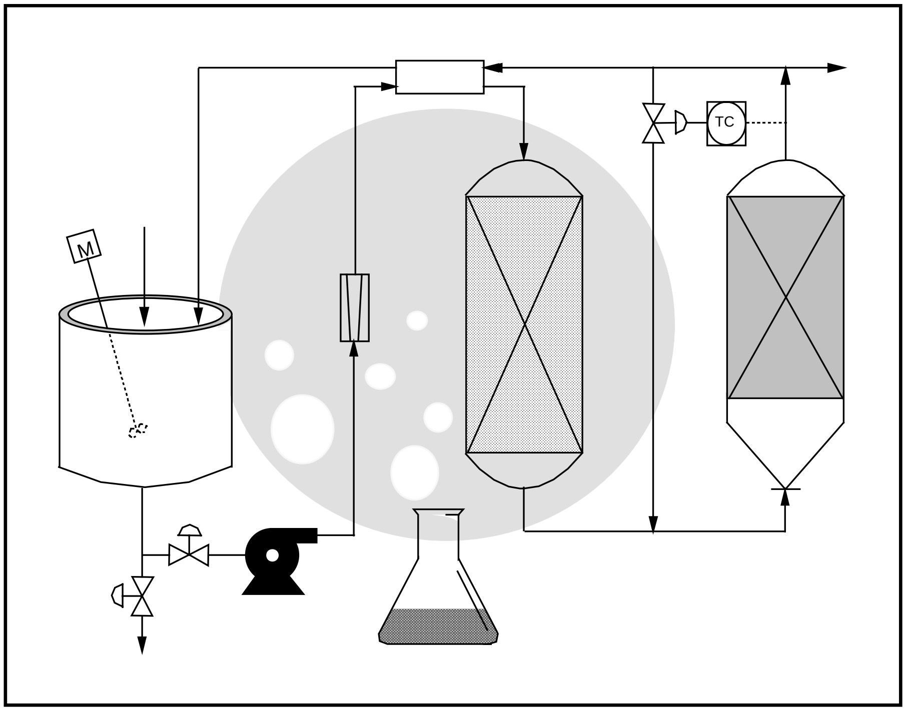
A Laboratory Manual For Fundamentals Of Engineering Design

Chemical Engineering Module: Measurements Laboratory



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Contents

Part I Some Basic Concepts for Measurements and the Analysis of Measured Data

Part II Laboratory Experiments

Introduction

The following material contained in this text was written with the intent to guide and assist the student in obtaining the maximum educational benefit from the Fundamentals of Engineering Design course and the Chemical Engineering Laboratory module.

Students are encouraged to make use of various electronic computational facilities available on campus as well as small programmable calculators and minicomputers. This will enable the student to reap two additional benefits:

1. Reduce calculation time required for the data analysis in the report
2. Broaden student capability by enabling on-line data reduction, immediate data analysis, and more intelligent determination of the following process test conditions.

The purpose of any of our chemical engineering laboratory courses is to serve several important functions in a student's program of development that reflect clearly expectations of abilities of a technical professional. Among the most important are:

1. To teach students to communicate results obtained from experimentation through a written document in a clear and concise fashion
2. To put theory into practice in a realistic sense, through a set of instructions, which will require independent logical thinking (the intent here is to compare the idealistic (theoretical) teachings in the classroom with the real-world operations (experimental equipment) and to realize the limitations of each)
3. To acquaint the student with the availability and use of published data and the various sources for obtaining these references
4. To illustrate the difficulties associated with leadership and group effort approaches in solving particular problems. In essence, these

difficulties include the complexities of people working together and contributing to a common goal

5. To teach students how to prepare and present an industrial seminar. WRITTEN AND ORAL COMMUNICATION WILL LARGELY DETERMINE IN AN INDUSTRIAL ENVIRONMENT WHAT MANAGEMENT THINKS ABOUT YOUR EFFORTS AND WILL THEREFORE BE THE PRIMARY INFLUENCE IN YOUR PROMOTION, ADVANCEMENT, AND CONSEQUENTLY YOUR EARNINGS.

The overall objective is to improve the students' capabilities in these areas and thereby increase their professional competence. It is expected that students will perform and develop in laboratory courses with the same attitude and goals as in theory-oriented courses.

In summary, the student's goals should be:

1. To relate the laboratory experiments to theory courses and reinforce the principles learned in the classroom
2. To obtain practice and develop an interest in planning an experimental test
3. To obtain practice in interacting with the experiment and with other personnel involved in the group effort
4. To develop a proficient style in technical communication, both written and oral
5. To develop an appreciation of the open ended type of problems in research and design and the multiple paths available in the problem solution.

This laboratory is an important first step in an individual's career as an engineering student and assists in bridging the span between high school and college material.

FED Laboratories

The FED laboratory and its associated apparatus are utilized to introduce the students to the concepts of measurements and subsequent data analysis. It undertakes a “hands-on” experimental approach in teaching and learning. The experiments undertaken are in the areas of Momentum Transport, fluid flow and its measurement, and Energy Transport, temperature and heat changes. Associated with the operation of the apparatus to obtain data is also the analysis of the data in attempting to rationalize its meaning in the light of theoretical considerations as well as attempting to explain the “goodness” of the measurements.

The core of the experiments will be some device, an instrument, which will measure a property of interest in a particular process stream parameter. These measurements are important to establish the envelope that contains the process variables. As an example: suppose in a process, take a steam plant, a process discharge stream has a high temperature associated with it, so that it can not be discharged as vapor into the atmosphere or as a liquid into a stream because of adverse environmental impact. We would want to measure the quantity generated, fluid flow, and its energy content, with temperature measurement. If possible we would examine our process with two goals in mind:

a) Pollution Prevention

b) Pollution Abatement

In the case of b) we would be looking at end of pipe treatment which essentially gives us no use of the stream and its properties but allows for disposal. This choice in today’s industrial environment is not preferred. For case a) we would examine the process with intent of process modification to minimize or eliminate the stream or incorporate a process reuse or recycle step into the system. No matter which we use we would need to have measurement data followed by analysis.

Each of the experiments undertaken will require the student team to share responsibilities of data recording and analysis, report writing and for the experiment, an oral presentation.

In addition to the technical problems involving measurements and the analysis of the resulting data, students today must become aware of pollution prevention. In October 1990, the new regulatory agenda was highlighted by the Pollution Prevention Act of 1990. President Bush stated,

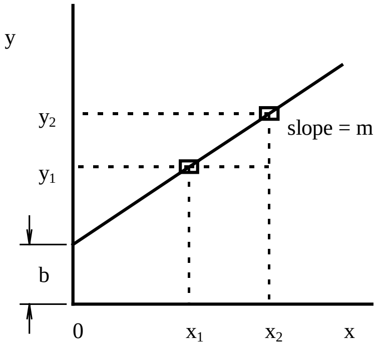
"Environmental programs that focus on the end of the pipe or the top of the stack, on cleaning up after the damage is done, are no longer adequate. We need new policies, technologies and processes that prevent or minimize pollution -- that stop it from being created in the first place."(1)

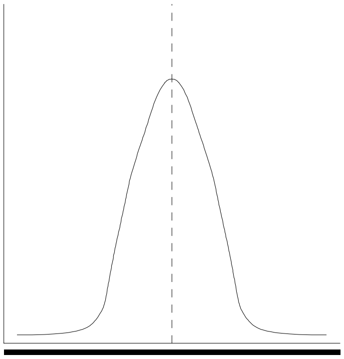
The emphasis had changed from pollution abatement to pollution prevention. Thus, the old proverb that we all learned as children, "an ounce of prevention is worth a pound of cure"
was being re-emphasized.

Engineering students, therefore, must begin their studies with pollution prevention and waste minimization consciousness being equal to the technical aspects of their education. Pollution prevention must be stressed throughout their studies. Thus, a mindset on pollution prevention will be developed by the students which can be taken with them to their jobs at graduation and can be taken with them into their personal lives and thinking. This Fundamentals of Engineering Design course is one point where developing this mindset will begin at our Institute.

Part I

Some Basic Concepts
For Measurements
and the Analysis of
Measured Data





I. Basic Concepts of Measurements

Experimental methods and measurements require a basic terminology, definition of terms, and measurement instruments (2).

A. *Instruments*

Measurements are made with instruments that range from simple to more complex. Examples are:

- Meter stick
- Ammeter
- Gas chromatograph and recorder

B. *Terminology and Definition of terms*

In working with these instruments a terminology has developed and these terms have been precisely defined. Some of the more important terms are discussed. These are:

1. Readability
2. Least count
3. Sensitivity
4. Hysteresis
5. Accuracy
6. Precision
7. Calibration

1. *Readability*

This term indicates to the experimenter the closeness to which the scale of the instrument may be read.

Example:

A 12-inch scale has a higher readability than a 6-inch scale with same range for the measurement. Reading 0-12 amps on a 12-inch scale is better than reading 0-12 amps on a 6-inch scale.

2. ***Least count***

This term represents the smallest difference between two indications that can be detected on the instrument scale.

Example:

1 millimeter on a meter stick

0.1 amps on an ammeter with a 12-inch scale

Both readability and least count depend on:

- scale length
- spacing of graduations
- size of pointer or pen
- parallax effects (the apparent change in the position of an object (pointer) resulting from the change in direction or position from which it was viewed)

3. ***Sensitivity***

This term refers to the ratio of linear movement of the pointer (pen) on an analog instrument to the change in measured variable causing the motion.

Example:

One millivolt (mV) with a 25 centimeter scale on an analog instrument

Sensitivity of linear scale is therefore,

$$\frac{25\ cm}{1\ mV} = 25\frac{cm}{mV}$$

For digital instruments - the manufacturers specify sensitivity for a certain scale setting.

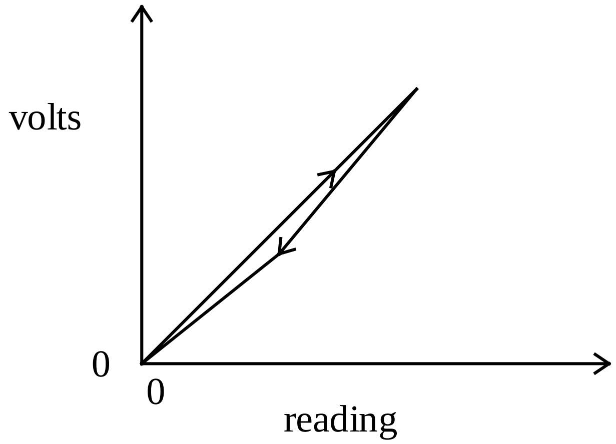
Example :

The specifications will read 100 nanoamperes (10 $^{-9}$ *amps) on a 200 microamp scale range (200 μ amps or 200 x 10* $^{-6}$ *amps).*

4. *Hysteresis*

Some instruments are dependent upon the direction that is used. For example, one can measure voltage either in the increasing direction or in the decreasing direction.

An instrument will show hysteresis if there is a difference in reading depending upon if you are moving up scale or down scale



Hysteresis is caused by:

- mechanical friction
- magnetic effects
- elastic deformation
- thermal effects

5. *Accuracy*

The term accuracy of an instrument indicates the deviation (error) of the reading from a known input, expressed as a percent of full scale reading.

Example:

A pressure gauge has a full scale reading of 1000 kiloPascals (1000 kPa). If the accuracy is 1 percent, the instrument is accurate to ± 10 kPa for the full range. In this case, at full scale the accuracy is only good to ± 10 kPa. The true, accurate reading could therefore range from 990 kPa to 1010 kPa. The error is ± 10 kPa.

6. *Precision*

Precision differs from accuracy in that this term indicates the ability of an instrument to reproduce a certain reading with a given accuracy.

Example:

Consider voltmeter readings for a known voltage of 1000 Volts (1000V). Repeated readings give the following data:

Reading	*Volts*
1	*1010*
2	*1020*
3	*990*
4	*980*
5	*1005*
Average =	*1001V*

The accuracy is

1020 - 1000 = +20V

980 - 1000 = -20V

Therefore, accuracy is ±20 volts.

$$\frac{20}{1000} = 0.02 = 2\%$$

The precision is the maximum deviation from the mean reading. Hence, deviations from the mean are:

$$1020 - 1001 = +19$$
$$1010 - 1001 = +9$$
$$1005 - 1001 = +4$$
$$990 - 1001 = -11$$
$$980 - 1001 = -21$$

The precision is thus

$$\frac{\pm 21}{1000} = 0.021 = 2.1\%$$

Calibration improves the dependability of instruments.

7. *Calibration*

Calibration establishes the accuracy of an instrument. It is wise to check the manufacturer's specifications and calibrations.

Example:

A manufacturer can state that a 100 percent scale reading on a flowmeter (rotameter) is equal to 20 gallons per minute of liquid. The calibration curve may also be given with the instrument covering the entire range of 10-100 percent. These must be checked.

Calibrations compare the instrument with a known standard. There are three standards that can be used in this case. These are:

1) Primary standard

Calibrate flowmeter by comparing it with a standard flow measurement facility at the National Bureau of Standards.

2) Secondary standard

A secondary standard has a higher accuracy than the available instrument to be calibrated. In this case, one can compare the available flowmeter with another flowmeter of known accuracy.

3) A known input source as a standard

In this case, the flowmeter can be set at a fixed reading and the outflow is collected and measured over a known period of time. Thus, at 100 percent reading, 166.8 pounds of water (H_2O) are collected in one minute.

$$\frac{166.8 \text{ lbs } H_2O}{1 \text{ minute}} \times \frac{1 \text{ gal } H_2O}{8.34 \text{ lbs } H_2O}$$

= 20 gallons per minute

= 20 gpm

II. Standards, Units, and Dimensions

Standards, units and dimensions are important aspects of measurements. Standards are needed and have been established to enable experimenters to compare the results of their experiments on a consistent basis.

A dimension is a physical variable used to describe the nature of the system. For example, the length of a piece of wood is a dimension. The temperature of a gas is its thermodynamic dimension.

Units are the quantities by which the dimension is measured. For example, it may be stated that the piece of wood is 1 meter in length, or 39.37 inches in length. The meter and the inches are the units of the dimension length. The temperature can be 100 degrees Celsius (100°C) or 212 degrees Fahrenheit (212°F). The dimension is temperature and the units are Celsius or Fahrenheit. There are two systems of units. The old English system of units is still widely used in the United States but most of the world is on the SI system of units (Systeme International d'Unites).

A. *Standards*

For measurements to be meaningful, there must exist accepted standards for comparison.

1. *Standard units have been established for:*

- mass
- length
- time
- temperature
- electrical quantities

The National Bureau of Standards has the primary responsibility in the U.S.A. and, the National Physical Laboratory has the primary responsibility in the United Kingdom. The United Nations has become involved to develop standards to allow for measurement comparison regardless of where in the world the measurement was made.

2. *Some Standards*

Standards are accepted by agreement and the conversions from one system of units to another is established by law. For example, the standard meter is the length of a platinum-iridium bar maintained at very accurate conditions at the International Bureau of Weights and Measures at Sevres, France. The kilogram is the mass of a similar quantity of platinum-iridium kept at the same place.

Conversions are:

a) Mass

1 pound mass = 453.5924277 grams

b) Length

1 meter (defined at the General Conference on Weights Measures 1960)

1 meter = 1,650,763.73 wavelengths in a vacuum of the orange-red line in the spectrum of a Krypton - 86 lamp - Changed in 1982 to the distance that light travels in 1/299,792,548ths of a second.

1 inch = 2.54 centimeters

100 centimeters = 1 meter

c) Time

Standard units of time are measured
from known frequencies of
oscillations of a

- pendulum
- Torsional vibrational system
- Tuning fork
- 60 -Hz (Hertz) time voltage

(1) Second -

The second is defined as

$$\frac{1}{86400} \text{ of a mean solar day}$$

<u>Solar day</u> - time interval that sun passes a known meridian on the earth.

<u>Solar year</u> - time required for earth to make one complete revolution around sun. The mean solar year is

365 days
5 hours
48 minutes
48 seconds

In October 1967, at the Thirteenth General Conference on Weights and Measures, the

<u>Second</u> is defined by the duration of 9,192,631,770 periods of the radiation

corresponding to the transition between two hyperfine levels of the states of Cesium -135

d) Temperature

Temperature is measured in units of degrees Celsius (C) in the SI system and in degrees Fahrenheit (F) in the English system. These scales are both based upon the height of a column of mercury at the boiling point of water at sea level and 760 millimeters of mercury pressure (mmHg), and the freezing point of water at the same conditions. Thus,

	(1) **C**		**F**	
	degrees Celcius		degrees Fahrenheit	
Boiling point water, sea level 760 mmHg	100 C	scale divided into 100 equal divisions	212 F	scale divided into 180 equal divisions
Freezing point water, sea level 760 mmHg	0 C 32 F			
	Celsius		Fahrenheit	

The height of the mercury column is the same, but the markings and divisions are different. Hence,

1C difference = 1.8F difference

or $\Delta 1$ C = $\Delta 1.8$ F

(2) Absolute temperature

In 1854, Lord Kelvin proposed an absolute temperature scale or thermodynamic scale. Thermodynamically, Lord Kelvin defined absolute zero as the temperature when all molecular motion ceases. This absolute zero was equivalent to: -273.15 C

-459.67 F

Thus, degrees Kelvin on an absolute scale is

$$K = C + 273.15$$

and degrees Rankin on an absolute scale is

$$R = F + 459.67$$

Conversions between Celsius and Fahrenheit are:

$$C = \frac{F - 32}{1.8}$$

$$F = 1.8C + 32$$

Hence, by substitution

$$F = 1.8C + 32$$

$$R - 459.67 = 1.8(K - 273.15) + 32$$

$$R = 1.8K - 491.69 + 459.67 + 32$$

$$R = 1.8K$$

e) Electrical units (3)

Standard units of electrical quantities are derived from mechanical units of

- Force,N = Kg·m / s²
- Mass, Kg
- Length, m
- Time, s

The quantities are the:

Volt
Ampere
Ohm

(1) Volt

The unit volt was named after Alexandro Volta, an Italian physicist (1745 - 1827). It is based upon the work done by a charge moving between two points which have a known potential drop between them. Thus, this potential drop is the voltage, V, and the charge, Q, is doing work, W.

$$W = QV$$

or $$V = E = \frac{W}{Q}$$

where $W = N \bullet m$

$$= kg\frac{m^2}{s^2}$$

Q = charge in Coulombs

V = E = voltage, in Volts

Hence, voltage electrical force or potential drop is the work done by a <u>unit</u> charge (Q = 1) as the charge moves between two points.

(2) Coulomb and Ampere

The flow of the charge is measured in coulombs and amperes. A coulomb is the quantity of electricity equal to 3×10^{9} electrostatic units (esu) of charge. It is the electrons that flow. Since

1 electron = 4.80×10^{-10} esu

the coulomb is the charge of a number of electrons and

$$1 \text{ coulomb} = \frac{3\text{x}10^{9} \text{ esu}}{4.80\text{x}10^{-10} \text{ esu / electron}}$$

$$1 \text{ coulomb} = 6.25 \text{ x } 10^{18} \text{ electrons}$$

The coulomb was named after Charles A. Coulomb, a French physicist (1736 - 1806).

When electrons flow there is a current which is the time rate of flow of the electric charge. The unit of this flow is the transfer of one coulomb of charge past a point in one second. This unit of flow is called the ampere (amp) and

$$\text{Flow} = \text{I} = \frac{\text{Q}}{\text{t}} = \frac{\text{charge}}{\text{time}}$$

The ampere, I, was named after Andre M. Ampere, a French scientist (1775 - 1836).

Hence, it is easier to use current than to use charge and

$$\text{W} = \text{E Q}$$

$$\text{work} = \text{voltage x charge}$$

and $$\text{Q} = \text{I t}$$

$$\text{charge} = \text{current x time}$$

$$\text{W} = \text{E I t} = \text{N}\bullet\text{m}$$

If power, P, is work per unit time,

$$\text{P} = \frac{\text{W}}{\text{t}} = \text{E I}$$

$$\frac{N \bullet m}{s} = \text{volts x amps}$$

$$\frac{N \bullet m}{s} = \text{watts}$$

The unit of power, the watt, was named after the Scottish engineer, James Watt (1736 - 1819) who developed the steam engine

(3) Resistance

All flow depends upon a driving force and a resistance. In electrical flow, the resistance is called the ohm, named after Georg S. Ohm, a German physicist (1787 - 1854).

In metallic currents, current (I) was found to be proportional to the voltage, or potential difference, E. Thus

$$I \sim E$$
$$I = k \times E$$

k = proportionality constant

Thus, if the proportionality constant, k, was defined as

$$k = \frac{1}{R}$$

where R = resistance to electrical flow (analogous to friction in mechanical systems)

Then, $I = \frac{E}{R}$

$$E = I \text{ x } R$$

and Ohm's Law is

$$R = \frac{E}{I} = \text{ohms}$$

The unit value of $R = \frac{1 \text{ volt}}{1 \text{ amp}} = 1 \text{ ohm}$

The ohm is a resistance across which there is a voltage drop of 1 volt when the flow of current is 1 amp.

