

**SCHULICH**  
School of Engineering



# **LABORATORY MANUAL**

## **ENER480: ENERGY ENGINEERING FLUID MECHANICS**

Instructor: Dr. Poornima Jayasinghe

Revised: Dr. Jalel Azaiez (2013)

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## I- Report Writing Guidelines

The following are general guidelines of sections usually included in a laboratory report. The laboratory reports should be written using word processor (or equivalent) and submit in ENER 480 drop box located in END basement. Additionally, a copy should be e-mailed to the TA with a copy to the lab instructor. See course outline for more details.

### **1. Introduction (15%)**

- a. The problem being studied in the experiment should be described briefly.
- b. Make reference to previous work on the same problem (books, papers, etc.).

### **2. Objectives (5%)**

### **3. Experimental Procedure (10%)**

Should be a sequential synopsis of the steps conducted during the experiment. Although brief, it should include all relevant steps so that an individual unfamiliar with the experiment will be able to understand what occurred in the laboratory. In general, few well-written lines will adequately describe all the steps. Use paragraph style. No bullet points.

### **4. Results & Discussion (45%)**

- a. All numerical results should be placed in either tables or figures.
- b. The text should describe the data, including any noticeable trends.
- c. A description of how the results were obtained from the raw data should be given (Sample Calculation). All equations used must be referenced. Any symbol used in the report must be clearly defined (including units where applicable).
- d. The quality of the results (i.e. how accurate they are) needs not be evaluated.

### **5. Conclusions (10%)**

Should be connected to all other components of the report. Should briefly state the main conclusions that can be drawn based on the data that were obtained.

### **6. References (10%)**

- a. Should use the Canadian Journal of Chemical Engineering uses the following format, e.g.:  
Nightly, I. P., "101 Ways to Repair Rusty Bedsprings", Wiley Books, Boston, MA (1997), pp. 89-103
- b. The same format should be maintained throughout the References section.
- c. Ensure that the lab handout is included in the list of references.

### **Overall Organization (5%):**

e.g.:

- a. All figures and tables must have a descriptive caption.
- b. All figures and tables must be referred to in the text and should be included on the same page or the following page, where it is mentioned.
- c. S.I. units must be used for all calculations.

## II-Experiment#1: Flow Metering Devices

### Learning Objectives

The objective of this experiment is to see the Bernoulli equation at work and to use it to determine the variation of pressure in different geometries. These include different flow meters such as the venturi tube, orifice and nozzle.

**Reading:** Chapter III in textbook and related course materials.

The apparatus consists of four stations and the students will run experiments on one of the four stations.

Station 1 consists of a loop with a ½ inch copper pipe.

Station 2 and 4 consist of a loop with a ¾ inch copper pipe.

Station 3 consists of a loop with a 1 inch copper pipe.

### II-1 Description

#### Purpose

The objective of this experiment is to measure pressure variations around three types of metering devices: Venturi, Orifice and Nozzle meters (see Fig. 3.11 in the textbook).

#### Equipment

Water is circulated through the piping networks by a centrifugal pump and returned to the water storage tank. The water flow rate is metered with a rotameter and is regulated with a globe valve. Each station consists of two layers of pipe loops and the flow passes first through the back layer and then into the front layer.

The front layer is equipped with flow meters (Venturi, Orifice and Nozzle) and valves and will be used in this experiment (#1).

The back layer consists only of pipes and u-turns. It will be used to determine pipe losses during experiment #3. It is not used in this experiment on metering devices. Note that flow enters the back layer from the bottom and exits from the top.

Pressure is measured at different locations in and around the flow meters. Flexible tubing connects taps at these measurement locations to a pressure manifold through toggling valves that allow pressure at a given tap to be measured by reading the pressure gage. The locations of the pressure taps relevant to the present experiment are as follows:

<u>Tap Number</u>	<u>Tap connected to</u>
1	Venturi throat minus 20D (D is the pipe inside diameter)
2	Venturi throat minus 8D
3	Venturi throat
4	Venturi throat + D

