surface area A and perimeter p) (*a*) Upper surface of a hot plate (or lower surface of a cold plate)  (*b*) Lower surface of a hot plate (or upper surface of a cold plate) 	A_s/p	10^4–10^7 10^7–10^{11} 10^5–10^{11}	$Nu = 0.54Ra_L^{1/4}$ (9-22) $Nu = 0.15Ra_L^{1/3}$ (9-23) $Nu = 0.27Ra_L^{1/4}$ (9-24)
Vertical cylinder 	L		A vertical cylinder can be treated as a vertical plate when $D \geq \frac{35L}{Gr_L^{1/4}}$
Horizontal cylinder 	D	$Ra_D \leq 10^{12}$	$Nu = \left\{0.6 + \frac{0.387Ra_D^{1/6}}{[1 + (0.559/Pr)^{9/16}]^{8/27}}\right\}^2$ (9-25)
Sphere 	D	$Ra_D \leq 10^{11}$ ($Pr \geq 0.7$)	$Nu = 2 + \frac{0.589Ra_D^{1/4}}{[1 + (0.469/Pr)^{9/16}]^{4/9}}$ (9-26)

ÇENGEL, Y. A. (2002). *Heat transfer: a practical approach*. Boston, Mass, WBC McGraw-Hill.

Experiment 7: Boiling Heat Transfer

I. Objectives:

1- To study the effects of phase change on convection by observing the three modes of boiling (convective, nucleate and film boiling).
2- Determination of heat flux and surface heat transfer coefficient up to and beyond the critical condition at constant pressure.

II. Test Standard

- NA

III. Theory:

This experiment is concerned with measurement of heat transfer coefficients for boiling. It is also possible to make an evaluation of heat transfer processes which occur in a condenser.

Visual observations of flow regimes play an important role in this experiment since there are substantial effects on heat transfer coefficient when the flow regime changes. S.Nukiyama 1934 noticed that boiling takes different forms, depending on the value of the excess temperature ΔT_{excess}. Where:

$$\Delta T_{excess} = T_s - T_{sat}$$

Four different boiling regimes are observed: *natural convection boiling, nucleate boiling, transition boiling,* and *film boiling* (Fig. 1).

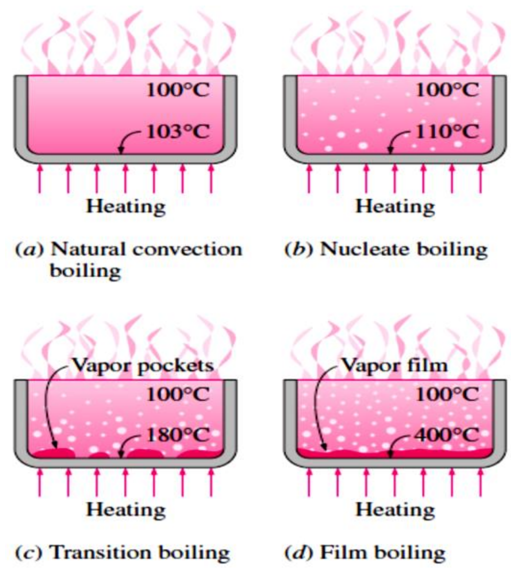


Figure 1 Boiling modes

Newton's Law of Cooling,

$$q_s = h\,(T_s - T_{sat}) = h\,\Delta T_{excess}$$

Where ΔT_e is called the excess temperature defined as the temperature difference between heat source and saturation temperature of the fluid.

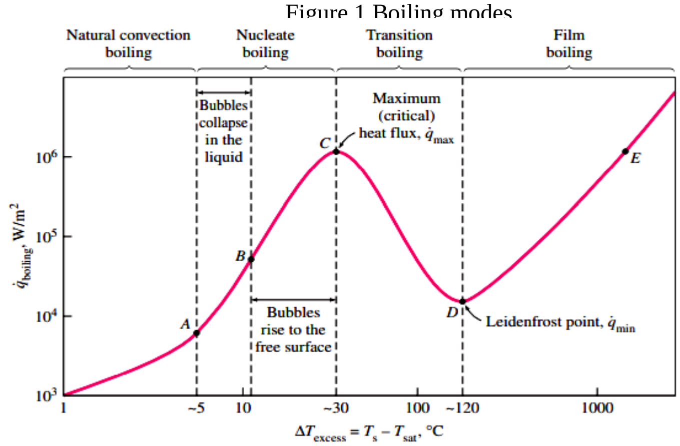


Figure 2 Typical boiling curve for water at 1 atm pressure.

IV. Apparatus:

The unit consist of the following :

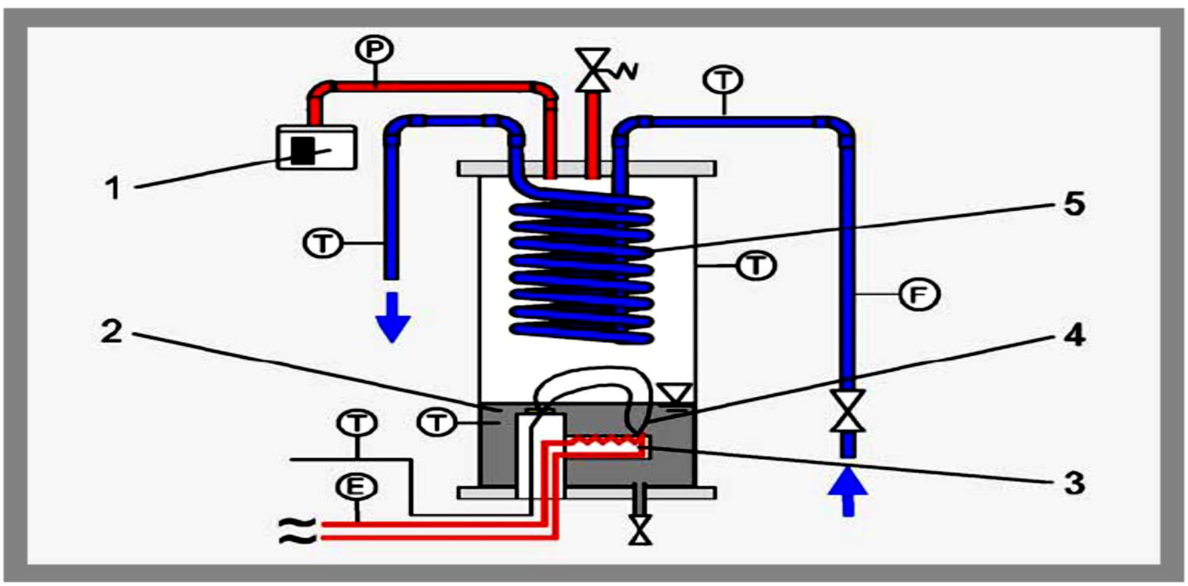
t1: Heated cylinder surface Temp. sensor.

t2: Liquid temperature sensor.

t3: Vapour temperature sensor.

t4: Cooling water inlet temperature sensor.

t5: Cooling water outlet temperature sensor.