3. *International System of Units (4)*

The Système International d' Unités, SI, was established by the Eleventh General Conference on Weights and Measures.

a) Basic SI Units

The basic SI units are:

• mass - kilogram	kg
• length - meter	m
• time - second	s
• amount of substance, mole	mol
• thermodynamic temperature,	K
• electric current, ampere	A
• luminous intensity, candela	cd

b) Standard Multiples and Sub - Multiples

Standard multiples and sub-multiples are usually given in tables using prefixes. For example,

ten .... 10^1...................deca

10^1 meters = 10 meters

= 1 decameter

one tenth .... 10^{-1}..................deci

10^{-1} meters = 0.1 meters

$= 1$ decimeter

one millionth .... 10^{-6}................micro (μ)

10^{-6} meters $= 0.000001$ meters

$= 1\ \mu$ meter

Table of Important Prefixes

Prefix	Symbol		Meaning
nano	(10^{-9})	(n)	One-thousand millionth
micro	(10^{-6})	(μ)	One millionth
milli	(10^{-3})	(m)	One thousandth
centi	(10^{-2})	(c)	One hundredth
deci	(10^{-1})	(d)	One tenth
Unity	(10^{0})	--	--
kilo	(10^{3})	(k)	One thousand
mega	(10^{6})	(M)	One million
giga	(10^{9})	(G)	One thousand million

c) Old English System of Units

Britain converted to the SI system of units in 1965, but the U.S.A. still maintains the old English units. Hence,

mass - pound	lb_m
length - foot	ft
time - seconds	s

4. *Dimensions*

As was previously mentioned, dimensions are different from units

A <u>dimension</u> is a physical variable that is used to specify some characteristic of a system. Hence,

- mass,
- temperature,
- and length

are dimensions.

A unit is used to define a dimension. Hence for,

$$\begin{aligned} \text{mass} &= 10 \text{ kg} \\ &= 10 \text{ lb}_m \end{aligned}$$

the dimension is mass with units of kilograms (kg) or pounds (lb_m). And for,

$$\begin{aligned} \text{length} &= 5 \text{ m} \\ &= 20 \text{ feet} \end{aligned}$$

the dimension is length with units of meters (m) or feet (ft).

III. Conversion of Units

A. *Basic units (4)*

The basic units are:

• mass,	kg	kilogram
• time,	s	second
• length,	m	meter
• temperature,	C	Celsius
• amount of substance,	mol	mole
• electrical current,	amp	ampere

B. *Derived units*

All derived units can be expressed from basic units. Examples are:

Flow, $\frac{\text{mass}}{\text{unit time}}$,	$\frac{\text{kg}}{\text{s}}$
Volume, $(\text{length})^3$,	m^3
Volumetric flow, $\frac{\text{volume}}{\text{unit time}}$,	$\frac{\text{m}^3}{\text{s}}$
Density, $\frac{\text{mass}}{\text{volume}}$,	$\frac{\text{kg}}{\text{m}^3}$

C. *Rules for Significant Figures (5)*

1. *All non - zero digits are significant*

Example:

5.34 cm = 3 significant figures

4.293 cm = 4 significant figures

2. ***Zeros between non - zero digits are significant***

Example:

106 g = 3 significant figures

1.02 g = 3 significant figures

3. ***Zeros beyond the decimal point at the end of a number are significant***

Example:

8.00 ml = 3 significant figures

8.020 ml = 4 significant figures

4. ***Zeros proceeding the first non - zero digit are <u>not</u> significant***

Example:

0.008 g = 1 significant figure

2×10^{-3} *= 1 significant figure*

0.0204 = 3 significant figures

5. ***When multiplying or dividing, the answer will have as many significant figures as the smallest number of significant figures used for the calculation***

Example:

Concentration of Reaction Product in an Air Stream Available for Recovery

moles = 2.540 mol

volume = 375.00 ml

concentration = 2.540 mol / 375.00 ml

concentration of reaction product, moles per milliliter $= 0.00677333 \frac{\text{mol}}{\text{ml}}$

Apply rules:

concentration of reaction product $= 0.006773 \frac{\text{mol}}{\text{ml}}$

Since the numerator (2.540) has 4 significant figures and the denominator (375.00) has 5 significant figures, the answer can have only 4 significant figures.

6. ***When adding or subtracting, the number of digits beyond the decimal point in the result is the same as the least quantity of digits beyond the decimal point in the numbers being added or subtracted.***

Example:

The weight of a mixture of various chemical components in a fixed sample of a slurry that is processed to avoid pollution before it is discharged into a stream

$CaCO_3$ = *1.021 g*

$CaSO_4$ = *0.20 g*

Water = *256 g*

Total *257.221 g*

Apply rules:

Total weight = *257 g*

The least quantity of digits that can exist beyond the decimal is determined by the weight of water (256 g), hence the answer is 257 g.

7. *Exact numbers are not considered in calculations*

Example:

1 L = 1000 mL

°F = 1.8 °C + 32

$$\begin{array}{c|c} 536.05\ \text{cm}^3 & 1\ \text{L} \\ \hline & 1000\ \text{cm}^3 \end{array}$$

The answer (0.53605L) has 5 significant figures because the exact numbers (1L and 1000cm^3*) are not considered.*

D. *Calculations*

1. *Method of unit conversions*

Examples:

a) *Convert the volume of a sample of a pollutant in an air stream from 322 mL to*

a. Liters

b. cm^3

c. m^3

$$\begin{array}{c|c} 322\ \text{mL} & 1\ \text{L} \\ \hline & 1000\ \text{mL} \end{array} = 0.322\ \text{L}$$

$$\begin{array}{c|c} 322\ \text{mL} & 1\ \text{cm}^3 \\ \hline & 1\ \text{mL} \end{array} = 322\ \text{cm}^3$$

$$\begin{array}{|c|c|c|c} 322\ \cancel{\text{mL}} & 1\ \cancel{\text{cm}^3} & 1\ \cancel{\text{L}} & 1\ \text{m}^3 \\ \hline & 1\ \cancel{\text{mL}} & 1000\ \cancel{\text{cm}^3} & 1000\ \cancel{\text{L}} \end{array}$$

$= 322 \times 10^{-6}\ \text{m}^3$

$= 3.22 \times 10^{-4}\ \text{m}^3$

b). *Convert the amount of reaction product, which is from a sulfur burner, SO_2, from a concentration of 2.00 mol/L to kgmol/m^3.*

2.00 g mol	1 kg mol	1000 L
L	1000 g mol	1 m³

$= 2.00\ \text{kg}\cdot\text{mol/m}^3$

c). *Calculate the volume occupied by 25.0 g of Aluminum.*

25.0 g Al	?

= cm³ Al

To convert the grams we need the density of Al:

density, $\rho = m / v = 2.70$ g Al / cm³ Al

25.0 ~~g Al~~	1 cm³ Al
	2.70 ~~g Al~~

= 9.26 cm³ Al

d). *Convert acceleration of 1 cm / s² to Km / yr²*

$$\frac{1\ \text{cm}}{\text{s}^2}\left(\frac{60\ \text{s}}{1\ \text{min}}\right)^2\left(\frac{60\ \text{min}}{1\ \text{hr}}\right)^2\left(\frac{24\ \text{hr}}{1\ \text{d}}\right)^2\left(\frac{365\ \text{d}}{1\ \text{yr}}\right)^2\frac{1\ \text{m}}{100\ \text{cm}}\,\frac{1\ \text{Km}}{1000\ \text{m}}$$

$= 9.95 \times 10^{9}$ Km / yr² *$= 1 \times 10^{10}$ Km / yr²*

e). *Typical source emission standards for the concentration of particulates discharging from an incinerator stack flow stream are given as 0.08 grains per standard cubic feet.*

Convert this concentration to grams per liter.

0.08 grains	64.7989 mg	1 g	1 ft^3	1 m^3
ft^3	1 grain	1000 mg	0.0283168 m^3	1000 L

$$= 0.00018\ g / L$$

$$= 0.0002\ g / L$$

Problems: Convert

a. 3 weeks to milliseconds

b. 26 miles / hr to ft / s

c. 26.7 $cm^4 / min^2 \cdot g$ to $m^4 / d^2 \cdot Kg$

d. 340 miles / s to Km / hr

e. 57.5 lb_m / ft^3 to g / cm^3

f. 120 horsepower (HP) to KJ / min

g. 10 light-years to miles

h. 5 mols / L to $lb_m \cdot mols / ft^3$

(Speed of light = 186,000 miles/s)

IV. Concepts for Correlation and Dimensional Analysis

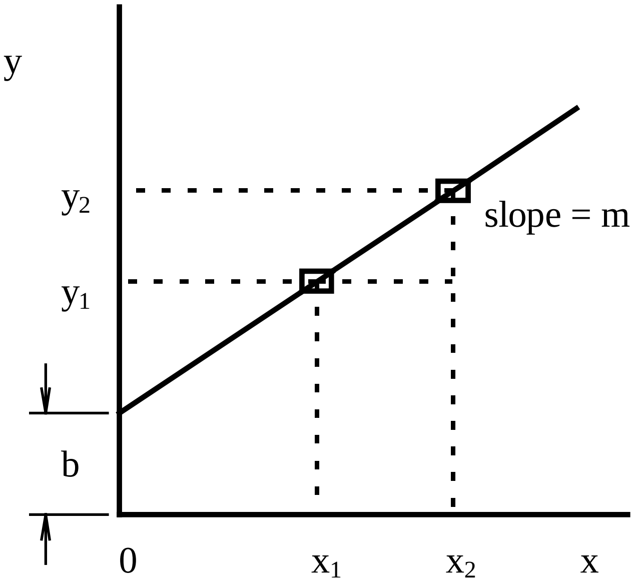
A. *Various types of mathematical correlations*

1. *Linear graphs*

For a linear equation of the form y = mx +b,

m = slope
b = intercept .

Hence, on arithmetic or rectangular coordinate graph paper, the ordinate would be y and the abscissa would be x. The slope, m, and the y-intercept, b, could be calculated by taking two points on the line.



$$\text{slope} = \text{m} = \frac{y_2 - y_1}{x_2 - x_1}$$

intercept = b , when x = 0

$$y = mx + b$$

$$b = y - mx$$

$$b = y_1 - mx_1 \quad \text{or} \quad b = y_2 - mx_2$$

2. *Semi-logarithmic graphs*

A semilogarithmic relationship involves the mathematical constant, e, which is the natural base of logarithms. The value of e is 2.71828.

The equation $y = be^{-mx}$

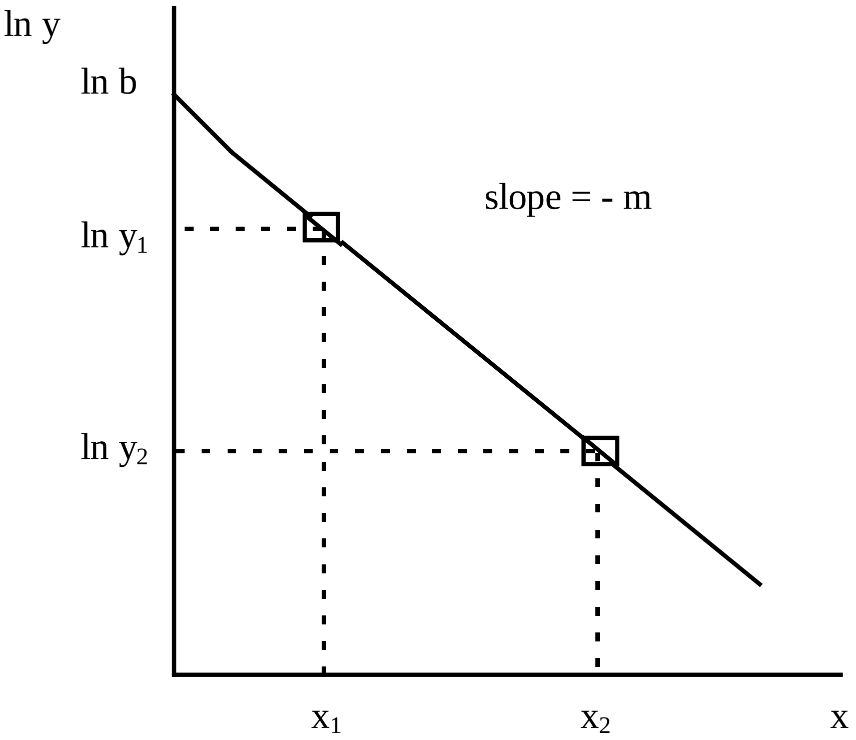
can be linearized as

$$\ln y = \ln b - mx \ln e$$

where, b = constant and -m = slope

$$\ln e = 1$$
$$\ln y = \ln b - mx$$

The ln *y* can be plotted versus *x* on arithmetic or rectangular coordinates. An alternate is to graph the actual value of *y* versus *x* on semilogarithmic graph paper.



$$\text{slope} = -\text{m} = \frac{\ln y_1 - \ln\, y_2}{x_1 - x_2} = \frac{\ln \frac{y_1}{y_2}}{x_1 - x_2}$$

intercept = ln *b* , when *x* = 0

$$\ln b = \ln y_1 + m x_1 = z$$
$$b = e^z \ = \ \text{constant}$$

3. *Logarithmic graphs*

The equation $y = bx^m$

where

b = constant

m = constant

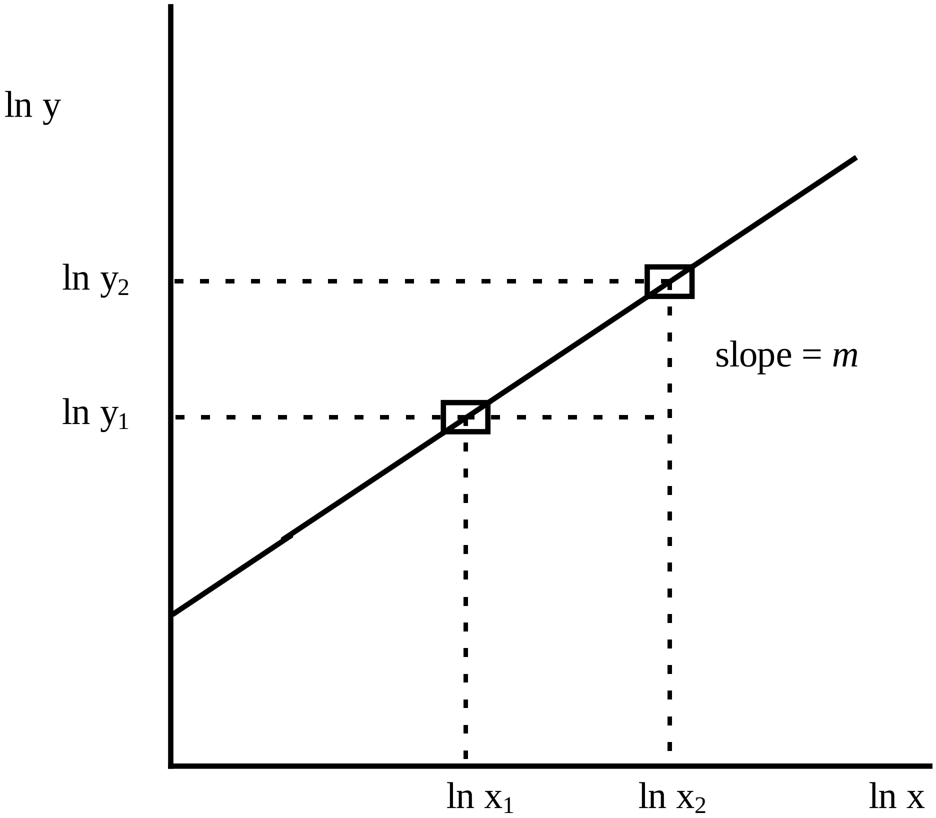
can be linearized to give

$$\ln y = \ln b + m \ln x$$

where $\ln\, b = \text{intercept}$

m = slope

The ln y can be plotted versus the ln x on arithmetic or rectangular coordinates or the alternative of using logarithmic graph paper and plotting the actual values of y and x can be used.



$$\text{slope} = \text{m} = \frac{\ln\ y_2 - \ln\ y_1}{\ln\ x_2 - \ln\ x_1} = \frac{\ln\frac{y_2}{y_1}}{\ln\frac{x_2}{x_1}}$$

intercept = ln b

$$\ln b = \ln y_2 - m \ln x_2 = z$$

$$b = e^z$$

b = constant

4. *Linearization*

a) ***The equation*** $y = mx^{\frac{1}{2}} + b$ can be linearized by letting

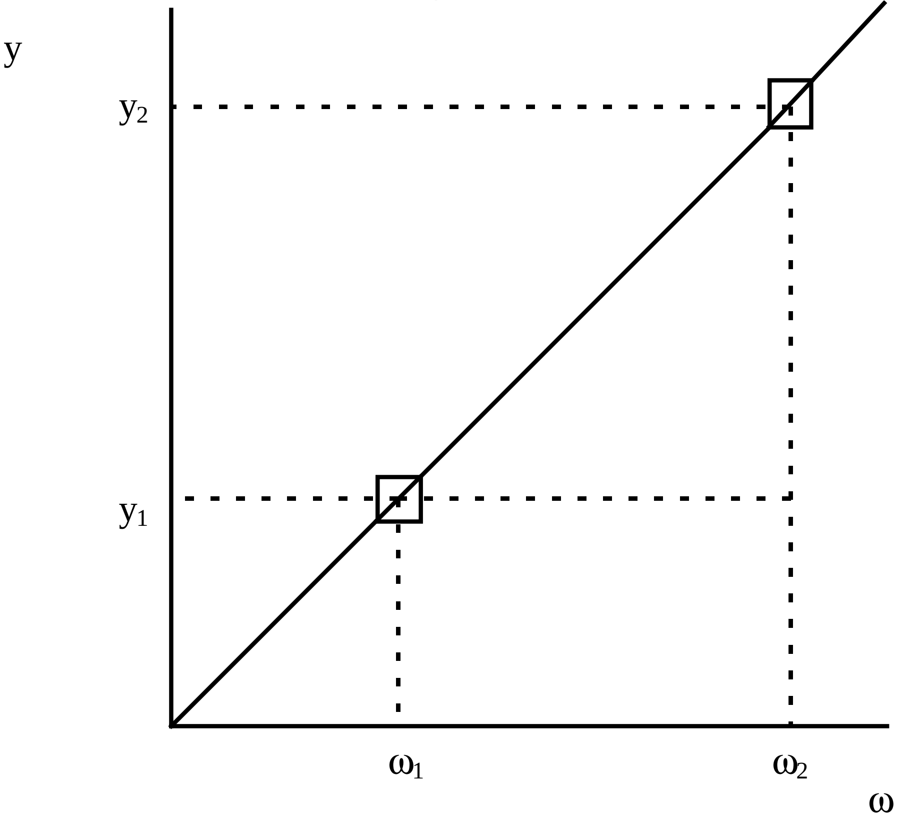
$$\omega = \mathrm{x}^{\frac{1}{2}}$$

where $y = m\omega + b$

Values of y and x

Y	x	$x^{1/2}$	ω
0	0	0	0
1	1	1	1
2	4	2	2
3	9	3	3

On arithmetic or rectangular coordinates



$$\text{slope} = \mathrm{m} = \frac{y_2 - y_1}{\omega_2 - \omega_1}$$

intercept = b

$$\mathrm{b} = y_1 - \mathrm{m}\omega_1 \quad \text{or} \quad \mathrm{b} = y_2 - \mathrm{m}\omega_2$$

$$y = \mathrm{m}x^{\frac{1}{2}} + \mathrm{b}$$

b) **The equation** $\left(y^2-1\right)=be^{m(x-2)}$

can be linearized by letting

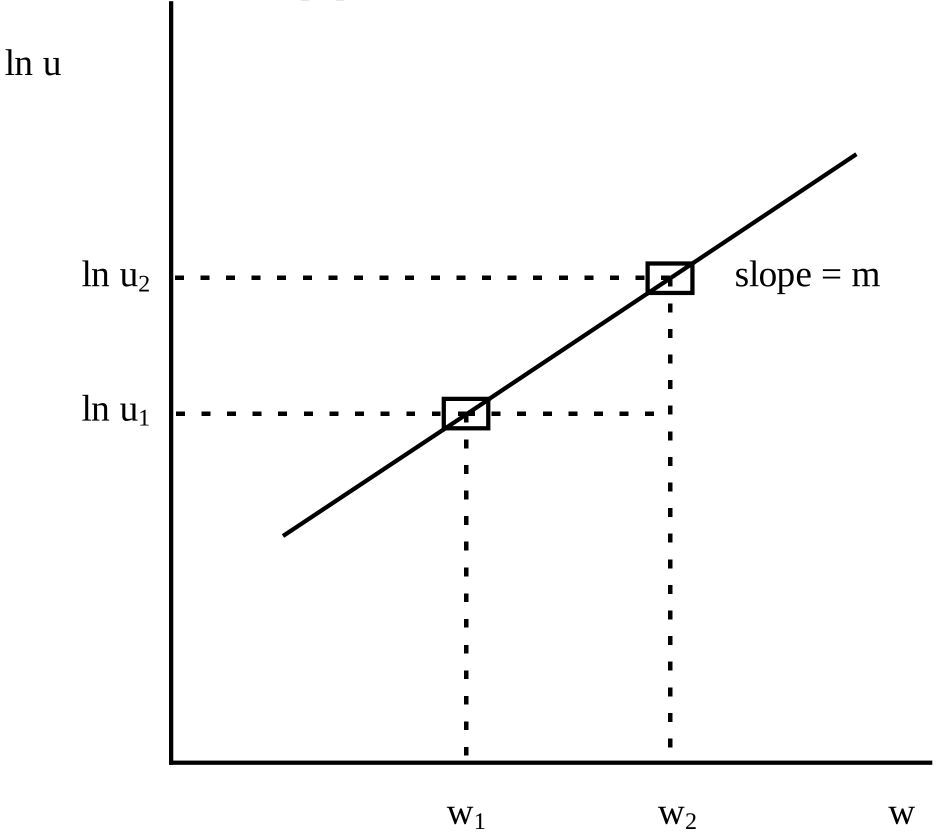
$$u = y^2 - 1$$

and $w = x - 2$

and $u = be^{mw}$

$$\ln u = \ln b + mw \ln e$$
$$\ln e = 1$$
$$\ln u = \ln b + mw$$

Plot a graph of ln *u* versus *w* on rectangular graph paper, or *u* versus *w* on semilogarithmic graph paper.



$$\text{slope} = \text{m} = \frac{\ln\ u_2 - \ln\ u_1}{w_2 - w_1} = \frac{\ln\frac{u_2}{u_1}}{w_2 - w_1}$$

intercept = ln *b*

$$\ln b = \ln u_2 - m w_2 = z \quad \text{or}$$
$$\ln b = \ln u_1 - m w_1 = z$$
$$b = e^z$$
$$u = b e^{mw}$$

Knowing b and m,

$$\left(y^2 - 1\right) = b e^{m(x-2)}$$
$$y^2 = 1 + b e^{m(x-2)}$$
$$y = \sqrt{1 + b e^{m(x-2)}}$$

In all cases, the process of linearization of the mathematical function followed by determination of the slope and the intercept is the key to solving the problem.