5	Venturi throat + 2D
6	Venturi throat + 3D
7	Venturi throat + 8D
8	Venturi throat + 20D
9	Venturi throat + 30D
10	Nozzle throat minus 20D (D is the pipe inside diameter)
11	Nozzle throat minus 8D
12	Nozzle throat minus D
13	Nozzle throat
14	Nozzle throat + D
15	Nozzle throat + 2D
16	Nozzle throat + 8D
17	Nozzle throat + 20D
18	Nozzle throat + 30D
19	Orifice throat minus 20D (D is the pipe inside diameter)
20	Orifice throat minus 8D
21	Orifice throat
22	Orifice throat + 3D/2
23	Orifice throat + 2D
24	Orifice throat + 3D
25	Orifice throat + 8D
26	Orifice throat + 20D
27	Orifice throat + 30D

## **II-2 Brief Description of the Experiment**

- Record pressure readings at each of the metering pressure taps listed above, for at least 4 different flow rates covering the full range available in the equipment.
- Explore the effect of the gate and globe valves on the flow through the loop.

## **II-3 Calculation Procedure**

- Convert the flow rates read on the rotameter ( $q$ ) to actual volumetric flow rates ( $Q$ ) using the following correlations:
  - Station1:  $Q$  (L/s) =  $7.6 \cdot 10^{-3} \cdot q$  (%)
  - Station2:  $Q$  (L/s) =  $7.0 \cdot 10^{-3} \cdot q$  (%)
  - Station3 and 4:  $Q$  (L/min) =  $1.011 \cdot q$  (L/min) - 0.36
- For the Venturi meter: Determine the pressure drop with respect to the meter throat (tap#3) for all taps 1 through 9. Plot the pressure drop versus pipe position. Put the results for different flow rates on the same graph.
- For the Nozzle meter: Determine the pressure drop with respect to the meter throat (tap#13) for all taps 10 through 18. Plot the pressure drop versus pipe position. Put the results for different flow rates on the same graph.
- For the Orifice meter: Determine the pressure drop with respect to the meter throat (tap#21) for all taps 19 through 27. Plot the pressure drop versus pipe position. Put the results for different flow rates on the same graph.

## III-Experiment#2: Agitation

### Learning Objectives

The objective is to see how dimensional analysis can be used effectively to simplify the analysis of complex problems. Students will also learn how dimensionless groups can be very useful in characterizing and describing a complex flow system that otherwise involves a large number of parameters.

**Reading:** Chapter VII in textbook. However, as the course textbook does not address agitation per se, students may want to consult lecture notes for examples on agitation. An additional reference that deals with agitation is: Coulson & Richardson (*Chemical Engineering, Vol. 1*). The book is available through Internet Access of the University library.

*The apparatus consists of three similar stations each consisting of two tanks containing a fluid to be agitated by a mixer. The two tanks in each station have the same fluid but at two different temperatures. Students will run experiments on just one station but for both hot and cold tanks.*

### III-1 Description

#### Purpose

The purpose of the experiment is to determine the variation of power consumption with agitator speed in the agitation of a vessel. Dimensionless groups that govern the system will be determined and used to describe the operating conditions.

#### Equipment

The equipment consists of a small jacketed and insulated tank. The fluid in the tank is agitated by a vertically mounted agitator. The agitator is driven by a DC motor whose performance is monitored with an *ammeter* and a *voltmeter*, so that electrical power consumption can be determined. The electrical drive can produce a continuous variation in agitator speed of rotation. The speed of rotation can be measured using an optical *tachometer*.

### III-2 Brief Description of the Experiment

Vary the DC voltage to the agitator through the full range available. At each setting, record the agitator speed of rotation, the voltage supplied to the motor and the ammeter reading. Confirm the results by duplicate measurements.

### III-3 Calculation Procedure for Each Temperature

- For each rotational speed  $N$ , calculate the electrical power  $P$  consumed by the motor:

$$P = V \cdot I \quad (1)$$

- Convert the units of the rotational speed  $N$ , from *rpm* to *Hz*. As you will have two tests for each voltage, average the rotational speeds from both trials.