Process schematic: 1 pressure switch, 2 evaporating liquid, 3 heater, 4 temperature sensor at heater surface, 5 condenser (water cooled);
sensors: E power, T temperature, F flow rate, P pressure

V. Procedure:

Before starting any test check that:

(a) The cooling water is connected and ready for use.

(b) The pressure and temperature of the R141b agree with those at saturation conditions – if not, it is probable that air is present and the **air venting** operation (below) should be carried out.

(c) The electrical supply is correctly connected, and that the unit is properly earthed.

During Use

Control the saturation pressure to desired value by:

(a) Variation of condenser water flow rate (or temperature) by use of water flow control and meter

(b) Variation of the power supplied to the heater, by use the heater control

Shutting Down After Use

Always

(a) Switch of the main switch and the electrical supply.

(b) Circulate cooling water until pressure has fallen to atmospheric or below, depending on ambient temperature.

Air Venting

To vent air from the condenser it is necessary to increase the condenser pressure to approximately 50 kN/m^2 above atmospheric pressure. With the heater control power set to about 150 Watts, close the control valve on the water flow control and meter. This will cause the condenser pressure to rise. The time taken to reach 50 kN/m^2 above atmospheric pressure will depend upon the local ambient temperature. Once 50 kN/m^2 is reached the air vent valve should be briefly opened and gas will be heard to vent. Close the valve well before the gauge pressure reaches 0 kN/m^2. Open the water flow control and meter and allow the condenser pressure to fall to its normal value

1. Switch on the mains electrical supply to H111 unit and the main switch on H111S console.
2. Check that the digital t1 temperature indicator is showing the same temperature as the liquid R141b thermometer. The instrument requires a few minutes to warm up.
3. Check that the saturation pressure at 20-25 ^0C (room temp.) is around 60-70 KN/m^2.
4. Adjust the heater power to about 30-50 watts and adjust the condenser water flow control until the desired pressure is reached (Ex. 100 kN/m^2)
5. Record the power, pressure t_1 and t_2 .

6. Repeat in similar increments until you reach the transition from maculate to film boiling. When film boiling is established the heat input should be rapidly reduced and readings continued until the heater temperature reaches 160 ^{0}C.

Note that the pressures recorded from the pressure gauge will be in gauge pressure. In order to obtain absolute pressure, the local atmospheric pressure must be added to the gauge pressure as follows. Absolute Pressure (kN/m^2) = Gauge Pressure (kN/m^2) + Atmospheric Pressure (kN/m^2) Note that units must be consistent (kN/m^2).

This unite has been designed to operate on R141b which has a low vapor pressure and allows operating in glass with safety and no other flowed should be charged into the system. An important feature of this unite is the use of glass for the chamber shell has a safe working pressure of 300 KN m^{-2} gauge and safety features are incorporated in the unit to ensure that this is not exceeded.

In all normal environments, R141b has a suitable pressure temperature relationship.
R141b has been selected for use with Boiling Heat Transfer Unit because of its saturation pressure at the temperature envisaged. It is values of ρ_g *and* h_g make it suitable for conditions at moderate heat fluxes.

VI. Experimental Work:

Table 1 experimental readings

Heat input $\dot{Q}_{watts}$	50	65	112	190	250	305	315	film	25	27	32	38
Liquid Temperature t_2 ^{0}C												
Metal Temperature t_1 ^{0} C												

Heat Flux $\emptyset = \dot{Q}/A\ W\backslash m^2$											
Temperature Difference $(t1 - t2)$ K											
Heat Transfer coefficient $h = \frac{\dot{Q}}{A(t1 - t2)}$											

Discussion

1. Compare all your experimental results with what expected theoretically.

2. Discuss the sources of error in the experiment.
3. Draw the relation between Heat Flux (kw\m^2) (VS) Surface-liquid temperature difference
4. What is the most desirable and undesirable regimes in boiling.
5. Find the critical heat flux according to your results.
6. Draw the relation between surface heat transfer coefficient (kw $m^{-2}k^{-1}$) and surface to liquid temperature difference (k).
7. Calculate the heat transfer coefficient using Zuber and Tribus Correlation and compare it with your results.

Reference:

ÇENGEL, Y. A. (2002). *Heat transfer: a practical approach*. Boston, Mass, WBC McGraw-Hill.

USEFUL DATA

Dimensions of heating surface:	Effective length = 42mm Diameter = 12.7mm Surface area = 0.0018m^2 (including area of end)
Condenser surface area:	0.032m^2
Maximum permitted surface temperature:	220°C
Heater cut out temperature:	160°C
Fluid:	1,1-Dichloro-1-fluoroethane (R141b) $C\,Cl_2\,F\text{-}CH_3$
Quantity of fluid:	**Liquid** level to be not less than 50mm above heating element. (Approximately 0.55 litre).
Dimensions of glass chamber:	Nominal internal diameter = 80mm Length = 300mm Volume = 0.0015m^3
Specific heat capacity of water (C_{pw}):	4.18 kJ kg^{-1} K^{-1}

The thermocouple location are as follows:-

t1 **Heated cylinder(3)** surface temperature
t2 Liquid temperature
t3 Vapour temperature
t4 Cooling water inlet temperature
t5 Cooling water outlet temperature.

Experiment 8: Batch Settling

I. Objectives:

1- To study the characteristics of sedimentation (settling) process.
2- To obtain the batch settling data for the given material, i.e. the settling rate versus concentration of slurry)
3- Demarcate the different settling regimes. ('free settling" and 'hindered settling')

II. Test Standard

- NA

III. Theory:

In Settling; the particles are separated from the fluid by gravitational forces acting the particles. At the beginning of a batch sedimentation process, the solid is uniformly distributed in the liquid, as shown in Fig. 1 .1. The total depth of the suspension is Zo. After a short while, the solids have settled to give a zone of clear liquid, zone A and zone D of settled solids as in Fig. 1.2. Above zone D is a transition layer, zone C, in which the solids content varies from that in the original pulp to that in zone D. In zone B, the concentration is uniform and equal to the original concentration, since the settling rate is the same throughout this zone. The boundaries between zones D and C and between C and B may not be distinct, but the boundary between ones A and B is usually sharp.