5. *The relationship between* $\log_e x$ *and* $\log_{10} x$.

The natural logarithm is to the base e. However the logarithm to the base 10 is often used. The general relationship is:

$$(\log_b x)(\log_a b) = \log_a x$$

where a and b are the bases of the logarithms. If a = e and b = 10 then the equation becomes

$$(\log_{10} x)(\log_e 10) = \log_e x$$

and the value of $\log_e 10$ is 2.30259. Hence,

$$(\log_{10} x)(2.30259) = \log_e x$$

or $\log_{10} x = (0.43429) \log_e x$

or $\log_e x = (2.30259) \log_{10} x$

The $\log_e x$ is often written as $\ln x$. The quantities are therefore interchangeable. Thus, for the equation

$$y = be^{mx}$$

taking the natural logarithm of both sides gives

$$\log_e y = \log_e b + mx \log_e e$$

since $\log_e e = 1.0$,

$$\log_e y = \log_e b + mx$$

or $$\ln y = \ln b + mx$$

alternatively, $$\log_{10} y = \log_{10} b + mx \log_{10} e$$

and by substituting equivalent quantities

$$0.43429 \log_e y = 0.43429 \log_e b + mx(0.43429) \log_e e$$

$$0.43429 \log_e y = 0.43429 \log_e b + 0.43429 mx(1)$$

$$\log_e y = \log_e b + mx$$

or $$\ln y = \ln b + mx$$

and the two bases can be used interchangeably.

B. *Dimensional Analysis*

1. ***Dimensionless groups or, more appropriately, unitless groups are used frequently in chemical engineering correlations. They are numbers which result in generalized correlations that can be used more extensively to cover many situations. Dimensionless groups are a multiplicative combination of variables that result in unitless quantities.***

Example:

REYNOLDS NUMBER, N_{RE}

$$N_{Re} = \frac{D\nu\rho}{\mu}$$

where *D = diameter of pipe, m.*

ν *= velocity of fluid in pipe, m / s.*

p = density of fluid, Kg / m^3.

and μ *= fluid viscosity, Kg / m·s.*

$$N_{Re} = \frac{D\nu\rho}{\mu} =$$

M	*m*	*Kg*	*m-s*
	s	*M^3*	*Kg*

= dimenionless (unitless)

Example:

NUSSELT NUMBER, N_{NU}

$$N_{Nu} = \frac{h\,D}{k}$$

where h *= heat transfer coefficient, J / s·m^2·°C.*

D = diameter of pipe, m

k *= fluid thermal conductivity, J / (s·m^2·°C/m)*

or J / s·m·°C

$$N_{Nu} = \frac{h\,D}{k} =$$

J	*M*	*s· ·m· °C*
s· ·m· °C		*J*

= dimensionless (unitless)

Example:

PRANDTL NUMBER, N_{PR}

$$N_{Pr} = \frac{c_p \mu}{k} =$$

where c_p *= fluid heat capacity, J / Kg·°C.*

U = fluid viscosity, Kg / m·s.

k = *fluid thermal conductivity, J / m·s·°C.*

$$N_{Pr} = \frac{c_p \mu}{k} =$$

J	*Kg*	*s· ·m· °C*
Kg°C	*m s*	*J*

= dimensionless (unitless)

2. ***Dimensionless (unitless) groups can be correlated to give a generalized correlation.***

$$N_{Nu} = a\, N_{Re}^{m}\, N_{Pr}^{n}$$

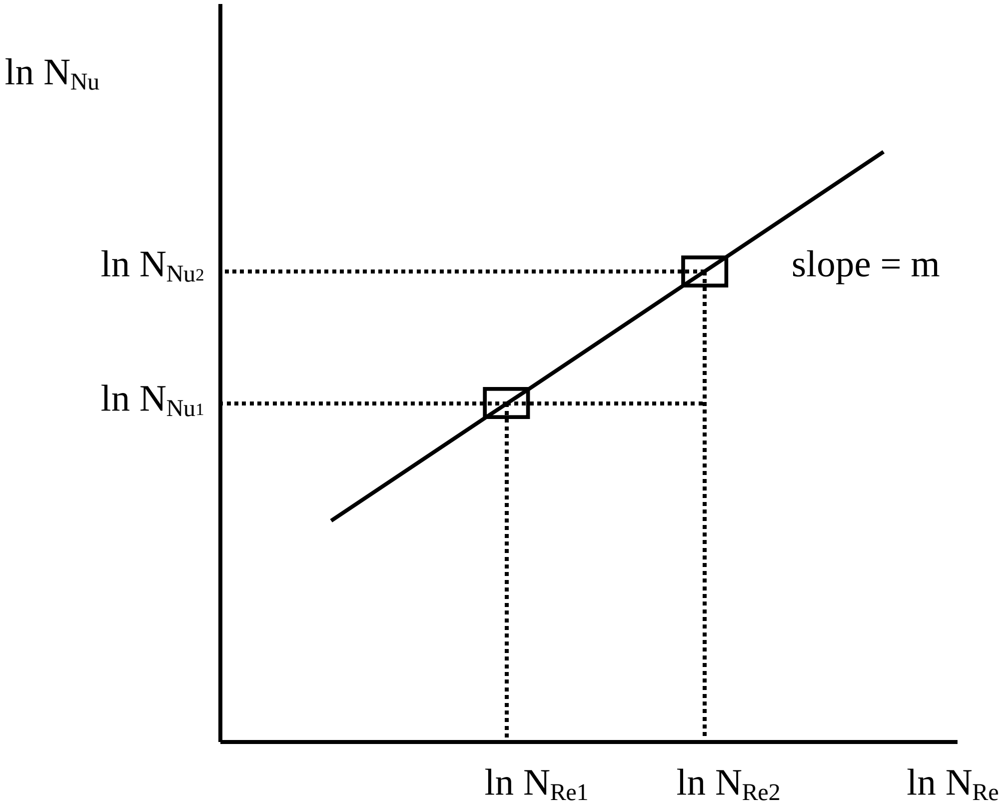
Assume N_{Pr}^{n} = constant

$$N_{Nu} = b\, N_{Re}^{m} \;, \quad \text{where } b = a\, N_{Pr}^{n}$$

Linearizing yields

$$\ln N_{Nu} = \ln b + m \ln N_{Re}$$

A graph of the ln(N_{Nu}) versus ln(N_{Re}) on arithmetic or rectangular graph paper or on logarithmic graph paper using N_{Nu} and N_{Re} directly gives a straight line with slope m.



$$\text{slope} = m = \frac{\ln N_{Nu_2} - \ln N_{Nu_1}}{\ln N_{Re_2} - \ln N_{Re_1}} = \frac{\ln \dfrac{N_{Nu_2}}{N_{Nu_1}}}{\ln \dfrac{N_{Re_2}}{N_{Re_1}}}$$

intercept = b

$$\ln b = \ln N_{Nu_1} - m \ln N_{Re_1} = z \quad \text{or}$$

$$\ln b = \ln N_{Nu_2} - m \ln N_{Re_2} = z$$

$$b = e^z = a\, N_{Pr}^n$$

C. *Homework Problems*

1. ***In a certain process, a process waste stream containing recoverable product exists and must be treated prior to disposal. The following data are collected.***

Rotameter Reading, R	Collection Time, min	Volume Collected, cm^3
1	1	300.4
3	1	489.2
5	0.6	406.8
7	0.6	520.1
9	0.4	422.2
10	0.4	460.0

Prepare a calibration graph in the form

$$Q\left(\frac{\text{cm}^3}{\text{min}}\right) = mR + b$$

Answers: $m = 94.4 \dfrac{\text{cm}^3}{\text{min} \cdot \text{reading}}$ $b = 206 \dfrac{\text{cm}^3}{\text{min}}$

2. ***In a certain chemical process an air pollutant can be transformed into a valuable product by a reaction at a high temperature. The specific rate at which the reaction proceeds is given by the equation***

$$k = k_o e^{-E/RT}$$

where
k = sec^{-1}
k_o = sec^{-1}
E = cal / mol
R = gas constant, 1.987 cal / mol
T = Temperature , K

The following experimental data are obtained

k, sec^{-1}	T, °K
0.1	400
2.91×10^4	600
1.57×10^7	800
6.848×10^8	1000

Calculate the value of k_o and E

Answer: E = 30,000 cal / mol

$k_o = 2.4694 \times 10^{15}\ \text{sec}^{-1}$

3. ***Calculate the Reynolds number in a pipe that transfers waste water from one process unit to another which produces a valuable co-product from potential pollutants, if***

D = 2.067 inches

$\nu = 4.57$ m / sec

$\rho = 800$ Kg / m^3

$\mu = 4.46 \times 10^{-3}$ Kg / m·sec

$$N_{Re} = \frac{D \nu \rho}{\mu}$$

Answer: $N_{Re} = 43{,}037$

4. ***Calculate the Prandlt Number of a stream at the front end of a process which feeds a reactor designed to improve yield and thus reduce potential pollutants.***

$$N_{Pr} = \frac{c_p\ \mu}{k}$$

$c_p = 0.50$ BTU / lb$_m$·°F

$\mu = 12.23$ lb$_m$ / ft·hr

$k = 0.083$ BTU / (hr·ft^2·°F/ft)

Answer: 73.7

5. ***Air containing a toxic pollutant must be cooled in a heat exchanger prior to feeding the gas mixture to a gas***

absorption column to recover the air pollutant. The air can then safely be discharged into the atmosphere. It is known that the heat transfer coefficient is 62.2 watts / m²·°K and the tube diameter of the heat exchanger is 25.4 mm. The thermal conductivity of the gas mixture is 0.03894 watts / m·°K.

Calculate the Nusselt number

$$N_{Nu} = \frac{h\,D}{k}$$

Answer : 40.6

6. ***A wastewater stream has been treated for recovery of co-products. The hot stream, however, must be cooled prior to discharge to prevent any thermal pollution problems. A heat exchanger is used for this purpose. Data collected on the heat exchanger which has turbulent flow conditions (N_{Re}> 10000) indicate that the Dittus-Boelter equation can be used :***

$$N_{Nu} = a\,N_{Re}^{b}\,N_{Pr}^{c}$$

Where N_{Nu} = Nusselt Number
N_{Re} = Reynolds Number
N_{Pr} = Prandtl Number
and *a*, *b*, and *c* = constants

Measurements are taken on a system and it is found that N_{Pr} is constant and equal to 2.72 and *c* = 0.333. The following data are obtained:

N_{Nu}	N_{Re}
50.58	10000
88.59	20000
154.25	40000
213.36	60000
268.57	80000
321.6	100000

Find the values of a and b

Answer : $a = 0.023$
$b = 0.800$

V. Collection and Analysis of Experimental Data

The fundamental basis for any good investigation and reporting the results is data collection and record keeping (6). A good laboratory notebook serves as the basis for a good report. Often times, a considerable amount of time elapses between the data collection phase of a study and the eventual presentation of results. It is very important, therefore, that data be collected accurately, be well defined, and recorded in a permanent, bound laboratory notebook (6). The laboratory notebook must contain the following:

- Date
- Title of experiment
- Data

and at the conclusion of the day's effort, each page should be signed, witnessed and dated because, often times, the laboratory notebook serves as the legal evidence in patent litigation. In today's society, with pollution an ever present consciousness in people' minds, good notebooks are very important. The very important factors for pollution prevention efforts must be well documented.

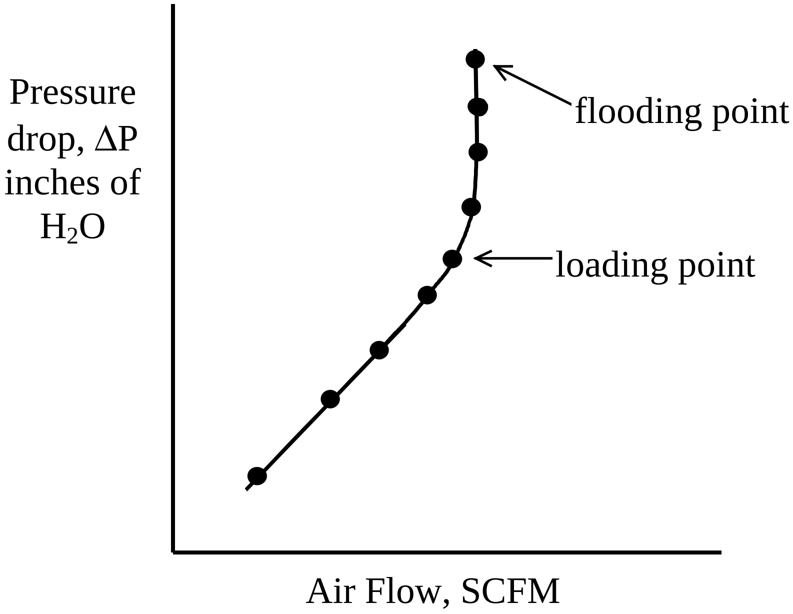
Some very useful factors in data collection are:

A. *Data Collection and Recording*

1. ***Where possible plot all results as the experiment progresses. A picture can define the conditions of future runs.***

Example:

PRESSURE DROP IN PACKING



Data can be collected evenly, however the important loading point and flooding point <u>must</u> not be lost because the air flow settings were not properly chosen.

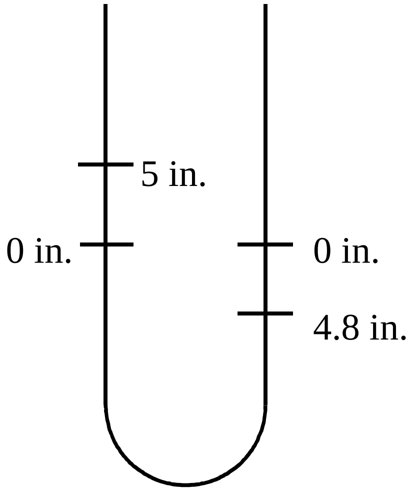
2. ***An important requirement is that the notebook, "should be so clear and complete that any intelligent person familiar with the field to which it relates but unfamiliar with the specific investigation could, from the notebook alone, write a satisfactory report on the experimental work" (6).***

3. ***Always indicate units of quantities that are measured.***

4. ***Always record chart reading or the readings that you actually measure.***

Example:

MANOMETER



L	R	ΔP
+5 in.	-4.8 in.	9.8 in.

record left and right readings, not only the derived quantity ΔP = 9.8 in.

5. ***Charts from recorders should be put into laboratory notebook. Label chart with***

   a) ***Title***
   b) ***Date***
   c) ***Exact significance of experiment***

Example:

UNSTEADY STATE HEAT TRANSFER

September 26, 1977

Heating and cooling curve for plastic cylinder

6. ***Sketches of experimental apparatus should be part of notebook. All important dimensions should be recorded.***

7. ***If procedure and apparatus are detailed in a publication it is not necessary to recopy. Simply refer to publication. However, define all differences.***

8. ***Never record a calculation, dimension or note on a loose sheet of paper.***

9. ***Notebooks become legal evidence in patent cases. Therefore, always date, sign and witness.***

   Example:

   Experiment 1. *Sept. 27, 1994*

   FLUID FLOW THROUGH
   PIPES AND FITTINGS

   Signed _______________9/27/94
   ________________9/27/94
   ________________9/27/94
   Witness ______________9/27/94

10. ***Notebooks should be neat. All data entries recorded in logical manner. Do not crowd. In general ink is used because penciled data can be erased. Do not erase. Simply draw a single line through bad data.***

11. *Use proper symbols for units*

Use	Not
inch	"
ft	'
pound or lb_m	#
percent	% in tables
dx/dy	'
d^2x/dy^2	"

B. *Tables in a Report or Laboratory Notebook*

Each table should be numbered, have a title and show all units.

Example:

Table 1.

PRESSURE DROP IN PACKED TOWER

Column diameter, 6 inches
Packed height, 5ft
Tower packing, 1/2 inch Berl Saddles

Flow Rate of Water, lbs/ft^2 hr	Flow Rate of Air, lbs/ft^2 hr	Pressure Drop, Inches of water per foot of packing	Column Holdup, Lbs of water per foot of packing
1000	100	5	0.5
1000	300	10	1.0
1000	700	15	1.5
2000	100	15	2.0
2000	300	20	2.5
2000	700	25	3.0

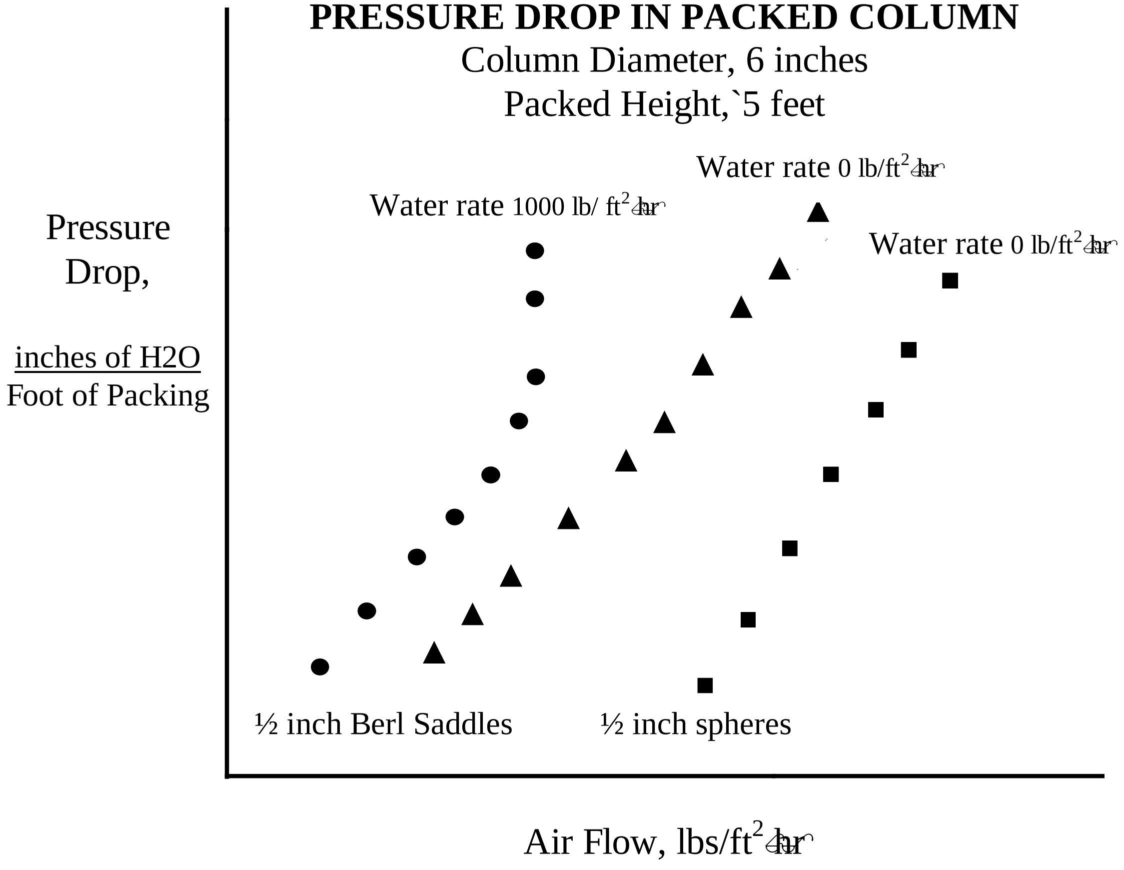
C. *Graphs in a Report or Laboratory Notebook*

All graphs should have a Figure number, have clearly labeled coordinates and all parameters labeled.
Label symbols should be used for different parameters.