- Plot  $P$  versus  $N$  on both linear and logarithmic scales ( $\ln(P)$  vs.  $\ln(N)$ ). Plotting on multiple scales will help you determine the relationship between  $P$  and  $N$ . As a large number of very repetitive calculations are required, it is *strongly* recommended that you do all your calculations using a program such as Microsoft Excel®.
- Correlate the results of the experiments using the appropriate dimensionless groups. The dimensionless groups are determined by first finding the physical properties that affect the required mixing power  $P$ . One may posit that:

$$P = f(\mu, \rho, N, g, D_a, D_t, E, W, L, H, J, B) \quad (2)$$

Where:

$$\begin{aligned} P &= \text{Mixing power (W)} \\ \mu &= \text{Fluid viscosity (Pa.s)} \\ \rho &= \text{Fluid density (kg/m}^3\text{)} \\ N &= \text{Rotational speed (Hz)} \\ g &= \text{Acceleration due to gravity (m/s}^2\text{)} \\ D_a &= \text{Diameter of the agitator (m)} \\ D_t, \dots B &= \text{Other dimensions of the mixing equipment (m)} \end{aligned}$$

Using the *Buckingham-Pi* theorem, the relationship between the above 13 variables can be reduced to a relationship involving only 10 dimensionless groups ( $\Pi$ 's):

$$\frac{P}{\rho N^3 D_a^5} = f\left(\frac{\rho N D_a^2}{\mu}, \frac{N^2 D_a}{g}, \frac{D_t}{D_a}, \frac{E}{D_a}, \frac{W}{D_a}, \frac{H}{D_a}, \frac{L}{D_a}, \frac{J}{D_a}, \frac{B}{D_a}\right) \quad (3)$$

Three particularly important dimensionless groups appear in equation (3):

$$\text{The Reynolds Number : } Re = \frac{\rho N D_a^2}{\mu} \quad (4)$$

$$\text{The Power Number : } N_p = \frac{P}{\rho N^3 D_a^5} \quad (5)$$

$$\text{The Froude Number : } Fr = \frac{N^2 D_a}{g} \quad (6)$$

You need to calculate values for each of the above three groups at each rotational speed tested. Graph the Power number ( $N_p$ ) versus Reynolds number ( $Re$ ) on a log-log scale. Note that for this  $N_p$  versus  $Re$  graph, you need only one single curve that includes data for both hot and cold fluids. In this experiment,  $D_a=10\text{cm}$  and other dimensions are posted in the lab room.

### III-4 General Guidelines

- Tabulate voltage supplied, current drawn and agitator speed for each trial at each temperature
- Calculate Power consumed by the agitator
- Provide one sample calculation for each series of calculations

**N.B.** Data for viscosity and density are posted in the lab.

## **IV-Experiment#3: Pipe Flows**

### **Learning Objectives**

The objective of this experiment is to determine major (viscous) and minor (in u-turn) losses and obtain a curve for the variation of the friction coefficient with the Reynolds number. This illustrates how the Moody graph and the related equations have been obtained and how they can be used to determine the losses in any pipe flow.

**Reading:** Chapter VIII in textbook and related course materials.

*The apparatus consists of four stations and the students will run experiments on one of the four stations.*

*Station 1 consists of a loop with a ½ inch copper pipe.*

*Station 2 and 4 consist of a loop with a ¾ inch copper pipe.*

*Station 3 consists of a loop with a 1 inch copper pipe.*

### **IV-1 Description**

#### **Purpose**

The objective of this experiment is to determine losses through piping at varying volumetric rates and to obtain a graph for the variation of the friction factor with the Reynolds number.

#### **Equipment**

Water is circulated through the piping networks by a centrifugal pump and returned to the water storage tank. The water flow rate is metered with a rotameter and is regulated with a globe valve

The 1/2" network consists of 1.45m long runs of copper tubing connected via 180 degree return bends. The inner diameter of the tubing is 14.4mm.

The 3/4" network consists of 1.85m long runs of copper tubing connected via 180 degree return bends. The inner diameter of the tubing is 20.6mm.

The 1" network consists of 1.30m long runs of copper tubing connected via 180 degree return bends. The inner diameter of the tubing is 26.0mm.

Pressure is measured at different locations along the loop. Flexible tubing connects taps at these measurement locations to a pressure manifold through toggling valves that allow pressure at a given tap to be measured by reading the pressure gage. The locations of the pressure taps relevant to this experiment are as follows:

Tap Number	Tap connected to
28	At the start of the back layer (bottom)
29	At the end of the back layer (top)
32	Before a U-turn on the back layer
33	After the same U-turn on the back layer

## **IV-2 Brief Description of the Experiment**

- Record the room temperature and pressure.
- For the back loop, note the total length of the pipe (excluding the U-turns) and the total number of U-turns between the taps at the inlet and outlet. Record the difference of elevation between the entrance and exit of the back loop.
- Record pressure readings at each of the metering pressure taps for at least 4 flow rates covering the full range available in the equipment.