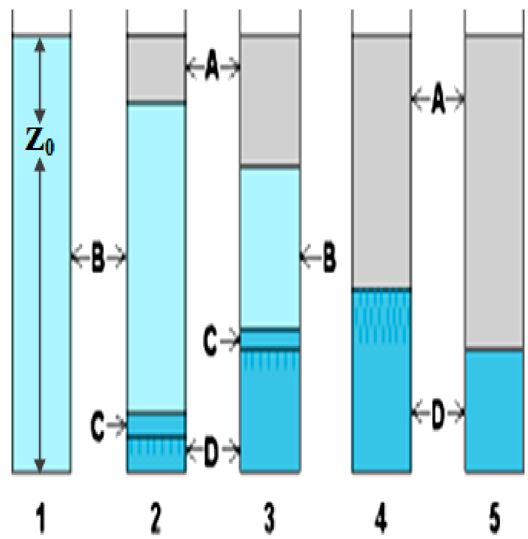


Figure 1 Sedimentation process

The depths of zones D and A increase as settling continues. The depth of zone C remains nearly constant, and that of zone B decrease as shown in Fig. 1.3. Eventually zone B disappears and the solids are all in zones C and D (Fig. 1.4). Meanwhile, the gradual accumulation of solid put stress on the material at the bottom, which compresses solids in layer D. Finally, when the weight of the solid is balanced by the compressive strength of the flocks, the settling process stops, as shown in Fig. 1.5. This entire process as shown in Fig. 1 is called sedimentation.

The total weight of the solid in the slurry is ($C_o.Z_o.S$), where (C_o) and (Z_o) represent the initial concentration and height of the suspended solid in a batch-settling test and (S) is the cross-sectional area of the cylinder in which the test is being performed. The quantity of solid passing through the limiting layer is d.C_L. S. $\theta_L(V_L+\bar{V}_L)$ where C_L is concentration of the limiting layer and θ_L is the time for this layer to reach the interface , V_L is the setting velocity and $\bar{V}_L$ is the upward velocity of the capacity limiting layer.

$$C_L.S.\theta_L(V_L+\bar{V}_L) = C_0.Z_0.S \dots\dots\dots (1)$$

If $\bar{V}_L$ is assumed to be constant and Z_L is the height of the interface at O_L:

Then:

$$\bar{V}_L = \frac{Z_L}{O_L} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$$

Substituting into equation (1) gives

$$C_L = \frac{C_0.Z_0}{Z_L + V_L.\theta_L} \dots\dots\dots\dots\dots\dots\dots\dots\dots (3)$$

The value of V_L is the slope of the plot of height of interface versus time and is equal to:

$$V_L = \frac{Z_i - Z_L}{\theta_L} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4)$$

$$Z_i = Z_L + V_L.\theta_L \dots\dots\dots\dots\dots\dots\dots\dots\dots (5)$$

Combing equation (3) and (5) gives:

$$C_L.Z_i = C_0.Z_0 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (6)$$

The average settling velocity for a particular plot at any given time(t_1) is then equivalent to: settling velocity = (original height -height at time t_1) / (time required to reach current height)

= slope at a particular point.

<u>Types of Settling</u>

Type I: ***Discrete particle settling*** - Particles settle individually without interaction with neighboring particles.

Type II: ***Flocculent Particles*** – Flocculation causes the particles to increase in mass and settle at a faster rate.

Type III: ***Hindered or Zone settling*** –The mass of particles tends to settle as a unit with individual particles remaining in fixed positions with respect to each other.

Type IV: ***Compression*** – The concentration of particles is so high that sedimentation can only occur through compaction of the structure.

IV. Apparatus:

Figure 2
Sedimentation unit

The unit consists of five equals sized glass cylinders mounted on a vertical back-panel, which is illuminated from behind. Measuring scales are provided for each of the cylinders to measure the suspension height. Each of the cylinders may be removed from the board for fitting and mixing of the solid particles as well as for cleaning.

V. Procedure:

1. Fill one of the graduated cylinders with water to a certain height.
2. Weight the required amount of solid and add to the water in the cylinder.
3. Prepare five different sets of the material as follows:

Cylinder 1
Concentration: 50g of material in 2L of water
Zo : 30cm
Cylinder 2
Concentration: 50g of material in 2L of water
Zo : 60cm
Cylinder 3
Concentration: 50g of material in 2L of water
Zo : 90cm

Cylinder 4
Concentration: 70g of material in 2L of water
Zo : 90cm
Cylinder 5
Concentration: 100g of material in 2L of water
Zo : 90cm

4. Shake the cylinder to make the solution homogenous.
5. Record the initial time, T_o.
6. Records the height of clear liquid interface from the base of cylinder, Z every 1 minute interval until the settling process stops. Refer to figure 1.
7. Record the final time, T_f.
8. Record the final heights, Z_f for each cylinder.

Suggested experimental variables :
a. Type of material.
b. Solid concentration.
c. Particle size.
d. Diameter of the cylinder.
e. Initial height.

See the link below for more explanations.

http://hmxearthscience.com/Warehouse/geology/surface_processes/animations/settling.swf

VI. Experimental Work:

Table Experimental measurements

Time (s)	cylinder 1	cylinder 2	cylinder 3	cylinder 4	cylinder 5
	Conc. 5 g/l	**Conc. 10 g/l**	**Conc. 15 g/l**	**Conc. 15 g/l**	**Conc. 15 g/l**
Z_0	30 cm	60 cm	90 cm	90 cm	90 cm

Discussion

1. Plot the batch settling curves for the first three runs on the same figure to investigate the effect of changing the initial height. (Height Vs time)
2. Plot the batch settling curve for the last three runs on the same figure to investigate the effect of changing the concentration.
3. Find the settling velocity of each run in the *constant rate settling region*.
4. Calculate the free settling terminal velocity U_t using the appropriate regime. Confirm that the assumption on Reynold's no. holds.
5. Discuss the effect of concentration and height on the settling velocity and time of settling depending on your experimental results.
6. Discuss the effects of the other suggested variables on the settling behavior of solids.