● ■ ▲ ▼ ⬢ ◆

Example:

Figure 1



D. ***Use of Calculators and Computers***

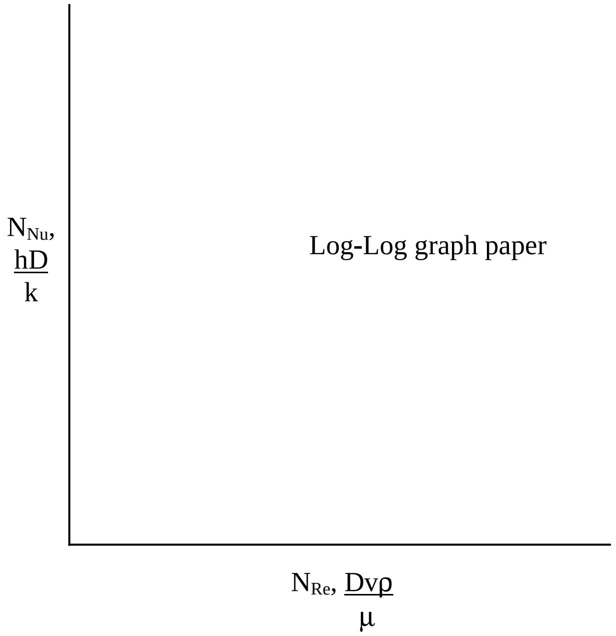
1. ***TR-20 analog computer (obsolete)***
2. ***TR-48 analog computer (obsolete)***
3. ***Pocket Calculators***
4. ***Digital Computers (main frames)***
5. ***Personal Computers (most current)***

E. *Data Analysis*

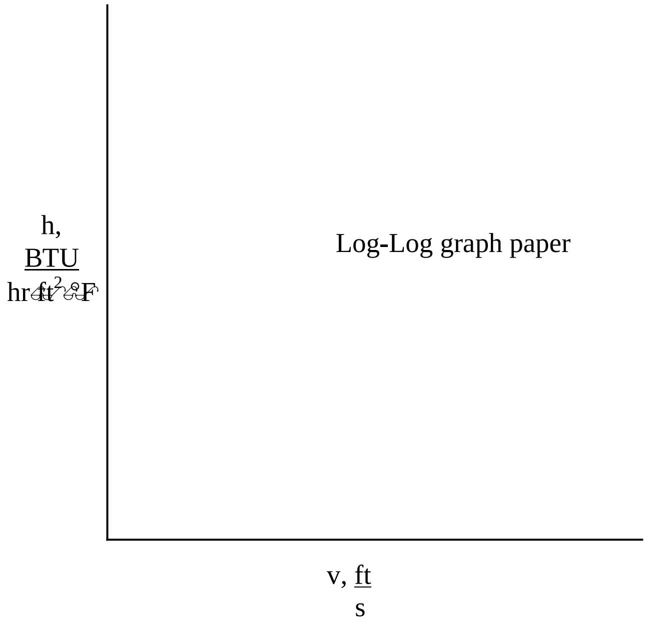
1. *Know what to correlate*

Example:

In Chemical Engineering we use dimensionless numbers. Thus:



is better than



In addition, $\frac{\text{lb}}{\text{ft}^2 \cdot \text{hr}}$ *is better than* $\frac{\text{lb}}{\text{hr}}$

ΔP in $\frac{\text{inches of H}_2\text{O}}{\text{feet of packing}}$ *is better than ΔP, inches of H_2O*

Always attempt to recalculate the measurements into meaningful quantities.

F. *Error Analysis of Experimental Data (4, 6, 7, 8, 9, 10, 11)*

All measurements are subject to errors. Hence, it is very important that following the measurement of data and the development of derived quantities from the data for presentation in a report, a careful statistical analysis be made of the measured results.

Some important points to consider in measuring data are:

1. *Even if you are careful, inaccuracies can occur*

There are:

1. Mistakes
2. Errors

A mistake is the recording of a wrong reading (236 recorded as 263 lbs.)

An error is of two forms:

1. consistent
2. random

A consistent error is a defect in the measuring device or the improper use of an instrument, for example, the use of a burette calibrated for 20°C but used at 30°C

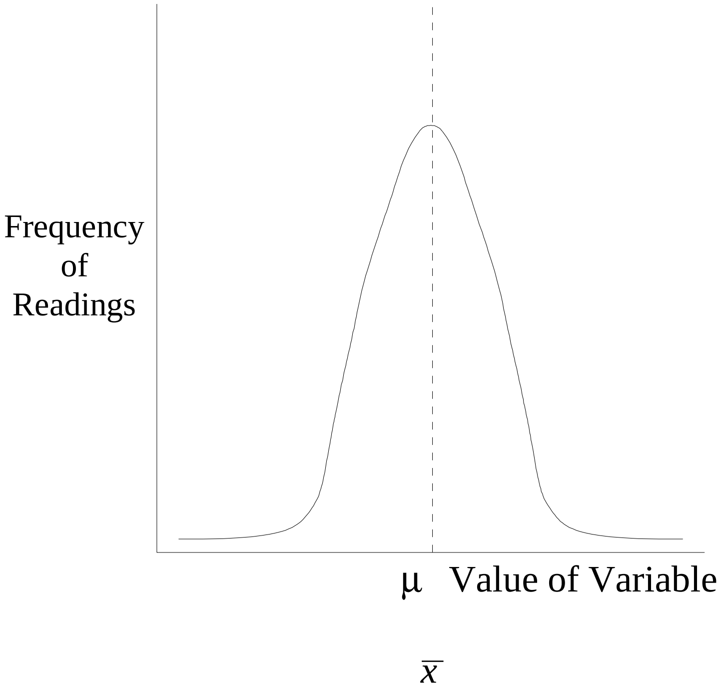
A wrong scale is an incorrect reading of a wet test meter. One can usually remedy consistent error by correction or a calibration.

Random errors are caused by fluctuations and sensitivity of the instrument or the poor judgment of the experimenter. An example would be a fluctuating rotameter.

2. *Associated with random error is the most probable value*

The more readings you take the more likely the average will be the most probable value. The analysis begins with the normal distribution curve or, as it is commonly called, the bell-shaped curve.

Normal distribution curve



Definitions

μ = true mean of a distribution (infinite number of determinations or very large number of determinations)

$\bar{x}$ = estimated mean for a finite sample size.

σ^2= true variance of a distribution (infinite number of determinations or a very large number of determinations)

s^2= variance as estimated from the spread of observations of a finite sample.

3. *Mean, $\overline{\mathrm{X}}$ and μ*

Let each reading = x

$x_1, x_2, x_3, \ldots x_N$

$$\sum_{i=1}^{N} x_i = x_1 + x_2 + x_3 + \ldots x_N$$

N= *i* = number of readings

$$\bar{x} = \frac{\sum_{i=1}^{N} x_i}{N}$$

$\overline{\mathrm{X}}$ is the estimate of μ for a small, finite number of measurements.

$$\mu = \frac{\sum_{i=1}^{N} x_i}{N}$$

when N = ∞ or is a very large number of measurements.

4. *True Variance, σ^2*

$$\sigma^2 = \frac{\sum_{i=1}^{N} (x_i - \mu)^2}{N}$$

when the true population mean, μ, is known

Standard deviation = $\sqrt{\sigma^2} = \sigma$

For an infinite number of determinations or a very large number of determinations, we can calculate σ, when μ is known.

5. *Estimate of the Sample Variance, s^2*

$$s^2 = \frac{\sum\left(x_i - \overline{x}\right)^2}{N-1}$$

$s = \sqrt{s^2} =$ estimate or sample standard deviation

$$s^2 = \frac{\sum_{i=1}^{N} x_i^2 - \frac{\left(\sum x_i\right)^2}{N}}{N-1}$$

$$s^2 = \frac{\sum_{i=1}^{N} x_i^2 - N\overline{x}^2}{N-1}$$

$N-1=$ degrees of freedom

s = standard deviation for a small, finite sample size

Example:

Five readings are taken for the weight of a given sample of wastewater to be analyzed for a stream pollutant and eventual pollution prevention studies to eliminate the stream pollutant.

Reading	Value of X, grams
1	102.36
2	102.31
3	102.40
4	102.51
5	102.29

Solution:

N = 5

N - 1 = 4

$$\bar{x} = \frac{\sum_{i=1}^{N} x_i}{N}$$

$$\bar{x} = \frac{\sum_{i=1}^{N} x_i}{N} = \frac{\sum_{i=1}^{5} x_i}{5}$$

$$\bar{x} = \frac{511.87}{5} = 102.374 \text{ grams}$$

$$s^2 = \frac{\sum_{i=1}^{N} x_i^2 - N\bar{x}^2}{N-1}$$

$$s^2 = \frac{52402.21 - 5(102.374)^2}{4}$$

$$s^2 = \frac{52402.21 - 52402.179}{4}$$

$$s^2 = 0.00775$$

$$s = 0.0880$$

6. *Confidence Interval*

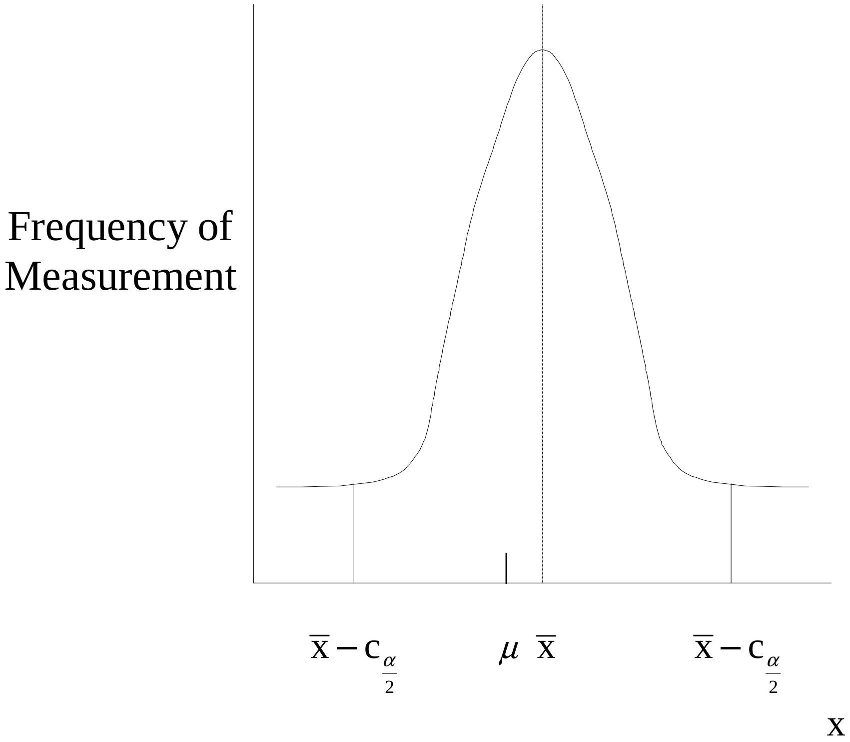
The confidence level, (1- α) is defined as the probability that a random variable ($\bar{x}$) (measured mean for a finite or small sample size) lies between a certain confidence interval.

This confidence interval will contain the true population mean, μ, for an infinite or large sample size. Hence, on the normal distribution curve, the estimated mean for a small, finite sample size is $\bar{x}$. The lower confidence interval is

$$x - c_{\frac{\alpha}{2}}$$

and the upper confidence interval is

$$x + c_{\frac{\alpha}{2}}$$



These results can be calculated by

$$x - c_{\frac{\alpha}{2}} = \bar{x} - \frac{t_{1-\frac{\alpha}{2}} s}{\sqrt{N}}$$

and $$x + c_{\frac{\alpha}{2}} = \bar{x} + \frac{t_{1-\frac{\alpha}{2}} s}{\sqrt{N}}$$

where α = level of significance

t = distribution used for small, finite sample size. Tables are available giving
values of t for various values of α (level of significance) and N-1 (degrees of freedom) and is known as Student's t (9).

s = standard deviation for a small, finite sample size

N = sample size

Therefore,

$$\bar{x} + c_{\frac{\alpha}{2}} = \bar{x} + \frac{t_{1-\frac{\alpha}{2}} s}{\sqrt{N}}$$

and

$$\bar{x} - c_{\frac{\alpha}{2}} = \bar{x} - \frac{t_{1-\frac{\alpha}{2}} s}{\sqrt{N}}$$

Example:

$\bar{x}$ *= 102.374 grams*

s = 0.0880

N = 5

N - 1 = 4 = degrees of freedom

The confidence intervals are

$$\bar{x} - \frac{t_{1-\frac{\alpha}{2}} s}{\sqrt{N}} \qquad \textit{and} \qquad \bar{x} + \frac{t_{1-\frac{\alpha}{2}} s}{\sqrt{N}}$$

A 95% confidence interval means that α *= 0.05. This value of* α *is chosen by the experimenter and is an indication of the confidence level one desires. It can be 95%, 99% or greater. Obviously, the greater the value of* α *the greater your confidence, but also the greater the value of* $\bar{x} \pm c_{\frac{\alpha}{2}}$ *and hence, the range.*

Hence, in this example, suppose we pick α *= 0.05 and we thus wish to define a range on the mean* $\bar{x}$ *such that the true mean value,* μ *(for a large number of measurements which are often not practical), will be contained somewhere within the range.*

Thus, for α *= 0.05,*

$t_{1-\frac{0.05}{2}} = t_{0.975} =$ *2.776 from Student's table of t values (9).*

Therefore,

$$102.374 - \frac{(2.776)(0.0880)}{\sqrt{5}} = 102.265$$

$$102.374 + \frac{(2.776)(0.0880)}{\sqrt{5}} = 102.483$$

Therefore, for α *= 0.05, 1 -* α *= 1 - 0.05 = 0.95. We have a 95 percent confidence that the true population mean,* μ *which is estimated by* $\bar{x}$ *will be in the interval* $\bar{x} - c_{\frac{\alpha}{2}}$ *and* $\bar{x} + c_{\frac{\alpha}{2}}$*,*

To estimate the value of $c_{\frac{\alpha}{2}}$*, Student's, t, statistic is used, "Student" was the pen name of W. S. Gosset who developed the t test in 1908. Thus,*

$$\bar{x} + c_{\frac{\alpha}{2}} = \bar{x} + \frac{t_{1-\frac{\alpha}{2}}\, s}{\sqrt{N}} \quad \textit{and} \quad \bar{x} - c_{\frac{\alpha}{2}} = \bar{x} - \frac{t_{1-\frac{\alpha}{2}}\, s}{\sqrt{N}}$$

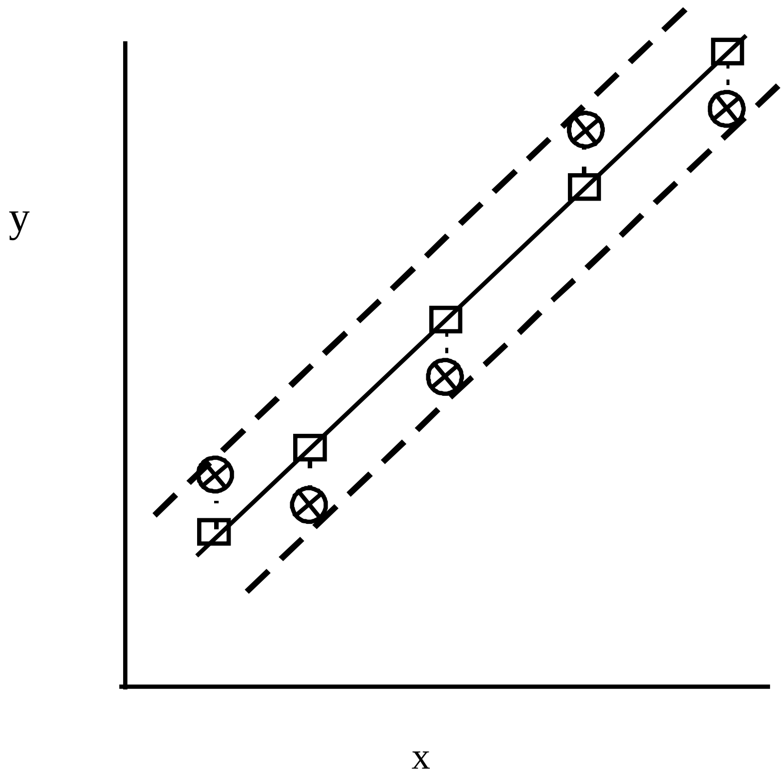
Hence, $102.265 \le \bar{x} \le 102.483$

and, we are 95 percent confident that the true population mean, μ *lies between 102.265 and 102.483 and* $\overline{x} = 102.374$ *is an estimate of the true mean.*

7. *Regression Analysis*

Regression analysis is used to determine the constants in a relationship between variables. It can be simple regression analysis of y versus x, multivariable regression analysis of y versus x_1, x_2, x_3, . . . x_n or curvilinear regression analysis using any mathematical equation which is desired to curve fit the measured data. We will consider only the simplest case or the method of least squares (10). In this simple case, y is only a function of x and the relationship is linear.

a) Method of Least Squares



In this case,

$$y = mx + b \text{ is linear}$$

and there exists a best line such that the sum of the deviations of the measured values (y_i) from the calculated values (y_{calc}) is minimized. Hence,

point ⊗ = y_i for each x_i , the measured values

point = y_{calc} for each x_i , the best value of y_i for each x_i

Therefore, $y_{calc} = m x_i + b$, and

the deviation = $y_i - y_{calc}$.

Define the error, E, as

$$\mathrm{E} = \sum_{i=1}^{N} \left[y_i - y_{calc} \right]^2$$

$$\mathrm{E} = \sum_{i=1}^{N} \left[y_i - \left(m x_i + b \right) \right]^2$$

Determine: the slope, m, and the intercept, b, that minimizes E, the sum of the squares of the deviations. Squares are used to change negative deviations to positive numbers.

Therefore, it is desired that

$$\frac{\partial \mathrm{E}}{\partial \mathrm{y}_i} = 0$$

and $$\frac{\partial \mathrm{E}}{\partial \mathrm{x}_i} = 0$$

For y = mx + b, a linear equation, taking the partial derivatives and solving for the two unknowns, m and b, the slope and intercept, respectively, can be determined.

Working equations have been developed and are presented (10) to facilitate the estimation of m and b.

Hence, we can calculate various defined quantities, S, which represent mean values of x_i, y_i, or their squares x_i^2, y_i^2 or their cross product $x_i y_i$.