## **IV-3 Summary of Theory**

Fluid flows in pipes are characterised as laminar and turbulent depending on the values of the Reynolds number,  $Re$ :

$$Re = \frac{\rho DV}{\mu} \quad (1)$$

Where

D	= Diameter of Pipe.
$\rho, \mu$	= Density and viscosity of the fluid, respectively.
V	= Average velocity = $4Q/\pi D^2$ where Q is the volumetric flow rate.

If  $Re < 2100$  then the flow is termed laminar. If  $Re > 4000$  then the flow is termed turbulent. If  $2100 < Re < 4000$  then the flow is in a transition regime, and is neither fully laminar nor fully turbulent.

Chapter VIII of the textbook by Young, Munson, Okiishi discusses the calculations of pressure losses for incompressible fluid flows through pipes and fittings. The pressure losses in a pipe of constant diameter (D) and of total length (L) are related to the average velocity in the pipe (V):

$$\Delta P_{losses} = f \frac{L}{D} \frac{\rho V^2}{2} + \sum_L K_L \frac{\rho V^2}{2} \quad (2)$$

The first term on the RHS of Eq.(2) represents viscous losses and is proportional to a parameter  $f$  called the Moody friction factor (Eq. 8.17 in the Textbook). The friction factor  $f$  is a function of the Reynolds number and the roughness of the pipe (see fig. 8.10 in the Textbook).

The second term on the RHS of Eq.(2) refers to the sum of all minor losses due for example to fittings such as valves, bends, U-turns, etc. (Eq. 8.20 in the Textbook). For this experiment, the losses are associated with the U-turns, and can be obtained either directly from the measured pressure drop around one bend, or empirically using a formula for minor losses of threaded return bend with a loss coefficient  $K_L$  is equal to 1.5 (see Table 8.2 in the Textbook).

**N.B.** There are different definitions of the friction factor, but they are all proportional to each other. In particular the Moody friction factor  $f$ , (called  $f'$  in Coulson and Richardson [C&R]) is four times the fanning friction factor (called  $f$  in C&R).

In the absence of any losses or gains of work or heat, the total pressure drop is the sum of the pressure losses and the hydrostatic pressure:

$$\Delta P = \Delta P_{losses} + \rho g \Delta h = f \frac{L}{D} \frac{\rho V^2}{2} + \sum_L K_L \frac{\rho V^2}{2} + \rho g \Delta h \quad (3)$$

Where  $\Delta h = (h_{exit} - h_{entrance})$  is the elevation difference between the entrance and exit of the pipe while  $\Delta P = (P_{entrance} - P_{exit})$  is the pressure drop in the pipe.

#### **IV-4 Calculation Procedure**

- Convert the flow rates read on the rotameter ( $q$ ) to volumetric flow rates ( $Q$ ) using the correlations already given in Experiment 1 (see page 6).
- Record the pressure reading at the entrance and exit of the back loop. Plot the pressure drop (kPa) vs. flow rate.
- Determine the value of the friction factor  $f$  for the flow in the back loop. Generate a plot similar to the Moody Chart in your textbook for the variation of  $f$  with the Reynolds number  $Re$  on a log-log scale.
- For the 180° return bend (U-turn), plot the pressure difference between the inlet and outlet vs. the volumetric flow rate.

# V-Experiment#4

## Flow Through Packed Beds and Fluidization

### Learning Objectives

The purpose of the experiment is to observe phenomena associated with the pressure drop through beds of solids. Changes in the flow patterns with the flow rate will be characterized including the bed expansion under fluidization and the variation of the bed porosity. The student will determine the variation of the pressure drop with the increase and decrease of the flow rate and will characterize the hysteresis.

**Reading:** Chapter IX in textbook. However, as the course textbook does not address packed bed flows and fluidization per se, students should read the brief theory summary below. For a more extensive description, students should consult the book of Coulson & Richardson (*Chemical Engineering, Vol. 2*). The book is on reserve for this course in the University library.

*The apparatus consists of four stations and the students will run experiments on one of the four stations. All stations are similar and consist of two columns, one is fluidized with air and the other is fluidized with water.*

### V-1 Description

#### Purpose

The purpose of the experiment is to observe and measure the phenomena associated with the pressure drop through beds of solids. Pressure drop is to be measured as the fluid flow rate varies up to, and through the minimum fluidization velocity. Bed expansion is also to be observed, both for particulate fluidization of glass beads with water and for particulate and bubbling fluidization of small diameter Flex-o-lite with air.