Useful equations

Free settling

$$U_t = (\frac{g(\rho_p - \rho)D_p^2}{18\mu})$$

$$D_p = (\frac{18\mu U_t}{g(\rho_{p-}\rho)})^{1/2}$$

$$C_D = 24/R$$

$$\varepsilon = 1 - C/\rho_p$$

Hindered settling

$$U_S = U_t \varepsilon^n$$

where ε is the volume fraction of the fluid and n is a constant.

where $\varepsilon = 1 - C/\rho_p$

In this case the following bulk values of density and viscosity are used instead of liquid density and viscosity.

$$\rho_b = \rho_s * (1-\varepsilon) + \rho_l * \varepsilon$$

$$\frac{\mu_b}{\mu_f} = \frac{10^{1.82*(1-\varepsilon)}}{\varepsilon}$$

Assuming that the concentration is nearly uniform over the cylinder, the concentration at any time is given by

$$C \quad \frac{C_0 H_0}{H}$$

where C_0 is the initial concentration,

H_0 is the initial height of the suspension-clear liquid interface (constant height before stirring),

H is the height at time t.

Reference:

MCCABE, W. L., & SMITH, J. C. (2004). *Unit operations of chemical engineering*. New York, McGraw-Hill.

Experiment 9: Jaw Crusher And Screen Analysis

I. Objectives:

- To study the comminution behavior of different materials, using a primary crusher (Jaw crusher) under various condition; taking in consideration power requirements

II. Test Standard

- ASTM G81 - 97a : Standard Test Method for Jaw Crusher Gouging Abrasion Test.

III. Theory:

Crushing is the process of reducing the size of solid particles into definite smaller sizes. Jaw crushers are major size reduction machines used in mechanical, metallurgical and allied industries. The crusher crushes the feed by some moving units against a stationary unit or against another moving unit by the applied pressure, impact, and shearing or combine action on them.

A jaw crusher has two jaws said to form a V-shaped at the top through which feed is admitted. One of the jaw is fixed in to the main frame and other is movable. The crushing faces are usually made of hard field Mn steel (12-14%Mn, 1%C). The jaw crusher speed varies from 100-400RPM.

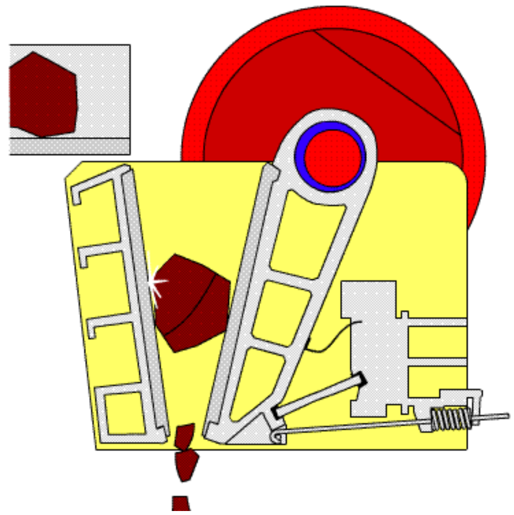


Figure 1 Jaw crusher

Crushing

A number of empirical laws have been put forward to estimate the energy required to affect a size reduction of a given material:

a. **Rittinger's law:**

$$\frac{P}{m} = K_R\left(\frac{1}{L_2} - \frac{1}{L_1}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

b. **Kick's law:**

$$\frac{P}{m} = K_c . ln\frac{L_1}{L_2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

c. **Bond's law:**

$$\frac{P}{m} = 0.3162. W_i . \left(\frac{1}{\sqrt{L_2}} - \frac{1}{\sqrt{L_1}}\right) \ldots\ldots\ldots (3)$$

Where:

L_1, L_2: Particles size of product and feed (mm).
P: Power required for crushing and grinding (Kw).
m: Feed rate (tons/hr).
W_i: Bond's work index (Kw.hr/ton).
K_R,K_c: Rittenger's constant and Kick's constant.

Screening

% Mass Retained = (Mass of Dry Soil) / (Sample Dry Mass) X 100% ……………………..(1)

To compute the % Cumulative Retained, add the % Retained on the sieve and all sieves above the sieve.

The % Finer is computed using Equation (2).

% Finer = 100% - % Cumulative Retained …………………………………………………(2)

The % Loss computed in Equation (3) should be less 2%.

% Loss = (Sample Dry Mass – Total Soil Mass Sieved) / (Sample Dry Mass) X 100% …...(3)

IV. Apparatus:

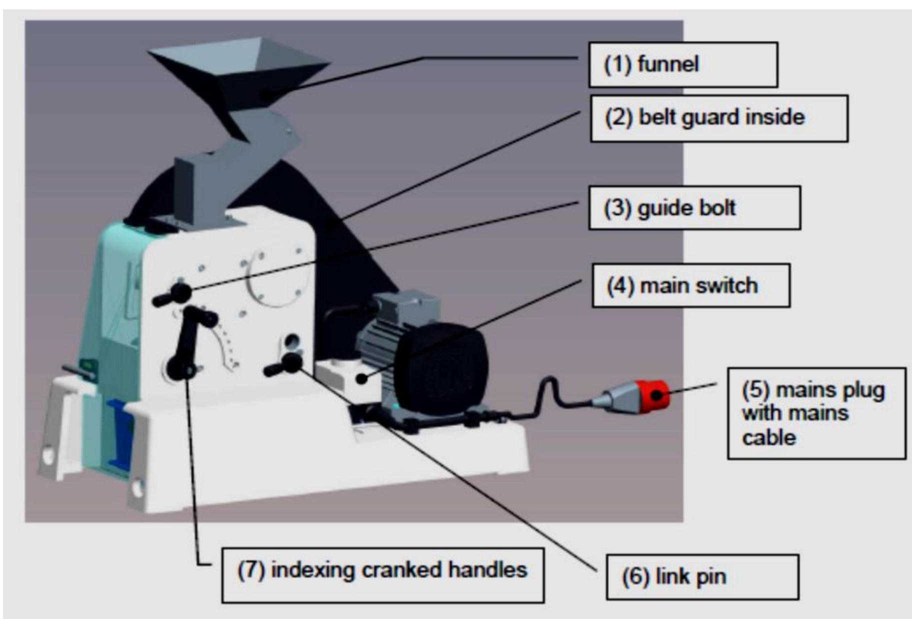
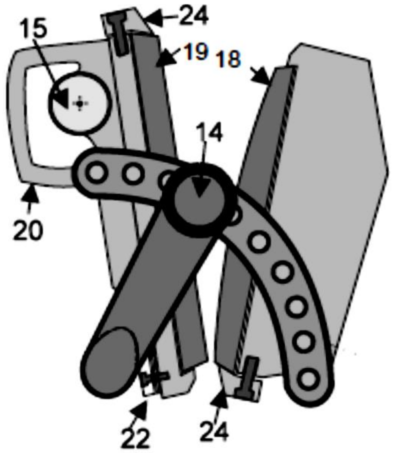