Hence,

Calculate:

$$S_x = \frac{1}{N} \sum_{i=1}^{N} x_i$$

$$S_y = \frac{1}{N} \sum_{i=1}^{N} y_i$$

$$S_{xx} = \frac{1}{N}\sum_{i=1}^{N} x_i^2$$
$$S_{yy} = \frac{1}{N}\sum_{i=1}^{N} y_i^2$$
$$S_{xy} = \frac{1}{N}\sum_{i=1}^{N} x_i y_i$$

Thus,

$$m = \frac{S_{xy} - S_x S_y}{S_{xx} - \left(S_x\right)^2}$$
$$b = \frac{S_{xx} S_y - S_{xy} S_x}{S_{xx} - \left(S_x\right)^2}$$

If the line passes through the origin, (if x=0, y=0), then

y = mx

and $m = \frac{S_{xy}}{S_{xx}}$

b) **The method may be extended to curve fit various equations by computer**

1. $y = a + bx + cx^2$
   parabolic fit
2. $y = a + bx + cx^2 + dx^3 \ldots$
   power law series

c) **There exist many software programs that curve fit**

8. *Calculate the Correlation Coefficient*

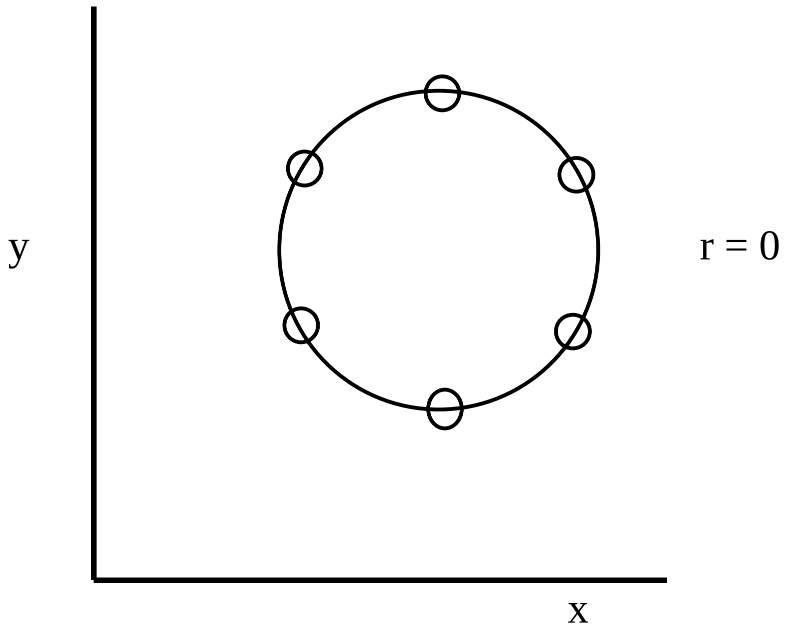
The correlation coefficient, r, is defined as a quantitative measure of the relationship between variables. In the simple case of a linear analysis,

$$y = mx + b$$

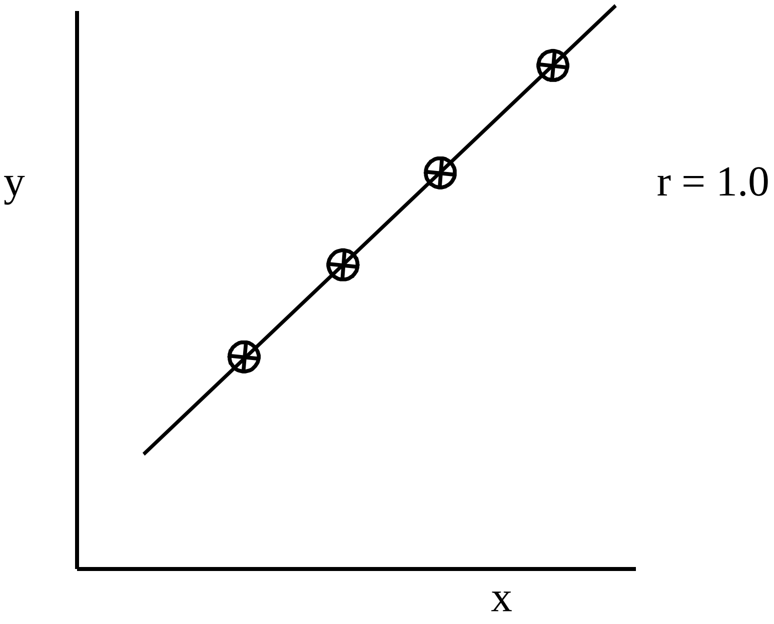
it is often desired to know how the measured values of y relate to the independent variable, x. The question often arises in investigators' minds,

> 'For the correlation between y and x by either least square analysis or curve fitting. How good is the fit?'

Thus, if y is measured for a given value of x and the data form a <u>perfect</u> circle (no correlation at all), r = 0.



On the other hand, for the linear relationship, if y versus x gives a <u>perfect</u> straight line, r = 1.0.



Hence, the correlation coefficient, r, is a quantitative measure of the data fit for the linear relationship.

This correlation coefficient, r, will have a value of

$$0 \le r \le 1.0$$

When r = 0, a perfect circle results and there is no correlation

When r = 1 a perfect fit results and there is a good correlation.

For y = mx + b,

$$r = \frac{N\sum x_i y_i - \left(\sum x_i\right)\left(\sum y_i\right)}{\sqrt{N\sum y_i^2 - \left(\sum y_i\right)^2}\sqrt{N\sum x_i^2 - \left(\sum x_i\right)^2}}$$

$$r = \frac{\frac{\sum x_i y_i}{N} - \frac{\sum x_i}{N}\frac{\sum y_i}{N}}{\sqrt{\frac{\sum y_i^2}{N} - \left(\frac{\sum y_i}{N}\right)^2}\sqrt{\frac{\sum x_i^2}{N} - \left(\frac{\sum x_i}{N}\right)^2}}$$

$$r = \frac{S_{xy} - S_x\,S_y}{\sqrt{S_{yy} - \left(S_y\right)^2}\,\sqrt{S_{xx} - \left(S_x\right)^2}}$$

Example

A rotameter has been installed in a chemical process which is part of a system to reduce the quantity of a potential pollutant in the front end of the process before the pollutant is formed. This process improvement is an essential part of the company's pollution prevention program.

The measured data are:

Flow Rate, Q Liters per Minute	Rotameter Reading, R Percent
15.0	10
35.0	20
60.0	35
100.0	55
140.0	80
170.0	95

Determine the calibration equation and the correlation coefficient for this system.

Solution:

Assume $Q = mR + b$

$$S_x = \frac{1}{N}\sum_{i=1}^{N} x_i$$

$$S_y = \frac{1}{N}\sum_{i=1}^{N} y_i$$

$$S_{xx} = \frac{1}{N}\sum_{i=1}^{N} x_i^2$$

$$S_{yy} = \frac{1}{N}\sum_{i=1}^{N} y_i^2$$

$$S_{xy} = \frac{1}{N}\sum_{i=1}^{N} x_i\,y_i$$

and

$$m = \frac{S_{xy} - S_x S_y}{S_{xx} - (S_x)^2}$$

$$b = \frac{S_{xx} S_y - S_{xy} S_x}{S_{xx} - (S_x)^2}$$

$$r = \frac{S_{xy} - S_x S_y}{\sqrt{S_{xx} - (S_x)^2}\sqrt{S_{yy} - (S_y)^2}}$$

Q = y	**R = x**	y_i^2	x_i^2	$x_i y_i$
15.0	10	225	100	150
35.0	20	1225	400	700
60.0	35	3600	1225	2100
100.0	55	10000	3025	5500
140.0	80	19600	6400	11200
170.0	95	28900	9025	16150
$\sum y_i = 520$	$\sum x_i = 295$	$\sum y_i^2 = 63550$	$\sum x_i^2 = 20175$	$\sum x_i y_i = 35800$

N = 6

$$S_y = \frac{520}{6} = 86.666667$$

$$S_x = \frac{295}{6} = 49.1666667$$

$$S_{yy} = \frac{63550}{6} = 10591.667$$

$$S_{xx} = \frac{20175}{6} = 3362.5$$

$$S_{xy} = \frac{35800}{6} = 5966.6667$$

$$m = \frac{S_{xy} - S_x S_y}{S_{xx} - (S_x)^2}$$

$$m = \frac{5966.6667 - (86.666667)(49.1666667)}{3362.5 - \left(49.1666667\right)^2}$$

$$m = \frac{1705.5555}{945.13896}$$

$$m = 1.80455$$

$$m = 1.805$$

$$b = \frac{S_{xx}\,S_y - S_{xy}\,S_x}{S_{xx} - \left(S_x\right)^2}$$

$$b = \frac{(3362.5)(86.666667) - (5966.6667)(49.1666667)}{945.13896}$$

$$b = \frac{291416.67 - 293361.11}{945.13896}$$

$$b = \frac{-1944.4486}{945.13896}$$

$$b = -2.057$$

Q = 1.805R - 2.057

Check:

when R = 80

Q = 140

Q = 1.805(80) - 2.057

Q = 142.3

$$\text{Error} = \frac{142.3 - 140}{140} x100 = 1.64\%$$

$$r = \frac{S_{xy} - S_x S_y}{\sqrt{S_{xx} - \left(S_x\right)^2}\sqrt{S_{yy} - \left(S_y\right)^2}}$$

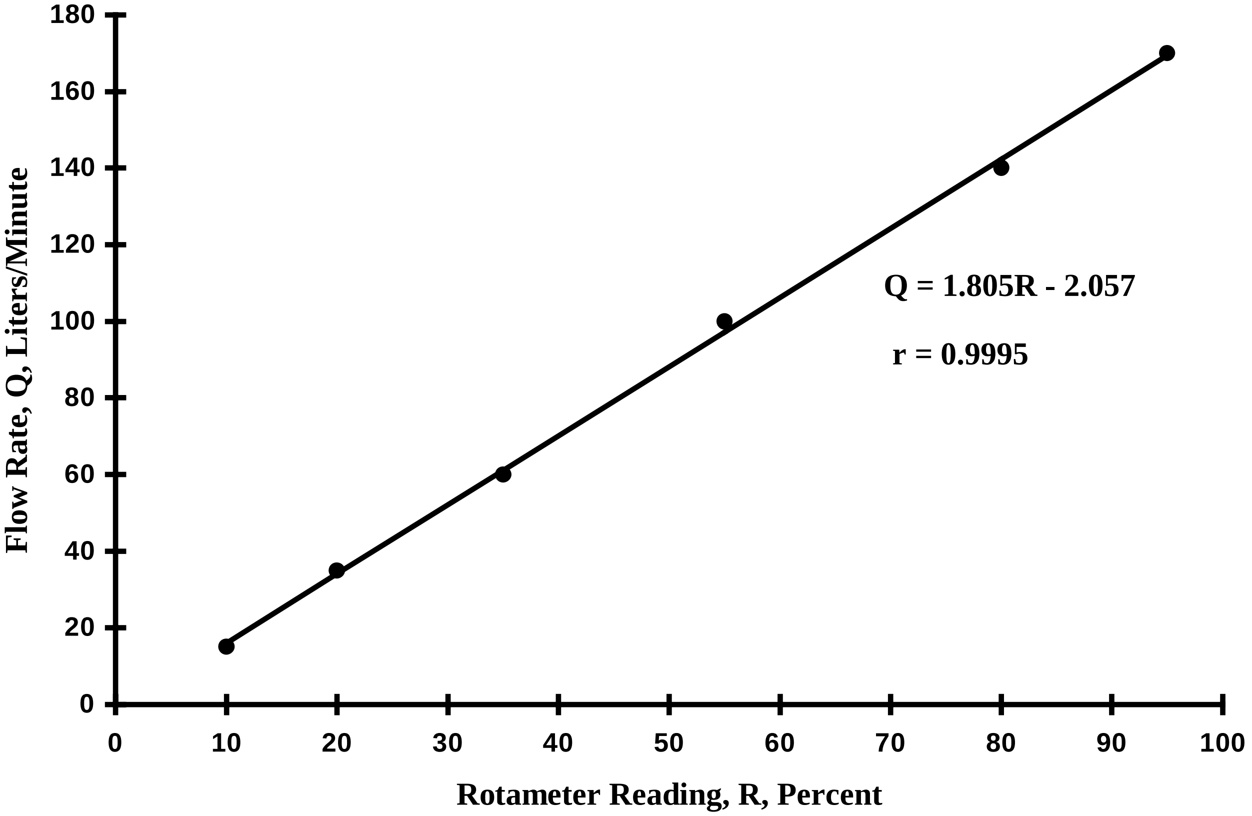
$$r = \frac{5966.6667 - (49.1666667)(86.666667)}{\sqrt{3362.5 - (49.1666667)^2}\sqrt{10591.667 - (86.666667)^2}}$$

$$r = \frac{1705.5555}{(30.743112)(55.502755)}$$

$$r = 0.9995$$

Figure 1

Calibration of a Rotameter



VI. Written and Oral Communication

The net result of any experimentation and measurements is to convey the facts from the investigator's mind to that of interested readers (6). Hence, good communication abilities, both written and oral, are paramount and are probably the most important part of the investigations. Most of the time the ability to communicate effectively both in written form and oral form will determine the level of promotion of an individual. Good writing and good speaking abilities are <u>very</u> important and are a <u>life-time</u> endeavor. We <u>never</u> reach perfection as long as we live but we must always try to reach perfection as long as we live.

We will consider reports

- Written
- Oral

A. *Written Reports*

1. *Generally speaking, we will consider only three types of written reports. These are:*

- Research
- Memo
- Letter

A research report is a <u>very detailed</u>, lengthy report on an investigation. A memo report is less detailed than a research report but has sufficient detail for the reader. A letter report usually is an executive summary of the study and gives the reader the key significant facts, results, conclusions and recommendations. Often,

> ". . . the real ability of a technical man remains unrecognized because the results of his work are poorly presented." Fred Hoffman Rhodes, "Technical Report Writing" 1941 (6).

a) The purpose of a written report is to convey a set of facts from the mind of the writer to that of the reader. The report must be written with

- Clarity
- Precision
- and Completeness

b) The literary prose used in ordinary, non-technical writing is

- Effective without being precise,
- Suggests rather than defines, and
- Implies rather than states.

c) Technical prose, on the other hand, must focus on

- Essentials
- Being clear and definite

For technical prose,

(1) The writer must understand the material that he/she is trying to present

(2) The material must be complete and organized

(3) The results must be presented in logical order, for example,

(a) experimental method
(b) experimental results
(c) conclusions

The report must be written in good language (English in the U.S.) and must have good sentence structure. Good formatting with proper paragraphing is essential. The report must be complete yet it must be concise because a concise report is easier to follow.

d) The requirements of a good report are:

- Clearness
- Completeness
- Proper organization of material
- Correctness of presentation

2. The steps in report writing are:

- Collect data
- Assemble data
- Analyze data
- Outline the report
    - the organization and order in which various topics are to be discussed with
        - Divisions
        - Subdivisions

It is very important to first prepare a detailed outline of what is to be discussed prior to any writing.

3. After the report is written,

Ask yourself,

- Is the discussion clear?
- Is the discussion complete?
- Is the material logically arranged?
- Have all unnecessary words and statements been eliminated?
- Are there any errors in grammar, punctuation, or spelling?

4. ***All tables and graphs should be near the point of discussion not all in the back of the report.***

5. ***Correct styles, conventions and correct usage of words is essential.***

Technical reports are usually written in impersonal style. For example,

Do not write:

> I opened the valve.
>
> We measured the distillate flow.

Instead, write:

> The valve was opened.
>
> The distillate flow was measured.

a) Sentences should be properly structured.

A good sentence length averages about 17 words because short sentences are too choppy and long sentences are too hard to follow.

Example:

A vertical kettle was used. It was cylindrical and made of steel. The kettle was three feet in diameter. It was six feet high. Both the top and the bottom were dished. It was provided with a steam jacket.

This paragraph can be better stated in one sentence:

The kettle was a vertical, steam jacketed, steel cylinder, three feet in diameter and six feet high, with dished heads.

b) The selection of words is very important. For example, the word obtained is used as:

- Temperatures are obtained
- Samples are obtained

The word obtained is used instead of the words

collected, drawn, taken, removed, read, computed, calculated, estimated, derived, or measured.

The word *undoubtedly* means certainly. Therefore, do not use *probably* when you mean undoubtedly.

6. *Colloquial expressions are never used.*

For example, to write, “the agreement is not too good” is a colloquial usage.

It is better to write, “The agreement is rather poor”.

The use of symbols instead of words is to be avoided.

Hence, do not say that the $\frac{dV}{d\vartheta}$ ' s vary as the 0.51 of the ΔP’s,

but rather say, the rate of flow varies as the 0.51 power of the difference in pressure.

B. *Organization of a Report (Formal)*

As stated, report forms discussed are:

- Formal (research)
- Memo
- Letter

The formal or research report is the most detailed. The structure of a research report is as follows:

1. ***Title:*** The title must be brief, but clear. For example,

"BATCH FILTRATION OF DIATOMACEOUS EARTH IN A PLATE AND FRAME FILTER."

and

“DISTILLATION OF METHANOL-WATER IN A SIEVE TRAY COLUMN.”

Do not use titles such as:

FILTRATION
or
DISTILLATION

2. *Table Of Contents*

3. *Abstract*

The abstract should state:

- what you did
- what the results are
- what the conclusions are
- what the recommendations are

The abstract must, in very short paragraph form, give the reader a complete overview of the study. To learn how to write good abstracts, study abstracts written in good technical journals.

4. *Introduction*

The writer should include somewhere in the report, the

- Purpose of work

  Why is filtration of slurries in a plate and frame press important?
- Previous work in literature
- Theory - if significant

  The writer must separate and discuss only the theory pertinent to the study.

5. *Apparatus*

A clear and complete sketch of the apparatus must be presented. The narrative accompanying the sketch must be complete.

Example

> *In the study of heat transfer, for a heat exchanger, describe the number and order of passes, number of tubes in each pass, and the ID, OD or BWG of each tube, the length of tubes, the material, the shell diameter, and the number and type of baffles, etc.*

In the first paragraph of the narrative, which accompanies the sketch, give the overview of the equipment.

In succeeding paragraphs give more details.

6. *Procedure*

In the first paragraph of the procedure section, give an overview.

In the succeeding paragraphs give many more specific details.

Present a flow sheet of the system and always assume that the reader has intelligence and will understand. For example, don’t say:

> "The steam was turned on by opening
> the valve in the steam line."

The reader knows that steam is turned on by opening a steam valve.

From the written report, the reader must be able to operate the system to reproduce the data that were measured, if necessary.

7. *Experimental data*

Experimental data is presented in tables, graphs, charts, etc. Tables and graphs must be complete and detailed.

8. *Discussion*

In writing a discussion, refer to the detailed outline of the study that was prepared. This procedure will insure that the report is written in <u>logical</u> order and is <u>complete</u>.

First, introduce with what was done, then discuss results in logical order from the outline, with the proper conclusions at each point of discussion.

Errors should also be presented in the discussion.

9. *Conclusions*

Conclusions are presented in terse form. For example,

The conclusions of this study are:
1.
2.
3.

There is **<u>no</u>** discussion in this section of the report.

10. *Recommendations*

Recommendations are presented in terse form also. For example,

The recommendations of this study are:
1.
2.
3.

There is **no** discussion in this section of the report. This section gives what you, as the investigator, feel is necessary for further studies.

11. *Bibliography*

The bibliography or reference section should be clear.

It is wise to check textbooks, journal articles, etc. for proper form. For example,

Book
Felder, R. M. and Rousseau, R. W. "Elementary Principles Of Chemical Processes", Second Ed., p.351, John Wiley & Sons, New York, 1986

Journal Articles
Ronald, M.C., "Investigation of the Teaching of English in Technical Schools" J. Eng. Educ. 43, L17 (1941)

Patents
Carlin, G. B. and C. U. Laytor, US Patent 1, 475, 236 (Aug. 12, 1971)

12. *The Nomenclature used must be clearly defined.*

13. *The Appendix contains all important but not necessarily high priority data. For example,*

- Sample calculations
- Unimportant calibration graphs
- Data charts from recorders

Equations in a report must be properly written. For example,

“the empirical equation for the orifice is:

$$\frac{dw}{d\vartheta} = 4280\,\Delta p^{0.5},$$

where $\frac{dw}{d\vartheta}$ = rate of flow of water, gal per minute

and Δp = drop in pressure across the orifice, pounds per square inch”

The definition of the terms in the equations can be presented with the equation in the main body of the report (as above), or one can place the definition of terms in the nomenclature section.

All **units** in technical reports, especially technical publications, are in SI units. Certain corporations in the U.S. may prefer the English system of units.

C. *Oral Reports*

The ability of an investigator to speak before a large or small audience is paramount. It is an invaluable asset which the investigator must develop. This development, like writing, is a life long process of trying to achieve perfection. Each presentation made should be better than the preceding one.

In making oral presentations,

- everyone must strive to be an effective speaker and
- we must all remember that everyone is nervous at first.

1. *Poor presentations are usually the result of*

- Lack of practice and
- Lack of skill in speaking

We do not read a paper before an audience and we must avoid “aaah’s” or “uh’s”.

We do not speak to the blackboard, and not only to the key people in the audience, but always to the entire audience.

Our speaking style should be conversational and not monotonous and, hence, boring.