#### Equipment

The equipment consists of two different beds of solids, both contained in columns with a 4.00 inch ID (10.16 cm).

The first column is filled with Flex-o-lite glass particles that are fluidized with air. Air is supplied through a rotameter. The pressure differentials are measured with manometers containing a manometer oil with specific gravity 1.000. Pressure taps are located 4 inches (10.16 cm) apart in the lower section of the column.

The second column contains glass beads that are fluidized by circulating water. The manometers attached to this column use an oil with specific gravity 2.95 and are connected to taps which are 8 inches (20.32 cm) apart in the bottom section of the column. The water flow rate is measured with a rotameter.

### Specifications:

Column distributor plates are 3/4 inch thick with 28 holes, 1/16 inch diameter.

Water bed: Glass beads;  $d_p = 3\text{mm}$ ,  $\rho_p = 2.52\text{ g/cm}^3$ , bed porosity  $\varepsilon = 0.38$

Air bed: Flex-o-lite;  $\rho_p = 2.50\text{g/cm}^3$ , bed porosity  $\varepsilon = 0.362$

<u>Particle diameter range</u>	<u>Mass Fraction</u>
$d < 150\mu\text{m}$	1.5
$150\mu\text{m} < d < 180\mu\text{m}$	4.5
$180\mu\text{m} < d < 210\mu\text{m}$	1.5
$210\mu\text{m} < d < 250\mu\text{m}$	91
$250\mu\text{m} < d < 300\mu\text{m}$	1.5
$d > 300\mu\text{m}$	0.0

The air rotameter was calibrated at a reference condition of 70° Fahrenheit and 14.7psia. The volumetric rate indicated (as a % of the maximum rate of 1.49ft<sup>3</sup>/min) must be corrected by multiplying by a correction factor using the absolute temperature ratio and the pressure ratio;

$$\text{Correction Factor} = \sqrt{\left(T_{ref}/T\right)\left(P/P_{ref}\right)}$$

P is the air pressure in the rotameter.

## **V-2 Description of the Experiment**

### Air column

Note carefully the location of all manometer taps and record the information. Vary the air rate to the column of Flex-o-lite beads and record the manometer readings and the bed height at each rate. Locate (within the capabilities of the set-up) the air rates at which particulate fluidization begins and at which bubbling fluidization begins. Repeat measurements by steadily increasing the air rate and by steadily decreasing the air rate so that any hysteresis effects can be noted. Inquire with the TA about the hysteresis and its significance.

### Water column

Vary the water rate to the column of glass beads in a manner similar to that used in observing the fluidization behaviour of the Flex-o-lite beads.

**N.B.** The flow rates for station1 is given in % and can be converted to L/min using the following correlation:  $Q(\text{L/min}) = 0.41 * q(\%)$

## **V-3 Summary of Theory**

### Fluidization

When a fluid flows through a packed bed at a certain velocity, the bed particles start leaving the bed to the fluid phase. This phenomenon is called fluidization. It is important in many industrial processes such as catalytic reactions, cracking of heavy crude oil and fluidized bed combustion.

At low velocities, the particles remain fixed in the bed and the pressure drop in the bed is described by an empirical equation known as Ergun equation:

$$\frac{\Delta P - \rho g \Delta h}{\rho L} = \left( \frac{1 - \varepsilon}{\varepsilon^3} \right) \left( \frac{1}{\phi_s D_{eq}} \right) \left[ 150 \frac{\mu(1 - \varepsilon)}{\rho} \left( \frac{1}{\phi_s D_{eq}} \right) V_0 + 1.75 V_0^2 \right] \quad (1)$$

where  $\Delta P$  is the pressure drop between two points,  $\Delta h$  the corresponding difference in elevation,  $\rho$  the fluid density and  $\mu$  its viscosity,  $L$  the bed height,  $\varepsilon$  its porosity and  $V_0$  is the superficial velocity;  $V_0 = \text{volumetric rate of flow} / (\text{column total cross-sectional area})$ .  $D_{eq}$  is the particles equivalent diameter, and  $\phi_s$  is called the particles sphericity.

At relatively low velocities, the pressure drop ( $\Delta P$ ) is an increasing function of the superficial velocity ( $V_0$ ) while the bed height is constant. At a certain critical value of the superficial velocity ( $V_{om}$ ) known as the minimum fluidization velocity, the particles are separated from the bed and the pressure drop becomes constant, while the bed height starts increasing.