Figure 2-a jaw crusher external components



14	gap setting lever
15	guide bolt
18	movable jaw
19	fixed jaw
20	crushing plate
22	pressure plate
24	clamping block

Figure 2-b jaw crusher internal components

The crusher consist of :

1. Body :Made from high quality steel plates and ribbed heavily in welded steel construction
2. Swing jaw Plate :Manganese steel
3. Fixed jaw plate :Manganese steel
4. Pitman : Crushers have a light weight pitman having white-metal lining for bearing surface
5. Toggle Double toggles, for even the smallest size crushers give even distribution of load
6. Flywheel :high grade cast iron
7. Tension Rod Pullback rods helps easy movement, reduces pressure on toggles and machine vibration.

Sieve shaker

The shaker can hold up to 10 sieves. It is fitted with a digital 1 to 999 minute timer, accessed through the digital control panel. This separate panel also gives the user control of the vibration intensity and pauses between sieving actions, which is particularly useful when sieving fine materials.

Figure 3 sieve shaker

V. Procedure:

1. Prepare the material to be tested and sort according to the size.
2. Measure the approximate size of the feed.
3. Choose three samples of different sizes and weigh the required amount as instructed by supervisor of each sample.
4. Adjust the jaw gap setting as required, and tighten the hand wheel.
5. Switch on the jaw crusher.
6. Put the weighed sample into the crusher and immediately start the stop watch.
7. Once the crushing is complete, stop the stop watch and record the time.
8. Arrange the test sieves according to the size of the aperture, noting that the biggest aperture should be at top, and the smallest at the bottom and then the pan.
9. Put the crushed sample on the top sieve, and put the sieves on the sieve shaker.
10. Switch on the shaker and allow the screen process to proceed for about 5-15 minutes.
11. Weigh the collected solid on each sieve and record the weight.
12. Repeat using the other samples.(if required)
13. The process can be repeated using one of the following variable:

    a. Initial material size.
    b. Jaw gap setting.
    c. Type of material

VI. Experimental Work:

Table 1 Experimental Calculations

Sieves size μm	Avg. Particle size (Dpi)	Mass retained on each sieve M_n(g)	Mass % retained on each sieve	Cumulative mass fraction	Percent finer (Passing)
pan					

Discussion

1. Calculate the mass retained, percent retained, and cumulative percent passing the sieves. Check that the sum of the mass of soil retained is close to the mass of the soil with which you started the test (discrepancies may exist due to soil particles retained on the sieves).
2. Calculate the average mean diameter (Sauter mean diameter D_s).
3. Using Bond's law, calculate the power required for grinding.
4. Check the validity of bond's law.
5. Plot percent of finer vs. grain-size D (mm) on **semi log scale**.
6. Use the grain size distribution to find the following:

   D_{60} = grain diameter at 60% finer
   D_{30} = grain diameter at 30% finer
   D_{10} = grain diameter at 10% finer

7. Mention three different types of crushers with a brief discretion of each one.

References:

MCCABE, W. L., & SMITH, J. C. (2004). *Unit operations of chemical engineering*. New York, McGraw-Hill.

Experiment 1: Plate And Frame Filter Press

I. Objectives:

1- To understand the basics and operation of plate and frame filtration.

2- To study the effect of certain variables on the resistances of filtration.

II. Test Standard

ASTM D6830 – 02 : Standard Test Method for Characterizing the Pressure Drop and Filtration Performance of Cleanable Filter Media

III. Theory:

Filtration separates suspensions into a solid(residue) and liquid (filtrate). This is achieved by a pressure change using a porous material, the filter material. The liquid passes through the pores or openings in the filter material, while the solids are retained by the filter material. The driving force is a pressure difference between the suspension on one side of the filter material land the filtrate on the other. The difference is created by a vacuum on the filtrate side or excess pressure on the suspension side (hydrostatic or pressure generated using pumps).

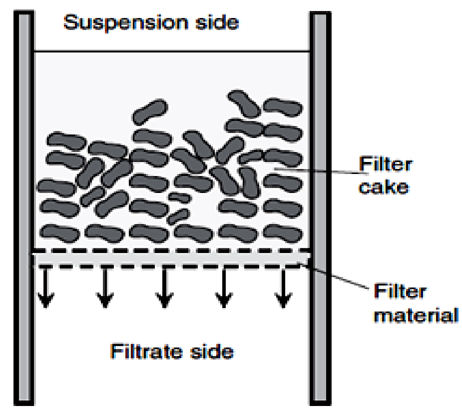


Figure 1 Cake filtration

Three types of filtration are differentiated:

• Surface filtration
• Deep bed filtration
• Cake filtration

Cake filtration:

The suspension fed onto the initially clean filter material first of all flows almost completely through the filter material with only the largest solid particles being retained. More and more solid Particles are gradually deposited on the filter material, creating a filter cake that becomes increasingly thick. The actual filtration only occurs when a sufficiently thick filter cake has formed. For the suspension to pass through this filter cake there must be a pressure difference between the feed side and the filtrate outlet side.

The fluid velocity is constrained by the fact that it has to pass through an irregular medium, through some channels formed in the interstices of the cake and filter medium. Then we can apply the law of Hagen-Poiseuille:

$$\frac{dv}{A.d\theta} = \frac{\Delta P}{\mu.\left[\alpha.\left(W/_{A}\right) + r\right]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots (1)$$

Where:

V: filtrated volume.
θ : filtering time.
A: surface area of the filters.
P: total pressure fall.
μ: Filtrate viscosity.
r : filtering medium resistance(constant)
W: cake weight.
α : Specific cake resistance.