2. ***A good presentation can be assured if we:***

- Prepare good audio-visual material which is <u>not cluttered</u>
- Practice the presentation
- Overcome the nervousness of the first few minutes of the presentation
- Speak to the audience, the entire audience and not only to key people
- Have the material well organized such that it is logical and easy to follow

3. ***In your presentation, tell the listeners:***

- What you will tell them
- Then tell them
- Then tell them what you have told them

In other words, always

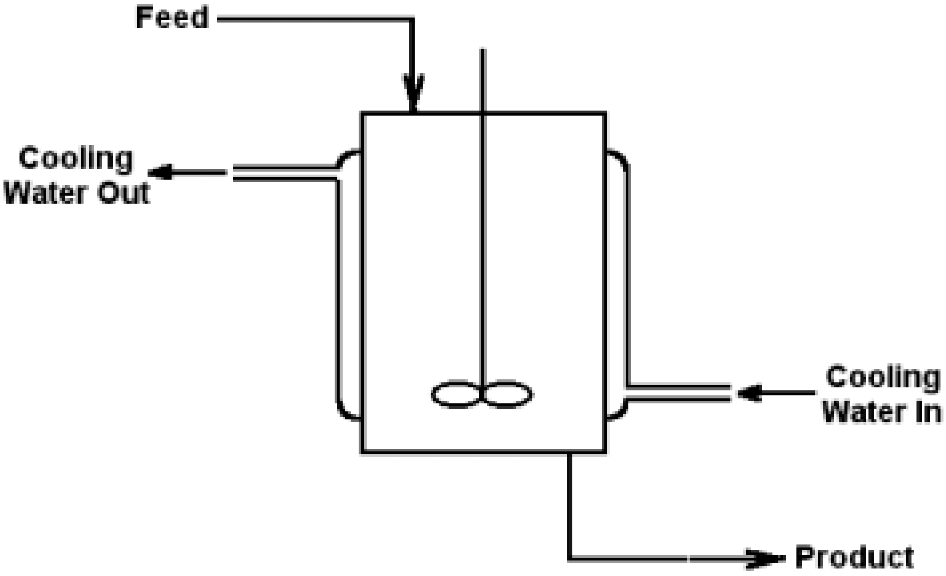
1. Introduce the main points that you will be discussing, then
2. Explain each point in detail, and finally,
3. Review and summarize the points that you have discussed.

References

1. Freeman, H., Harten, T., Springer, J., Randall, P., Curran, M.A., and Stone, K., “Industrial Pollution Prevention: A Critical Review,” U.S. Environmental Protection Agency, Cincinnati, Ohio, May (1992).
2. Holman, J.P., "Experimental Methods for Engineers", Sixth Edition, Mc Graw-Hill, Inc. New York, (1994).
3. Hausman, E. and Slack, E.P. "Physics," 2nd Edition, D. van Nostrand Company, New York, NY (1939).
4. Ray, M.S., "Engineering Experimentation Ideas, Techniques and Presentation", Mc Graw-Hill Book Co.New York, NY, (1988).
5. Reger, D. L., Goode, S. R., and Mercer, E. E., “Chemistry: Principles and Practice”, Harcourt Brace Jovanovich College Publishers, New York, NY, (1993).
6. Rhodes, F.H., "Technical Report Writing", Mc Graw-Hill Book Co. Inc. New York, N.Y., (1941).
7. Lyons, L., "A Practical Guide To Data Analysis For Physical Science Students", Cambridge University Press, Cambridge, CB2-IRP, UK, (1991).
8. Lipson, C. and Sheth, N.J., "Statistical Design and Analysis of Engineering Experiments", Mc Graw-Hill Book Co., New York, N.Y., (1973).
9. Dixon, W. J., and Massey, F. J., “Introduction to Statistical Analysis”, McGraw-Hill Book Co., Inc., New York, N.Y., (1951).
10. Felder, R.M. and Rousseau, R.W., "Elementary Principles of Chemical Processes", Second Edition, John Wiley and Sons, New York, N.Y., (1986).
11. Doebelin, E.O., "Measurement System Application and Design" Fourth Edition Mc Graw-Hill Publishing Co., New York, N.Y., (1990).

Part II

Laboratory Experiments



I. Laboratory Safety and Good Laboratory Practice

The following rules and regulations for chemical engineering laboratories are spelled out not as a deterrent for the student, but as a guide for the purpose of reducing accidents, preventing misunderstandings, having the student use time most efficiently, and allowing the laboratory to function in the most economical and efficient manner possible.

Safety in the chemical world is a way of life. It is a philosophy and it is an attitude. It is an inherent desire in each of us to protect ourselves, our colleagues and coworkers. It is a habit. Consequently, the proper undergraduate training in engineering must include the development of a proper safety program.

One simple approach is to always ask yourself the question, "What will happen if I ----

- speed in my automobile
- open this valve
- raise this temperature
- start this pump
- open this electrical switch
- etc."

Then, answer your question and proceed.

Safety also is a set of rules. For our laboratory these are:

1. Clothing: Shorts or skirts should not be worn to the lab. If either is to be worn in the lab, an approved laboratory coat is to be used. In addition, sandals are not an acceptable type of footwear. Tee-shirt type garments, not of the undershirt variety, are acceptable, but are not recommended. Hard hats are required in all high head areas. Confine long hair or neckties, so that they cannot get caught in moving machinery.
2. Eye Protection: Glasses are a required item to be worn in all areas of the laboratories. The departmental policy on eye protection is:

STUDENTS ARE REQUIRED TO WEAR EYE PROTECTION THROUGHOUT THE LABORATORY PERIOD WHILE IN THE LAB AREA.

3. <u>Hard Hats</u>: Students are required to wear hard hats in designated areas.

4. <u>Housekeeping:</u> All designated experimentation areas should be left in a clean orderly state at the conclusion of the experiment. Under this category the following items should be checked:

   a) All excess water is removed from the floor;

   b) all paper-type materials (towels, notebook paper, etc.) should be picked up and deposited in trash cans;

   c) all working surfaces (tables, chairs, etc.) should be cleaned if required;

   d) all miscellaneous items should be returned to their proper initial locations (kits to stockroom, tools to the tool shop, chemicals and glassware to proper stockroom);

   e) all hoses should be coiled and placed in designated locations (unless told to the contrary);

   f) all glassware should be washed prior to returning to the stockroom;

   g) all scales should have weights removed and scale arm locked;

   h) all manholes (sewers) should have lid closed;

   i) all drums or containers used should be checked;

   j) all valves and electrical units should be checked to ensure they are in the closed position (utilities off).

   A grading penalty will be associated with the failure to abide by the previously stated items.

5. <u>Horseplay:</u> Incidents of horseplay can lead to friction and accidents, and are not tolerated. A minimum penalty of one letter grade and a maximum penalty of a failure grade on that particular experiment may be incurred. Repeated incidents can lead to a failure grade in the course or charges of unprofessional conduct.

6. Equipment Difficulties: The student is encouraged to correct any minor equipment difficulties by taking the appropriate action. However, any major equipment difficulties should be reported to the shop attendant, instructor, or laboratory assistant, and the student should not attempt any further corrective action.
7. Tools: Tools should not be taken out of any stock or maintenance rooms without checking them out with the designated responsible person. Any tools checked out should be returned immediately at the completion of their required task, but in any case, no later than the conclusion of the particular day's laboratory period.
8. Electrical: In many instances electrical extension cords are required for the operation of auxiliary equipment. Special precautions should be taken when using these cords. When an electrical extension cord is checked out, be sure to examine its condition. If you find frayed or broken wires, insulation broken, prongs bent, no ground, etc., do not use but return to the stockroom, pointing out the faults to the attendant. When using extension cords be sure they do not lie on the floor, in particular, when the floor is wet, but are safely supported in such a fashion that they are not a bodily hazard. In addition, when making electrical connections be sure the area you are standing in is dry.
9. Accidents: Even with the greatest safety precautions accidents do happen. Be sure you are familiar with the locations of safety showers and medical first aid kits. If an accident happens, be sure to immediately inform an instructor. In the case of a serious accident, do not attempt first aid if you are not familiar with the proper technique but do attempt to make the person comfortable until aid arrives. The campus emergency number is Ext. 3111. Emergency phones (red telephones) are located in the corridors of Tiernan Hall.
10. Unauthorized Areas: Do not touch unauthorized equipment or experiments.
11. Food or Drink: Food and drink are forbidden in laboratories.
12. Smoking: Smoking is not permitted in laboratories. Smoke only in authorized areas, outdoors.

13. Ventilation: Be sure that hoods are functioning and areas you work in are properly ventilated.
14. Attendance: Mandatory attendance is the rule of the lab periods however, a limited number of absences is permitted with the approval of the instructor. Appropriate make-up requirements for these lab periods will be stated by the instructors. It is possible for an individual in a group to receive a failing grade for an experiment for absences, while the remainder of the group receives a passing grade. No experiments can be made outside of normal laboratory hours without presence of an instructor or assistant.

Experiments and activities in a chemical engineering or chemistry laboratory regularly involve the use of chemicals. Good laboratory practice requires that the amounts of the materials used should be as small as possible. Using too much is wasteful and costly and is not a trait of a thoughtful professional. All chemicals used should be handled and disposed of in an environmentally sound manner. Prevention of pollution starts with appropriate choices and carefully considered actions in the laboratory.

Where possible, groups of three will be formed with the students choosing their own group members. However, when necessary, the instructor may form the group. In order to clearly delineate responsibility for each experiment, the group will designate one person from the group as a group leader. This position is a rotating responsibility, with one person holding the title for each assigned experiment. Every member of the group shall hold this position, if possible, during the semester and the number of times each group member is assigned this task is a function of the number of experiments assigned during the semester and the number of individuals in the group.

The group leader's responsibility is to assign the tasks associated with a particular experiment to the group members. This includes such items as data taking, equipment operations, calculations, drawings, responsibility for report sections, etc. The setting of deadlines, overall coordination of report assemblage, etc., should be the responsibility of the group leader alone.

list of the persons designated as group leader for each experiment is to be turned in to the lab instructor no later then the beginning of the second class period. In addition, no group will be allowed to operate any equipment until its members have been quizzed by the instructors and demonstrated familiarity with the experimental theory and procedure.

As a motto in the laboratory one can say,

"WHEN IN DOUBT, ASK."

II. The Laboratory Notebook

Data Taking and Recording: Each group is required to purchase a standard, research quality, laboratory notebook. Details can be developed in class as notebook formats change. The following procedure must be followed for each experiment:

1. Title of Experiment and date must appear at the top of the page.
2. Data must be recorded neatly, stating all units and dimensions and listing all conversion factors.
3. Data must be recorded in duplicate.
4. At the end of each period, experimenters must sign the bottom of each page. The instructor must also sign as a witness.
5. The carbon copy of the data must be given to the instructor.

The kernel of the lab report is the data obtained from the experiment. No data should be taken on loose note paper. At the end of the semester the data book will be given to the Instructor and will be used in calculating the student's grade. The notebook and laboratory reports will be retained by the Instructor.

III. Flow Measurements and Energy Loss

The transportation of fluids, (gas or liquid), from one point to another is usually accomplished through the use of conduits (pipes) which are constructed in various shapes of different type materials. These transportation grids are made up of sections of conduits with fittings, such as valves, connectors, and measuring devices through which the fluid is moved. The fluid movement requires energy input from pumps, fans, blowers or compressors to overcome pressure drop (energy losses) throughout the system. The measurement of pressure drop and fluid velocity is important because they are related and impact on the sizing of the movement equipment. The oversizing (of equipment to any great degree) requires additional costs as well as inefficiency which increase energy use. This impacts throughout the system and increases pollution effects. It is in this sense of correct engineering design and specification that concepts of pollution prevention are incorporated in engineering. On the other hand, undersizing the equipment may reduce environmental impact but it also ensures the process or system unit does not operate as required. It is therefore important to understand the relationship between fluid flow and energy requirements (pressure drop) in a system under study or design. The system may be one in which a single fluid is being transported (as water is from the reservoir to a pumping station to your kitchen tap) from point A to point B in a circular pipe or for single phase (air) or two phase (water - air) in a packed tower.

Packed towers are widely used in the removal of gaseous substances in a gas stream by contacting with a liquid substance. It is commonly used in air pollution control systems in the chemical industry. A packed tower in the simplest sense is a cylindrical tube filled with inert material forming a process bed.

Various devices are used to measure pressure drop and fluid flow. For pressure drop (ΔP) a simple device is a U-tube manometer. This device is a long cylindrical tube which is formed into the shape of a U and contains a fluid. When connected into a system, such as a pipe, it allows the measurement of pressure difference (ΔP) between two points and gives an indication of energy loss.

In the case of measurement of the fluid velocity or the quantity of flow in a pipe, a rotameter is used. Rotameters may be scaled for direct reading of the quantity of flow in percent of total flow. These are visual devices. A rotameter used in conjunction with a manometer allows for determining the relationship between flow and energy requirements.

IV. **Experiments**

A. *Experiment 1 : Calibration of a Rotameter*

Introduction

The measurement of fluid flow is important in numerous applications ranging from the measurement of blood flow rate in a human artery to the measurement of the flow of liquid oxygen in a space rocket. Many research projects and industrial processes depend on the measurement of fluid flow to furnish data for analysis.

In today's world, one of the most important aspects of processes is that the operation must be conducted without harming the ecology of the earth. Hence, we must be able to manufacture all necessities like antibiotics, but, in the process, we cannot harm the earth's natural systems - atmosphere, soil or water.

Whether we deal with pollution abatement to reduce the discharge of waste into the earth's systems or pollution prevention to reduce the production of the waste at the front end of the process, we must measure. We must measure compositions but we must also measure flow.

Examples of everyday metering measurements are the gasoline pumps in a station, and the gas and water meters in residences. All of these measure quantities of fluids. At times one is interested in usage over a period of time, which is flow rate, rather than only the total quantity. Some commonly used terms for expressing flow rate are:

1 gallon per minute (GPM)
  = 231 cubic inches per minute (in^3/min)
  = 63.09 cubic centimeters per second (cm^3/s)

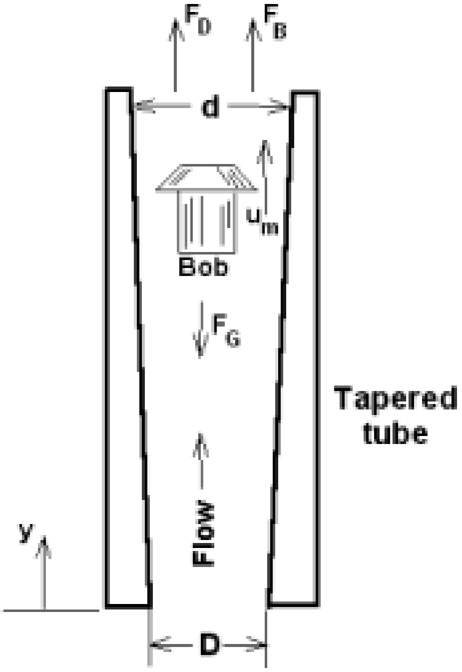
1 liter = 0.26417 gallons = 1000 cubic centimeters

1 cubic foot per minute (cfm or ft^3/min)
  = 0.028317 cubic meters per minute
  = 471.95 cubic centimeters per minute

1 standard cubic foot per minute of air (at 20°C and 1atm)
= 0.07513 pound-mass per minute
= 0.54579 gram per second

A rotameter is a common visual measuring device that can be used to measure the flow rate of fluid (liquid or gas) if it is calibrated. Figure 1 is an example of the principles involved in the operation of a rotameter.

Figure 1
Schematic of a Rotameter



There are three forces acting on the bob. These are;

F_D, the drag force which results from friction between the bob and the fluid as it passes by the bob. The fluid flowing past the bob tends to drag it along with its flow.

F_B, the buoyancy force, results from Archimedes' principle. This principle states "a body submerged wholly or partially in a fluid is buoyed up by a force equal to the weight of the fluid displaced".

F_G, the downward force, is the force of gravity caused by the mass of the bob.

As fluid flows past the bob, the bob will rise until

$$F_G = F_D + F_B$$

When the upward forces and downward force are equal, the bob will remain stationary. Hence, by calibration, the rotameter can be used as a flow measuring device.

Liquid measuring rotameters generally have subdivisions on the vertical measurement tube in divisions of percent flow from zero to one hundred in major increments of ten. At times it may be required to calibrate a rotameter either to check its calibration or to determine its range of flow rates. This can be done by the direct weighing techniques.

The flow rate of a non-volatile liquid like water may be measured by a direct-weighing technique. The time necessary to collect a quantity of the liquid in a tank is measured, and an accurate measurement is then made of the weight of liquid collected. The average flow rate is thus calculated very easily. Improved accuracy may be obtained by using longer or more precise time intervals or more precise weight measurements. The direct weighing technique is frequently employed for calibration of water and other liquid flowmeters, and thus may be taken as a standard calibration technique.

Experimental Objective

To obtain data in order to prepare a calibration curve for a specified flowmeter.

Procedure

Your instructor will specify which rotameter you are to calibrate. Trace the flow lines to determine which valves control the flow of water to the rotameter, to the drain and to the collection container. Set the valve opening to a predetermined setting on the rotameter. You should take 6 - 8 readings (runs) between the 0 and 100 percent markings in uniform divisions. Then start collecting water in the tared container for a given time. When either the predetermined time or weight is reached, stop your test and record the time of the run and the mass of water collected. Repeat the run two more times and then reset the rotameter reading and repeat the process.

Data Analysis

a. Prepare a plot of gallons per minute (GPM) versus rotameter reading (%) on rectangular coordinates.

b. Determine the constants in the linear regression equation

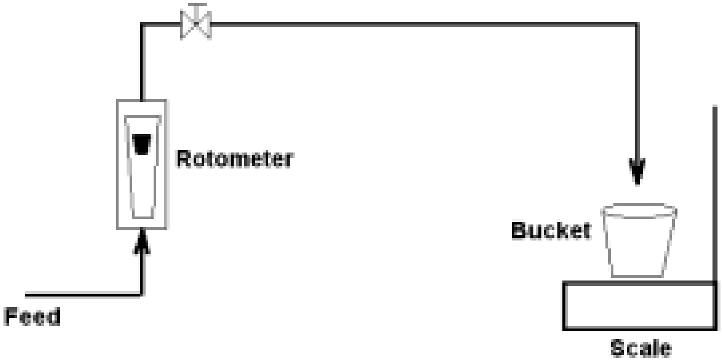
$$Q = mR + b$$

where Q = flow rate, GPM
R = rotameter setting, percent of scale
m and b are the regression constants

c. Compare your best results with the manufacturer's specification.

d. Calculate the correlation coefficient for your measured data.

Figure 2
Calibration of Rotameter by Direct Weight Method



B. ***Experiment 2 : Fluid Flow in Conduits***

Introduction

This experiment is designed to study the relationship between fluid velocity and pressure drop in a specified length of circular pipe. The relationship between fluid velocity and pressure drop in conduits has been documented both based on theoretical principles and empirical developments. Two flow regimes have been identified which are referred to as laminar flow, theoretically based, and turbulent flow, empirically based. These regimes relate what is called a friction factor, which is a parameter that is a function of pressure drop (ΔP), to the Reynolds number (a velocity function). The analysis of these data gives the energy loss in a system and, hence, can be used to determine the pump size. The calculated parameters are dimensionless numbers that are applicable to any fluid flowing in conduits. The interaction between these parameters is presented in graphical form on log-log paper.

Experimental Objective

The purpose of this experiment is to determine the relationship between the friction factor and the flow Reynolds number for a circular cross-sectioned pipe, 10 feet long.

Procedure

There are two parts to this experiment. In the calibration part, the pump characteristics of a centrifugal pump are determined and the rotameter is calibrated by direct weight. In the second part, the pressure drop characteristics of straight pipe are measured. Prior to both parts, however, the system must be bled of all air and filled completely with water. The Fluid Flow system is shown in Figure F-3.

Manometer Operation

Extreme care should be exercised when measuring pressure drop (Δp) with the U-shaped manometers in order to prevent “blowing” the manometer fluid out of the system.

Improper use of a manometer can lead to blowing the manometers. Blowing the manometer will be considered poor laboratory technique and appropriate grade reductions will be made. To avoid blowing the manometers, study the system in Figure F-4 carefully. Manometer A is filled with mercury (S.G. - 13.65) and manometer B is filled with Merriam Fluid (blue color, S.G. - 1.75). Always use the mercury manometer until the difference reading is less than one inch (0.0254m), then switch to the Merriam Fluid for the more accurate readings at lower pressure drops.

To use the manometer system,

1. Open valves 1, 2 and 3. Close valves 4, 5 and 6 in Figure F-4. The mercury manometer is ready for use.

2. To take a reading, slowly close valve 2, the equalizer valve and follow the change in the mercury columns. Do not close valve 2 completely if the mercury appears to leave the manometer. Valve 2 is your control.

3. If the mercury manometer reading is less than one inch (0.0254m), open equalizer valve 5, then 4 and 6. Close valves 1 and 3, and then close valve 2. The Merriam Fluid manometer is ready for service and equalizer valve 5, when open, will prevent blowing this manometer which is much more sensitive (ca 17 times) than the mercury manometer.