When particles are lifted from the bed at the minimum fluidization velocity ( $V_{om}$ ), there is a balance between the effective weight of the solid particles and the upward friction force on the right hand side of the above equation. This leads to the following equation:

$$(\rho_p - \rho)g = \left( \frac{1}{\varepsilon^3} \right) \left( \frac{1}{\phi_s D_{eq}} \right) \left[ 150 \mu V_{om} (1 - \varepsilon) \left( \frac{1}{\phi_s D_{eq}} \right) + 1.75 \rho V_{om}^2 \right] \quad (2)$$

In the above equation,  $\rho_p$  is the density of the solid and  $\rho$  that of the fluid.

#### Nature of Fluid Bed Behaviour

Fluidized beds of solids can behave quite differently depending on the fluid viscosity, the particle size and the difference in density between the fluid and solids. With a more dense fluid, the bed might expand in a uniform way as the velocity is increased; this kind of behaviour is called "particulate fluidization". When the density differences are larger and when the fluidizing medium has a low viscosity (e.g., when it is a gas), it is possible for bubbles of fluid to pass through the bed, retaining their identity, and without being forced through interstitial spaces. This kind of "bubbling fluidization" provides poor contacting between the solid and the fluid, and is not usually desirable.

### Bed Expansion.

Note that the left-hand side in the previous equation depends only on the two densities and not on the velocity or bed porosity. In *particulate fluidization*, the right hand side of the equation is assigned a constant value on the left even at velocities greater than the minimum fluidization velocity. The equation can be satisfied by letting the porosity change. The expansion of the bed is accounted for by the increasing porosity. The bed height (length) can be calculated through reasoning that the volume occupied by the solid is unchanged even if the porosity changes;

$$LS_o(1-\varepsilon) = L_M S_o(1-\varepsilon_M) \quad \text{therefore:} \quad \frac{L}{L_M} = \frac{1-\varepsilon_M}{1-\varepsilon} \quad (3)$$

where  $S_o$  is the total cross-sectional area of the column and the subscript  $M$  could apply at any velocity but is usually understood to mean the minimum fluidization point. It is possible to predict the bed height by calculating the porosity for a velocity above the minimum fluidization velocity and plugging into the previous equation.

### **V-4 Calculation Procedure**

- Record the pressure and temperature of the room.
- Characterize the nature of the fluidization at each of the rotameter readings.
- For the Air column, calculate the air rotameter correction factor.
- For the Air column, obtain particle mean-diameter for the flex-o-lite using:

$$D_s = \frac{1}{\sum \frac{W_i}{D_{pi}}} \quad (4)$$

$W_i$  : mass fraction of particle in the  $i^{\text{th}}$  category  
 $D_{pi}$  : average diameter of particle in the  $i^{\text{th}}$  category

- Calculate the superficial velocity:

$$V_o = \frac{Q}{S_o} = \frac{4Q}{\pi D^2} \quad (5)$$

$V_o$  : superficial velocity (m/s)  
 $Q$  : flow rate ( $\text{m}^3/\text{s}$ )  
 $D$  : diameter of bed

- Determine the pressure drop:  $\Delta P = (\rho_{fm} - \rho_{fc})g \sum h$  (6)

$\rho_{fm}$  : density of manometer fluid  
 $\rho_{fc}$  : density of fluid in column (air or water).  
 $\sum h$  : sum of height difference measured in tubes 1,2,3 and 4

- Find the porosity at a bed height  $L$ , using:  $\varepsilon = 1 - \frac{L_o}{L}(1-\varepsilon_o)$  (7)

$L_o$  : bed height at flow rate = 0  
 $L$  : uniformly expanded bed height at desired flow rate  
 $\varepsilon_o$  : initial porosity at flow rate = 0  
 $\varepsilon$  : Porosity at  $L$

- Plot the following: Bed height vs. superficial velocity.  
Pressure drop vs. superficial velocity.  
Porosity vs. superficial velocity.
- Obtain the minimum fluidization velocity from the graphs.
- Describe Hysteresis effects if any.

### **V-5 Suggested Reading**

Fluidization is not discussed in the course textbook but is covered in the course lectures. For an extensive description, students may consult the book of Coulson & Richardson (*Chemical Engineering, Vol. 2*).