If we consider the approximation that the cake is non-compressible and uniformly compacted, the mass of filter cake (W) is related to the volume of filtrate (V) using the following mass balance.

$$W = c.V \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (2)$$

- **Constant pressure filtration testing:**

It is clear that at a constant pressure the rate of filtration will decrease as the thickness of the cake increases and also its resistance to filtration. Therefore the Hagen-Poiseuille relation can be written as follows:

$$\frac{d\theta}{dV} = \frac{\mu.\alpha.w}{\Delta P.A^2}.V + \frac{\mu.r}{\Delta P.A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots... (3)$$

Then the specific resistance of the cake(α) and filtering media resistance (r) can be calculated.

- **Constant rate filtration testing:**

In this case, the pressure will increase as the filtration process happens due to increasing the thickness of the cake and also the resistance to leakage.
For the study of filtration in these circumstances we can start from the Hagen-Poiseuille law as described above in equation (3).
Solving the expression to be:

$$\Delta P = \frac{\mu.\alpha.w}{A^2}.\frac{dV}{d\theta}.V + \frac{\mu.r}{A}.\frac{dV}{d\theta} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (4)$$

IV. Apparatus:

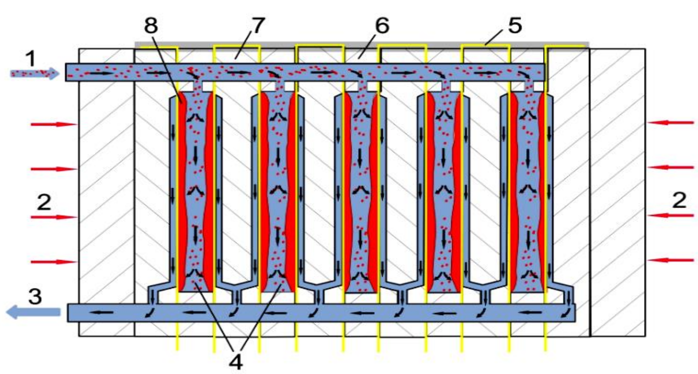
Figure 1 Filter press

The unit consists of :

1 Unit frame	10 Pressure gauge at filter inlet
2 Suspension tank with drain valve	11 Filter outlet pipe
3 Measuring tank drain stop valve	12 Collecting trough
4 Measuring tank drain and overflow	13 Collecting tray overflow stop valve
5 Measuring tank	14 Pressure gauge on the pump
6 Bypass stop valve	15 Thermometer on the pump
7 Filter in feed pipe diaphragm valve	16 Pump in suspension tank (covered)
8 Hand wheel with spindle	17 Control cabinet
9 Plate and frame filter press	

The filter part consist of :

1 suspension inlet, 2 press forces, 3 filtrate outlet, 4 separating chambers, 5 filter cloth, 6 filter frame, 7 filter plate, 8 filter cake



Fundamental principle of a plate and frame filter press

V. Procedure:

Investigating the filter effect

In this experiment, the suspension is conveyed through the cleaned plate and frame filter press. Each time the measuring cylinder is filled with filtrate up to a certain level, a sample of the filtrate is taken and the opacity of the sample taken is measured using an opacimeter.

1. Open a little the stop valve on the bypass.
2. Fully open the diaphragm valve at the filter in feed pipe
3. Read and note the filter inlet pressure on the pressure gauge.
4. Stop the pump at when 15 L of filtrate are in the measuring cylinder
5. To measure the opacity, take a sample from the measuring cylinder. Record the measured value.
6. Open the stop valve at the measuring cylinder outlet and drain off the filtrate into a suitable container.
7. Close the stop valve at the measuring cylinder outlet when the measuring cylinder is drained.
8. With the same settings, repeat the opacity measurement for further 15 L volumes and note the filter inlet pressures in each case.

Investigating the filtration quantity

1. Open a little the stop valve on the bypass.
2. Fully open the diaphragm valve at the filter in-feed pipe.
3. Measure the filter inlet pressure.
4. Read the filter inlet pressure on the pressure gauge immediately after starting the pump and note it.
5. A stopwatch is required to measure the volumetric flow, to measure the time required for the volume of water in the measuring cylinder to rise from 0 to 15 L. Record the elapsed time, for example at 5 L intervals.
6. Stop the pump and repeat the procedure again.

VI. Experimental Work:

Table 1 Experimental measurements 1

Filtrate-L	Opacity NTU	Pressure-bar	Time-s
15			
30			
45			
60			

Table 2 Experimental measurements 2

Filtrate-L	Opacity NTU	Pressure-bar	Time-s	$\Delta\theta/\Delta V$

5				
10				
15				
20				
25				
30				
35				
40				

Discussion

1. Plot $\Delta\theta/\Delta V$ versus V to obtain r and α for the constant pressure filtration.

   Where $\frac{\Delta V}{\Delta \theta}$ is the volumetric flow rate.

2. From the slope and intercept of the plotted line, values of r and α should be found. Given that: Filter layer dimensions 200 mm x 200 mm.
3. Draw the relation between the filtrate (L) and opacity for the first experimental part.
4. What are the assumptions made in your calculations?

   (*Include a discussion on the result noting trends in measured data and comparing measurements with theoretical predictions when possible. Include the physical interpretation of the result, the reasons on deviations of your findings from expected results, your recommendations on further experimentation for verifying your results and your findings.)*

References:

MCCABE, W. L., & SMITH, J. C. (2004). *Unit operations of chemical engineering*. New York, McGraw-Hill.

Experiment 11: Shell And Tube Heat Exchanger

I. Objectives:

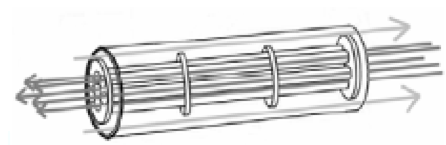
1. To determine the overall heat transfer coefficient using shell and tube heat exchanger.
2. To investigate the effect of flow pattern (co-current or counter current) on the heat transfer coefficient.
3. To establish energy balance on the heat exchanger.

II. Test Standard

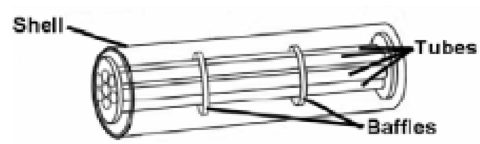
- NA

III. Theory:

The shell and tube heat exchanger is commonly used in the food and chemical process industries. This type of exchanger consists of a number of tubes in parallel enclosed in a cylindrical shell. Heat is transferred between one fluid flowing through the tubes and another fluid flowing through the cylindrical shell around the tubes.