Bleeding the System

1. Open suction and discharge line from the centrifugal pump.

2. Open block valves in entrance and exit of study pipe system.

3. Open all valves in panel measuring system for specified pipe.

4. Open all valves on the manometer system.

5. Open all bleed valves to bubblers on panel.

6. Start the centrifugal pump and the circulate water until no air appears in the bubblers. Close exit valves in header to help force out air.

7. When the system is bled, close all valves needed on panel board except 1, 2 and 3 in Figure F-4.

Calibrations

1. Calibrate the rotameter by direct weight method using the calibration tank. (The calibration tank is calibrated in ten pound increments.)

2. For the rotameter use 6 - 8 readings covering the entire scale.

3. Always start with the highest flow rates and work downward.

Pressure Drop Measurement

After recording the rotameter calibration and pump data for a given flow reading, measure the pressure drop for the ten (10) foot length of pipe on the U tube manometer. (Be sure to follow the instructor's directions in this step).

At the conclusion of the experiment, a minimum of 6 - 8 data points should have been investigated which span the rotameter's range in flow.

Data Analysis

a. Prepare the following rotameter calibration curves: (use rectilinear paper)

   1. Mass collected per Unit Time vs. Rotameter Reading

   2. Gallons per minute vs. rotameter reading

b. Pump curve (rectilinear paper)

   1. Plot the pressure drop (ΔP) (in feet of water) difference of the suction and discharge of the pump vs. the flow (in gallons per minute).

c. Ten (10) feet length of pipe (on log-log paper)

   1. Plot the pressure drop (ΔP) over the length of the pipe vs. the velocity of the fluid in the pipe.

   2. A generalized correlation can be presented in dimensionless form for the plot in part c-1 (above) which has parameters of:

f (the Fanning friction factor) given by

$$f = \left(\frac{\Delta P}{4\rho}\right)\left(\frac{D}{L}\right)\left(\frac{2g_c}{v^2}\right)$$

and N_{Re} (the Reynolds number) given by

$$N_{Re} = \frac{Dv\rho}{\mu}$$

This plot of f versus N_{Re} is made on log-log paper. Note for a particular pipe the diameter, length, and fluid properties, the plot is inverse to the plot in part c-1.

Nomenclature

The following nomenclature is used with English units:

ρ = density, $\frac{lb_m}{ft^3}$

μ = fluid viscosity, $\frac{lb_m}{ft\ s}$

D = pipe diameter, ft

L = pipe length, ft

v = fluid velocity, $\frac{ft}{s}$

ΔP = pressure drop, $\frac{lb_f}{ft^2}$

g_c = gravitational constant = 32.2 $\frac{ft\ lb_m}{lb_f\ s^2}$

f = Fanning friction factor (dimensionless)

N_{Re} = Reynolds number (dimensionless)

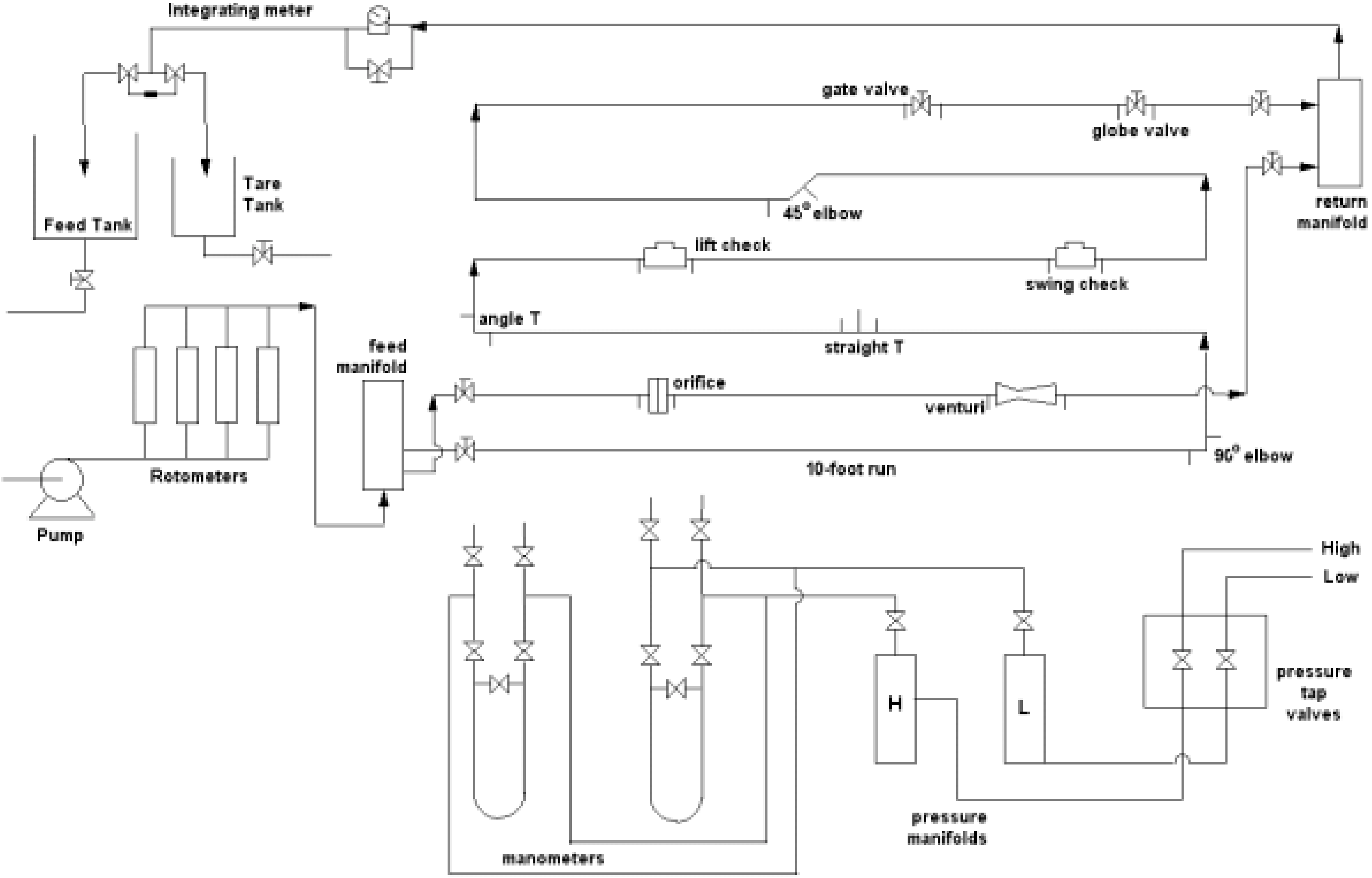
References (Experiment 2)

1. Geankopolis, C.J., "Transport Processes and Unit Operations," Third Edition, Prentice Hall, Englewood Cliffs, New Jersey (1993).

2. McCabe, W.L., Smith, J.C., Harriot, P., "Unit Operations of Chemical Engineering," Fifth Edition, McGraw Hill Inc., New York, New York (1993).

3. Hanesian, D., "Chemical Engineering Laboratory Manual," Second Printing, Fall 1984.

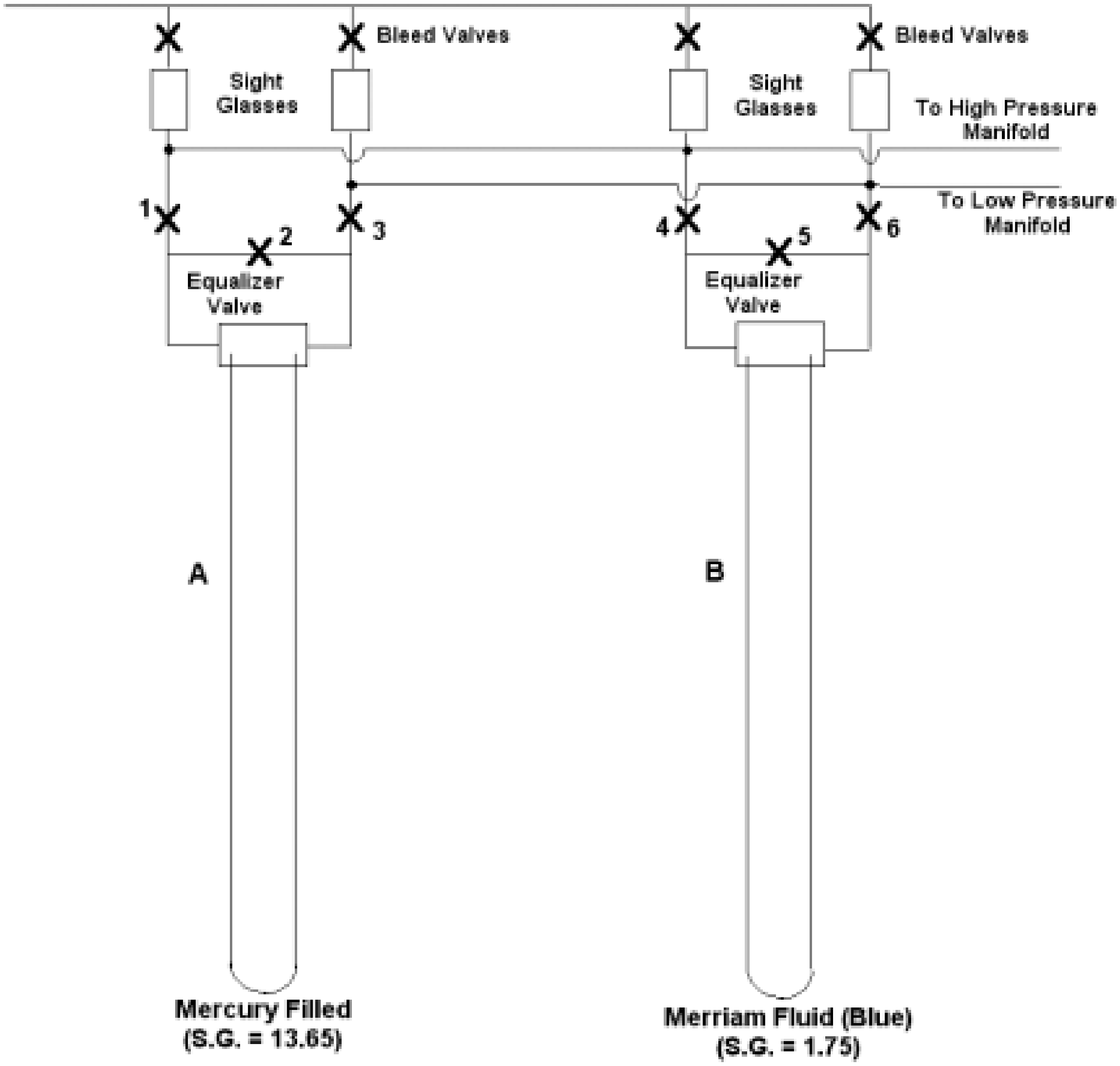
Figure 3
Fluid Flow System



Hanesian (3) (Figure developed by R. Barat, 1979)

Figure 4

Manometer System



C. *Experiment 3 : Pressure Drop in Packed Towers*

Introduction

Packed towers are used in pollution abatement to remove pollutants from an air stream by scrubbing the air stream with a fluid, usually water if the pollutant is soluble in water, prior to releasing the air to the atmosphere. Packed towers are very important in both pollution prevention and pollution abatement. The packing material provides surface contact area for mass transfer but it also results in a pressure drop because of friction and, hence, an energy loss. A low pressure drop and , hence, low energy consumption is very important in the performance of packed towers.

The performance of packed towers depends upon the hydraulic operating characteristics of the packing contained in the tower. Two types of hydraulic operating characteristics can be examined. These are the characteristics of wet and dry packing. In dry packing, only the flow of a single fluid phase through a column of stationary solid particles is considered. For many chemical engineering operations this is all that need be considered insofar as hydraulics is concerned. Examples of such flow are: flow through a fixed-bed catalytic reactor, flow through absorption and ion-exchange columns. However, in most mass transfer operations, knowledge of the performance of the dry packing does not guarantee adequate performance of the equipment used. In packed towers, two-phase (usually counter-current) flow is encountered. In absorption or distillation, the phases will be a gas and a liquid. Since the liquid flows over the packing and since the liquid occupies some of the void volume in the packing normally filled by the gas, the performance of wet packing is different from that of dry packing.

An important consideration in the design of any packed tower is the power required to force the gas through the packing. Packing shapes in this experiment consist of spheres, Raschig rings, Berl saddles and Intalox saddles. The power requirement will depend not simply on whether the tower is operated dry or wet but will be a function of the liquid flow rate if the packing is wet.

For a column, it is truly economically advantageous to maximize one of the flow rates. If either the liquid rate or gas flow rate, or both, is increased, a certain point will be reached due to the increased gas pressure drop, and at this point it is observed that the liquid which is normally dispersed is no longer able to trickle down freely through the packing. Instead, pools or pockets of liquid are produced which drastically reduce the available area for gas flow. Any further increase in gas flow rate is accompanied by abnormally large increases in pressure drop. Although it is not examined here, column performance in mass transfer (separation) will fall off materially in this region due to the elimination of the interfacial area for contact as provided by the packing. This undesirable condition is known as loading. If one continues to increase the gas flow rate, the liquid pools formed in loading will consolidate across the entire cross sectional area of the column. The gas can only get through the liquid by bubbling through. A transformation from gas continuous - liquid dispersed situation to liquid continuous - gas dispersed situation has occurred. The column begins to fill with liquid causing the gas pressure drop across the column to increase without bound. The column takes on the appearance of filling with liquid that seems to be boiling, and with the manometer readings increasing continuously. This unstable condition will usually continue until the pressure drop across the column is sufficient to blow the liquid seals or until liquid is carried out over the top with the exit gas.

In some instances liquid holdup in a packed tower is important. This would be true, for example, in unsteady state operations or in the unusual situations in which long exposure to the conditions existing within the column might result in some deleterious effect, such as a decomposition of some product within the liquid stream.

Experimental Objective

The purpose of this experiment is to measure the pressure drop in packed columns as a function of the gas mass velocity for dry packing and for two different liquid flow rates.

Theory

The pressure drop suffered by the gas in flowing through a bed of packed solids is the result of viscous-energy losses and kinetic-energy losses. Hence, by considering both of these sources of energy loss, Ergun has correlated the pressure drop for any single fluid flowing through a packed bed, including the flow of gases through dry, random packing of the type considered here, by the relation given in Foust (1)

$$-\left(\frac{\Delta P}{L}\right)\left(\frac{D_p g_c}{\rho_v v^2}\right)\left(\frac{\varepsilon^3}{1-\varepsilon}\right) = 150\left(\frac{1-\varepsilon}{N_{Re}}\right) + 1.75 \qquad (1)$$

A log-log plot of Equation (1) (left side versus N_{Re}) for air flowing over dry packing should result in a slope of -1 at low N_{Re}, and a constant value of 1.75 at high N_{Re}.

When the packing has a shape different from spherical, an effective particle diameter may be used:

$$D_p = \frac{6V_p}{A_p} = \frac{6(1-\varepsilon)}{A_s} \qquad (2)$$

The porosity, ε, which is the fraction of total volume that is void is defined as:

$$\varepsilon = \frac{\text{volume voids}}{\text{volume of entire bed}} = \frac{\text{volume of entire bed} - \text{volume of particles}}{\text{volume of entire bed}}$$

$$= \frac{\pi \frac{D^2}{4} L - \frac{\text{weight of all particles}}{\text{particle density}}}{\pi \frac{D^2}{4} L} \qquad (3)$$

A_S and ε are characteristics of the packing. Experimental values of ε are ordinarily easy to determine from Equation (3) but A_S for non-spherical particles is usually more difficult to obtain. Values of A_S and ε are normally tabulated for the most common commercial packing in the various references. A_S for spheres may be readily computed from the volume and surface area of a sphere.

For wet packing, the pressure drop is given by Leva (2)

$$\frac{\Delta P}{L} = \alpha (10)^{\beta L_l} \left(\frac{G_v^2}{\rho_v} \right) \qquad (4)$$

using data below the loading point. (See data table for units in Equation 4).

Procedure

1. A column designated by the instructor will be studied. There are four columns of 6-inch diameter standard Pyrex glass pipe in the system.

2. For each column studied, determine the pressure drop at various air flow rates (correct rotameters for pressure and temperature) keeping constant the liquid flow rate at the following values,

$$L_l = 0 \frac{\text{lb}}{\text{ft}^2\ \text{hr}} \left(0 \frac{\text{Kg}}{\text{m}^2\ \text{s}} \right)$$

$$L_l = 1000 \frac{\text{lb}}{\text{ft}^2\ \text{hr}} \left(2.715 \frac{\text{Kg}}{\text{m}^2\ \text{s}} \right)$$

$$L_l = 2000 \frac{\text{lb}}{\text{ft}^2\ \text{hr}} \left(2.715 \frac{\text{Kg}}{\text{m}^2\ \text{s}} \right)$$

a). For each column, when $L_l = 0$, gradually increase the air flow rate.

At each air flow rate determine (ΔP) and plot a graph of (ΔP) versus air rate as you determine each point. Shut off air flow at end.

b). Increase the water rate to $L_l = 1000\frac{\text{lb}}{\text{ft}^2\ \text{hr}}\left(2.715\frac{\text{Kg}}{\text{m}^2\ \text{s}}\right)$. Keep it constant. Again, increase the air rate slowly. At each value of air rate determine the pressure drop (ΔP) and plot on graph. Determine loading point and flooding point.

c). Repeat for $L_l = 2000\frac{\text{lb}}{\text{ft}^2\ \text{hr}}\left(2.715\frac{\text{Kg}}{\text{m}^2\ \text{s}}\right)$.

Each of the runs with wet packing will provide plots unlike that of the dry packing in that "knees" occur. These "knees" will correspond to loading and flooding points and will occur when the slope of the correlation of $\frac{\Delta P}{L}$ vs. G_V changes (1). At each liquid flow rate, it is essential that a sufficient amount of gas flow be used to ascertain the knee points precisely. The working plot will be used for this purpose. Bring 2-cycle log-log graph paper to class with you.

In the wet packing maximum limitations on gas flow rate will be determined by the onset of flooding.

CAUTION:

1. Do not, under any circumstances, allow the column to operate in such a manner that liquid is carried out with the exit gas. Deductions in grade will occur if it is detected.

2. Always be sure the legs of the seal are filled with water before beginning a new run.

3. Allow some time for the steady state to be achieved after each adjustment and before recording data. This is particularly important if the column has been flooded. It takes awhile to unflood.

At the conclusion of the experiment, close the supply air and water valves on the wall and crack open the control valve. Drain the system completely and close the drain valves. Do not forget to record the packing height in the column.

Data Analysis

1. Plot a graph of $\frac{\Delta P}{L}$, $\frac{\text{inches } H_2 0}{\text{ft packing}}$ versus G_V for each column. Compare data with Leva (2).

2. For the runs with dry packing correlate your data by Equation (1).

3. For all three runs, correlate your data by Equation (4), by linearization.
   Data: Leva (2)

$$\frac{\Delta P}{L} = \alpha (10)^{\beta L_l} \left(\frac{G_v^2}{\rho_v} \right)$$

$$\frac{\Delta P}{L} = \frac{\text{inches } H_2 0}{\text{ft packing}}$$

$$L_l = \frac{\text{lbs}}{\text{ft}^2 \text{ sec}}$$

$$G_V = \frac{\text{lbs}}{\text{ft}^2 \text{ sec}}$$

$$\rho_V = \frac{\text{lbs}}{\text{ft}^3}$$

Determine your measured values of α and β and compare with published data (2).

Nomenclature

A_S = interfacial area of packing per unit of packing volume, $\frac{ft^2}{ft^3}$ or $\frac{m^2}{m^3}$.

D_p = hydraulic particle diameter (not to be confused with diameter of packing), ft or m.

D = inside diameter of column, ft or m.

G_V = vapor mass flow rate per unit of column cross section, $\frac{lb}{hr\ ft^2}$ or $\frac{kg}{m^2\ s}$.

L_l = liquid mass flow rate per unit column cross section, $\frac{lb}{hr\ ft^2}$ or $\frac{kg}{m^2\ s}$.

g_c = conversion factor 32.174 $\frac{ft\ lb_m}{lb_f\ s^2}$ or 1 in SI units.

ε = bed porosity, dimensionless

N_{Re} = average Reynolds number based on superficial vapor velocity and hydraulic particle diameter $\frac{D_p G_v}{\mu}$, dimensionless

ρ_V = vapor density, $\frac{lbs}{ft^3}$ or $\frac{kg}{m^3}$.

ρ_L = liquid density, $\frac{lbs}{ft^3}$ or $\frac{kg}{m^3}$.

μ = vapor viscosity, $\frac{lbs}{ft\ hr}$ or Pa s.

μ_L = liquid viscosity, centipoise or Pa s.