In this miniature exchanger, baffles inside the shell increase the velocity of the fluid and hence the rate of heat transfer. The exchanger has one shell and seven tubes with two transverse baffles in the shell.



The heat flow (Q) is determined from the mass flow rate m, the specific heat capacity and the absolute temperature (T).

$Q = m\ Cp\ T$ ………………………………(1)

For hot fluid

$Q_h = m_h Cp_h\ (Th_{,in} - Th_{,out})$ ……………….(2)

For cold fluid

$Q_c = mc\ Cp_c\ (Tc_{,out} - Tc_{,in})$ ....(3)

If no exchange of heat with the surroundings, then $Q = Q_h = Q_c$

IV. Apparatus:

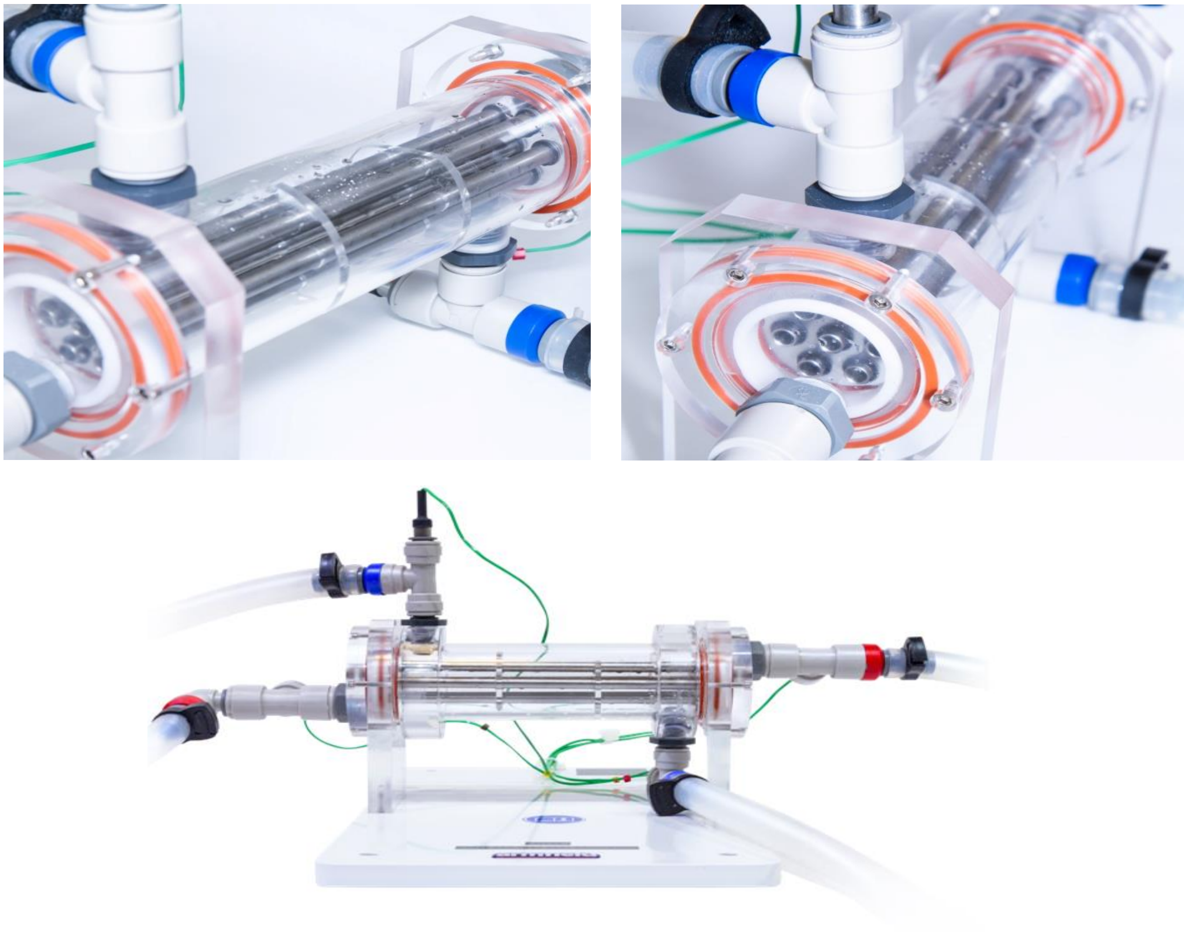


Figure 2 Shell and tube heat exchanger unit

V. Procedure:

9. This experiment consist of two parts:

   A. Experimental study of the heat exchanger.
   B. Simulation of shell and tube heat exchanger.

10. Each student should do both co and counter-current runs.

Simulation of shell and tube heat exchanger.

1. Select flow rates for both shell and tubes sides.

Shell and tubes flow rates should be in the range of (0.00001 to 0.0001 m^3/s).

2. Click the Ok button and click Start button to start the experiment.
3. Note down the temperature at four axial locations of the heat exchanger at a time interval of one minute from the table at the bottom of the heat exchangers.

VI. Experimental Work:

Table 1 Experimental readings

TIME **min**	**FOW DIRECTION**	**HOT TEMPERATURE IN ^{O}C**	**HOT TEMPERATURE OUT ^{O}C**	**COLD TEMPERATURE IN ^{O}C**	**COLD TEMPERATURE IN ^{O}C**

Discussion

1. Calculate Logarithmic mean temperature difference (LMTD)
2. Calculate Q for the hot and cold fluids.
3. Calculate the heat loss percentage.
4. Calculate U if the area is known assumed to be 0.6 m^2 .
5. Calculate the required area if U is known (select a value from literature).
6. Draw temperature as a function of time for the hot and cold waters.
7. Compare the co current and counter current operation depending on your results.
8. Calculate the number of tubes required if the tube length is 0.3 m.

References:

ÇENGEL, Y. A. (2002). *Heat transfer: a practical approach*. Boston, Mass, WBC McGraw-Hill.

Experiment 12: Design Of Experiment

I. Objectives:

4. To design an experiment on the fields of fluid mechanics or solid separation or heat transfer.
5. To enhance the group work and communication skills.

II. Test Standard

- NA

III. Description

The purpose of this activity is to achieve the design part of student outcome (2).
Students in the lab will be divided into groups of 3-5 students, each group of students should develop a new technique in the lab, so that they can conduct a new experiment to achieve specified one or more goals or functions and report the results. Students can use any of lab equipment, tools, instruments beside their own accessories, tools instruments to setup their own experiments.
The design of an experiment can be integrated in the lab through different approaches:

- ***Design-build-test approach.***
- ***Modifying an existing experimental setup.***
- ***Utilizing instrumentations from other experiment to study a certain phenomenon.***

The final report should include:

- ***Objectives:*** Statement of what you are going to achieve.
- ***Experimental setup:*** the apparatus, devices, and instruments used to conduct the experiment should be clearly specified [figures or photos may be added].
- ***Theoretical background:*** the theory related to the experiment, including all assumptions and needed equations should be specified.
- ***Procedure of the experiment:*** clear procedure should be specified.
- ***Experimental results:*** represent all raw data.
- ***Analyze and interpret data:*** develop a mathematical model or computer simulation to correlate or interpret experimental results.
- ***Discussion and conclusions:*** list and discuss several possible reasons for deviations between predicted and measured results from an experiment.
- ***References and appendix.***

As a first stage each group should submit a proposal for their work before week 9, the proposal should describe the idea of the experiment, the objective, tools, instruments, experiment setup, governing equations, and analysis of the data.

Suggested new Experiments

1- Hydrostatic forces and center of pressure on plane surfaces submerged in water.
2- Affecting factors on Sedimentation process
3- Laminar and turbulent flow in pipes.
4- Flow through orifice.
5- Verification of Bernoulli equation.
6- Filtration techniques.
7- Reynolds experiments
8- Increasing settling velocity (addition of chemicals)
9- Thermal conductivity calculations.
10- Study of unsteady heat transfer.
11- Conduction through composite materials.
12- Applications of Bernoulli equation.
13- Hydraulic systems .
14- Heat of vaporization.
15- Solar water heater.
16- Tank draining.
17- Viscosity of mixtures.

Modification on available experiments.

1. Study of radial and extended surfaces heat transfer.
2. Calculation of radiation and convection.
3. Pressure effect on critical heat flux.
4. Conductivity of gases.

APPENDIX

FULL REPORT EVALUATION SHEET

	Reporting, interpreting and analyzing SO(b)	Grade	Max.
1	Abstract, Objectives, Apparatus, Procedure, theory and equations		15
2	Table of measurements.		5
3	Table of results and calculations.		5
4	Sample calculations		15
5	Discussion, sources of error, conclusion and recommendations		25
	Total		65

	Writing, Editing, and Presentation SO(g)		Max.
1	Cover Page, table of content		5
2	Numbering of Pages, tables, figures, and organizing the report		10
3	Language and typing		10
4	Appendices, citations and Referencing		10
	Total		35

Report Grade		**100**

Notes:………………………………………………………………………………………
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SHORT REPORT EVALUATION SHEET

	Reporting, interpreting and analyzing SO(b)	Grade	Max.
1	Abstract		5
2	Table of measurements		5
3	Table of results and calculations		5
4	Sample calculations		15
5	Figures, Sources of error and validation of results		20
6	Discussion, conclusion and recommendations		20
	Total		70

	Writing, Editing, and Presentation SO (g)		Max.
1	Cover Page and table of content		5
2	Numbering of Pages, tables, figures, and organizing the report		10
3	Typing		5
4	Citations &Referencing		5
5	Language		5
	Total		30

Report Grade		**100**

Notes:………………………………………………………………………………………
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DEPARTMENT OF CHEMICAL ENGINEERING

ChE 306: Chemical Engineering Lab I

COVER PAGE

NAME OF EXPERIMENT:
STUDENT NAME:
STUDENT ID:
DATE & TIME:

General Safety Rules:

1. Read all directions for an experiment and follow the directions exactly as they are written. If in doubt, ask the teacher.
2. Never perform experiments that are not authorized by your teacher. Always obtain permission before experimenting on your own.

3. Never handle any equipment unless you have specific permission.
4. Take care not to spill any materials in the lab. If a spill occurs, ash your teacher immediately about the proper clean-up procedure.
5. Dispose of all material according to the teacher's instructions. Never empty materials into the sink or trash can.
6. Never eat in the laboratory. Wash your hands before and after each experiment.
7. Never horse play or run in the laboratory. This will earn you a zero and dismissal from the lab.
8. Know the location and function of all laboratory safety equipment.

Laboratory Dress Code:

1. Always wear goggles and aprons anytime sharp instruments or chemicals are used in the laboratory.
2. Tie back long hair and loose clothing when performing laboratory experiments involving open flames.
3. Remove jewelry before lab activities.
4. Always wear closed-toed shoes in the laboratory.

First Aid:

1. Report all accidents to the teacher immediately.
2. Apply direct pressure to any severe cuts to stop the bleeding
3. Know the location of the first aid kit
4. Know the location and use of the fire blanket.

Heating and Fire Safety:

1. Never reach across an open flame.
2. Know how to light and extinguish the Bunsen burner, never leave a burner unattended.
3. Point the test tube or bottle away from you and others when being heated, chemicals can rapidly boil out of the container.
4. Never heat a liquid in a closed container.
5. Always use a clamp or tongs when handling hot containers.

Chemical Safety:

1. Never touch, taste, or smell, any questionable chemicals in the laboratory without the teacher's permission.
2. Only as instructed by the teacher, gently wave your hand over the opening of a container toward your nose. Do not inhale fumes directly from the container.
3. Keep all lids to chemicals closed.
4. Dispose of all chemicals as instructed by your teacher.
5. Pour acids and bases over a sink in case of spillage.
6. Never pour water into an acid, pour the acid into the water.
7. Never eat or drink from any laboratory glassware.
8. Never use chipped or broken glassware, cuts and scratches can occur.

Electrical Safety:

1. Make sure electronic equipment is OFF when plugging or unplugging from an outlet.

2. Make sure the work area for electrical equipment is clean and dry.
3. Do not “daisy-chain” electrical power cords.
4. Inspect power cords for cuts or abrasions that revel bare copper wire.
5. Be very aware of the location of power cords to avoid tripping and damage to persons.

End of Laboratory activity rules:

1. Clean all laboratory equipment and return to their locations
2. Unplug and store properly any electrical device.
3. Wash your hands after every experiment.
4. Extinguish all candles and burners and the conclusion of the lab activity.
5. Turn off all gas lines to the Bunsen burners.

Be safe, enjoy, and follow the lab rules!