L = bed height, ft or m.

(ΔP) = pressure drop across the bed, $\frac{lbs}{ft^2}$ or Pa.

α, β = packing constants

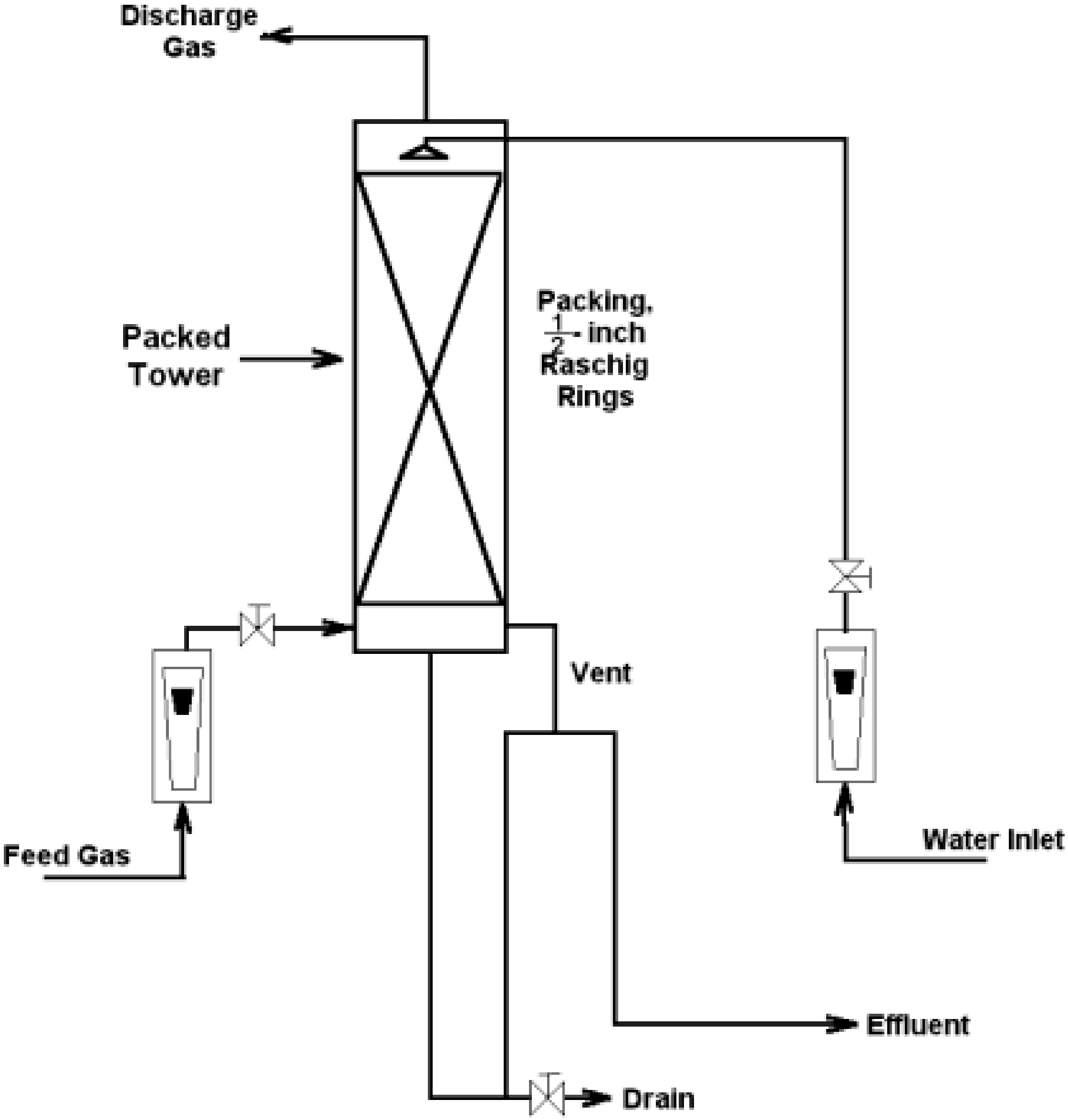
V_p = particle volume, ft^3

A_p = particle surface area, ft^2

v = superficial gas velocity, $\frac{ft}{s}$ or $\frac{m}{s}$

Figure 5

Packed Tower



References (Experiment 3)

1. Foust, A.S., Wenzel, L.A., Clump, C.W., Maris, L., Andersen, L.B., "Principles of Unit Operations", Second Edition, John Wiley & Sons, New York, N.Y. (1980).

2..Leva, M., "Tower Packings and Packed Tower Design", Second Edition, U.S Stoneware Co., Akron, Ohio (1953).

D. *Experiment 4 : Pressure Drop in a Fluidized Bed*

Introduction

Fluidization is observed in a solid-fluid system when the fluid passes at a high velocity vertically up through a solid bed such that the fluid phase is continuous and the solid phase is discontinuous. Fluidized beds have found extensive use as chemical reactors because of good contact and heat transfer in solid-fluid systems. The most classical example is the fluid catalytic cracking reactor used in refineries to convert higher molecular weight hydrocarbons into the smaller molecules used for the gasoline fraction.

Fluid bed reactors become important factors in pollution prevention because the objective of pollution prevention is to improve reactor conversion and yield and reduce side reactions at the front end of the process. Thus, the reaction step is a very important factor in pollution prevention because we aim to reduce the amount of pollutant initially made rather than removing the pollutant after it is made.

In a liquid-solid system when fluidization is smooth and large bubbling or heterogeneity is not observed, particulate or smooth, or homogeneous fluidization occurs. In most solid-fluid systems, however, large bubbles and channeling of gas occurs at fluidization. The flow of solids is not uniform or smooth and aggregate fluidization, or bubbling fluidization occurs. In long, narrow fluidized beds, the phenomenon of slugging can occur at high velocities. Gas bubbles coalesce and become large enough to cover the column cross sectional. Slugging is very undesirable because it produces serious solid entrainment problems.

Experimental Objective

The purpose of this experiment is to study the change in column pressure drop with superficial gas velocity before and after fluidization, and to determine the point of minimum fluidization.

Theory

Many factors are important in fluidization. A few of the more important are;

1. properties of solid

2. properties of fluid

3. bed geometry

4. fluid flow rate

5. type of fluid distribution

6. vessel internals, screens, baffles, heat exchangers

In this experiment, the pressure drop characteristics of a fluidized bed is studied as a function of fluid velocity. The solid particles are polyethylene and the fluidizing medium is air. The bed of solid particles is of uniform size; multi particle size fluidization is not studied.

At low gas velocities, the pressure drop characteristics are those of a fixed bed and the Ergun (1, 2, 3, 4,) equation applies:

$$\left(\frac{\Delta \mathrm{P}}{L}\right)\left(\frac{\mathrm{d_p g_c}}{\rho_{\mathrm{v}} \mathrm{v}^2}\right)\left(\frac{\varepsilon^3}{1-\varepsilon}\right) = 150\left(\frac{1-\varepsilon}{\mathrm{N_{Re}}}\right) + 1.75 \qquad (1)$$

As the gas velocity increases, a maximum pressure drop is reached. The particles begin adjusting to minimize the resistance to flow, the bed begins to expand and there is a slight down turn in pressure drop. The point of maximum pressure drop is the point of minimum fluidization.

Further increases in gas velocity fluidize the bed, the pressure drop rises very slightly until, eventually, slugging and entrainment occur.

At the point of minimum fluidization,

$$\left(\begin{array}{c}\textbf{the upward}\\\textbf{drag force}\end{array}\right) = \left(\begin{array}{c}\textbf{weight of particles}\\\textbf{in the bed}\end{array}\right)$$

$$\left(\begin{array}{c}\textbf{the pressure}\\\textbf{drop across the}\\\textbf{bed}\end{array}\right)\left(\begin{array}{c}\textbf{cross}\\\textbf{section}\\\textbf{al area}\end{array}\right) = \left(\begin{array}{c}\textbf{volume}\\\textbf{of bed}\end{array}\right)\left(\begin{array}{c}\textbf{fraction of}\\\textbf{solids}\end{array}\right)\left(\begin{array}{c}\textbf{specific}\\\textbf{weight of}\\\textbf{solids}\end{array}\right)$$

Thus,

$$(\Delta P)(S) = W = (SL_{mf})(1-\varepsilon_{mf})\left[(\rho_s-\rho_v)\frac{g}{g_c}\right] \qquad (2)$$

or

$$\frac{(\Delta P)}{L_{mf}} = (1-\varepsilon_{mf})(\rho_s-\rho_v)\frac{g}{g_c} \qquad (3)$$

If Equation 3 is combined with Equation 1 then v_{mf} can be calculated by trial and error from the quadratic equation:

$$\frac{1.75}{\phi_s\varepsilon_{mf}}\left(\frac{d_p v_{mf}\rho_v}{\mu}\right)^2 + \frac{150(1-\varepsilon_{mf})}{\phi_s^2\varepsilon_{mf}^3}\left(\frac{d_p v_{mf}\rho_v}{\mu}\right) = \frac{d_p^3\rho_v(\rho_s-\rho_v)g}{\mu^2} \qquad (4)$$

Wen and Yu (5) have shown that for many systems, Equation 4 simplifies to:

For small particles

$$v_{mf} = \frac{d_p^2(\rho_s - \rho_v)g}{1650\mu}, \quad N_{Re} < 20 \qquad (5)$$

For large particles

$$v_{mf}^2 = \frac{d_p(\rho_s - \rho_v)g}{24.5\rho_v}, \quad N_{Re} > 1000 \qquad (6)$$

Procedure

Prior to undertaking the experiment, check with instructor for any special operating or safety instruction. Familiarize yourself with the experiment and determine where main and operational air control valves are located.

Data Analysis

1. On log-log graph paper correlate the pressure drop versus the superficial gas velocity.
2. From your graph determine the minimum fluidization velocity.
3. Compare your measured minimum fluidization velocity with either Equation 5 or 6.

Basic Data

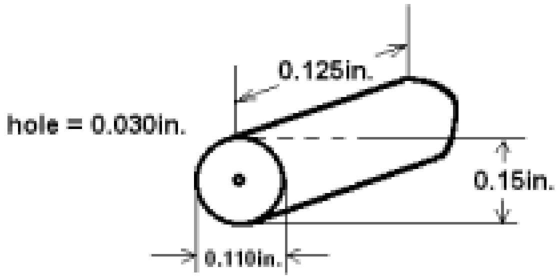
Column: 6-inch diameter Standard Pyrex glass pipe

Packing: Elliptical Cross Section Polyethylene Pellets

$$\text{Approximate Bulk Density} = 0.636\frac{\text{g}}{\text{cc}}$$

$$\text{Approximate Particle Density} = 0.964\frac{\text{g}}{\text{cc}}$$

Approximate Voidage = 0.34



Approximate Size =

$$\text{Volume of Sphere} = \frac{4}{3}\pi R^3 = \frac{\pi d_p^3}{6}$$

Volume of Ellipsoid = πabL

Nomenclature

d_p = particle diameter, ft or m

g_c = constant, 32.174 $\frac{\text{ft lb}_m}{\text{lb}_f\ \text{s}^2}$ or 1 in SI units.

ΔP = pressure drop, $\frac{\text{lbs}}{\text{ft}^2}$ or Pa.

L = bed height, ft or m

ρ_v = gas density, $\frac{\text{lb}_m}{\text{ft}^3}$ or $\frac{\text{kg}}{\text{m}^3}$.

ε = bed void fraction, dimensionless

N_{Re} = Reynolds number, $\frac{d_p v \rho_v}{\mu}$, dimensionless

μ = gas viscosity, $\frac{\text{lbs}}{\text{ft hr}}$ or Pa s.

S = cross sectional area of column, ft^2 or m^2

w = mass of bed, lb_m or kg

ρ_S = particle density, $\frac{\text{lb}_\text{m}}{\text{ft}^3}$ or $\frac{\text{kg}}{\text{m}^3}$

g = gravitational constant, 32.2 $\frac{\text{ft}}{\text{s}^2}$ or 9.81 $\frac{\text{m}}{\text{s}^2}$

v = superficial gas velocity, $\frac{\text{ft}}{\text{s}}$ or, $\frac{\text{m}}{\text{s}}$ based upon empty column cross sectional area

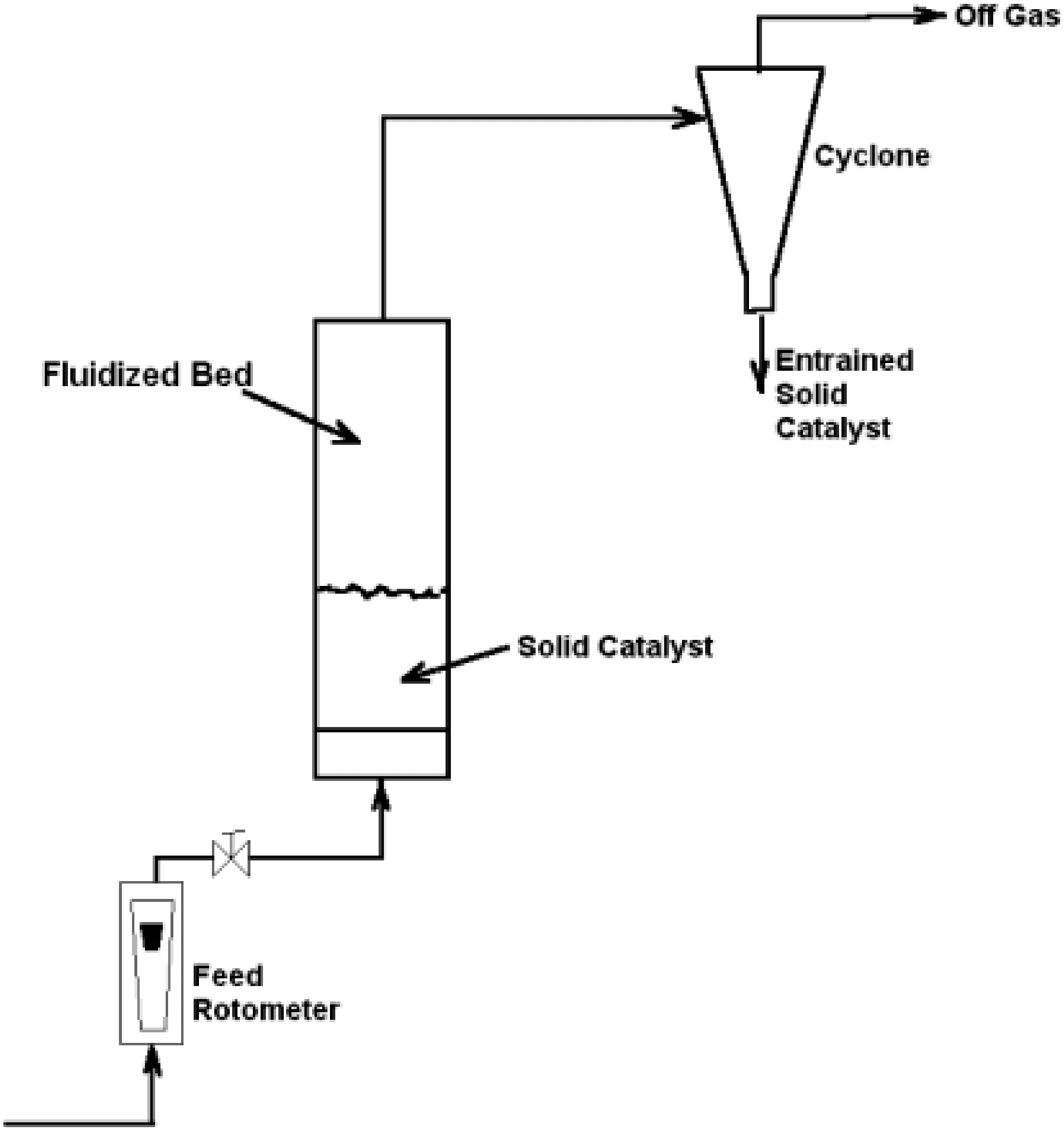
Subscripts

o = initial conditions

mf = minimum fluidization

Figure 6

Fluidized Bed



References (Experiment 4)

1. Kunii, D., and Levenspiel, O., “Fluidization Engineering”, John Wiley & Sons, Inc., New York, N.Y. (1969).

2. Foust, A.S. et al., “Principles of Unit Operations”, Second Edition, John Wiley & Sons, Inc., New York, N.Y. (1980).

3. Geankopolis, C.J., “Transport Processes and Unit Operations,” Third Edition, Prentice Hall, Englewood Cliffs, New Jersey (1993).

4. McCabe, W.L., Smith, J.C., Harriot, P., “Unit Operations of Chemical Engineering,” Fifth Edition, McGraw Hill Inc., New York, New York (1993).

5. Wen, C.Y. and Yu, Y.H., AIChE Journal, 12, 610, (1966).

E. *Experiment 5 : Efflux Time From a Tank*

Introduction

Chemical processes can be classified under two broad categories which relate to their operation, namely continuous or batch. In some large industrial plants combinations of both operations are encountered. Most operations the student is exposed to are of the continuous type but this should not imply that batch operations are unimportant. In the pharmaceutical industry, for example, nearly all chemical syntheses are carried out using batch processes. Good engineering control and planning for these operations are critical for pollution prevention. Examples of batch operations commonly encountered are the emptying of hoppers containing solids, i.e. coal, ore and grain hoppers, and the discharging of tanks, i.e. reaction vessels, and liquid storage tanks. This experiment deals with the emptying of a tank containing water and comparing the experimental data with the theoretical equations.

Experimental Objective

The purpose of this experiment is to study the measured efflux time (drainage time) from tanks.

Theory

In actuality it is impossible to obtain a completely rigorous solution to the efflux problem. In engineering work, it is often necessary for researchers to make reasonable simplifying assumptions which will enable the investigator to develop a correlation, extract the fundamental constants for the system, and hence use the measured data to proceed with a system design. However, by making certain assumptions it is possible to obtain a reasonable approximation of the situation. Some of the assumptions made are justified by the geometry of the experiment.

The simplified model for the emptying of a tank, referred to as efflux time, has been developed by Crosby (1). Using a mechanical energy balance with friction loss in the drain pipe, Crosby (1) showed that

$$\mathrm{t_e} = \left(\frac{8\mu \mathrm{Lr}^2}{\mathrm{gr}_0^4 \rho}\right) \ln\left(\frac{L+H_1}{L+H_2}\right) \qquad (1)$$

for laminar flow, $\mathrm{N_{Re}} = \frac{\mathrm{Dv}\rho}{\mu} < 2000$, and

$$\mathrm{t_e} = \frac{7}{3}\left(\frac{\mathrm{r}}{\mathrm{r}_0}\right)^2 \left(\frac{0.0791 L \mu^{\frac{1}{4}}}{2^{\frac{1}{4}} \mathrm{g} \rho^{\frac{1}{4}} \mathrm{r}_0^{\frac{5}{4}}}\right)^{\frac{4}{7}} \left((L+H_1)^{\frac{3}{7}} - (L+H_2)^{\frac{3}{7}}\right) \qquad (2)$$

for turbulent flow, $\mathrm{N_{Re}} = \frac{\mathrm{Dv}\rho}{\mu} > 4000.$

The adequateness of an analytical model can be determined by comparison with experimental data obtained from a constructed prototype. This experiment attempts to undertake this exercise by comparing the correlations given by Crosby (1) with measured data.

Procedure

Check with the laboratory instructor prior to undertaking the experiment as to which part of the experiment the student is to study and any safety precautions.

Examine the experimental apparatus in order to determine where the tank inlet water control valves are. After the instructor identifies which column and exit pipes (length and diameter) are to be used, open the main water valve. Then screw into the valve (or column) the first adapted pipe to be studied. Then open the water valve to the study column and fill the column to a previously determined height with water. (A good starting point is 48 inches, or 1.2192 m, as measured on the column proper and not from the middle of the valve). Then close the water valve to the column. The student should keep this level the same for every run in order to have a valid initial comparison point.

Open the quick opening valve and allow the level to drop to 44 inches (1.118 m) then start the timers at this point. Record the time required for the level to fall every 4 inches (0.1016 m) until the level reaches 4 inches (0.112 m) from the bottom of the column, then terminate your run (turn off time) for that pipe. Repeat this procedure as many times as required by the number of pipes and columns specified for the experiment. Be sure to record time-height datum).

For the system without a valve in the discharge line (column #3), hold the palm of your hand at the outlet of the discharge pipe to stop the flow, then follow the procedure for the valved column for filling the column. Removing your palm allows flow which is the same as opening a valve.

NOTE: Be sure to have the discharge collection tank under the study column and the tank discharge hose in or on the drain.

Data Analysis

The principle variables in this study are tank diameters, pipe diameters, and pipe lengths. Since each group will have a different combination of these variables, the student should be certain all variable effects are properly ascertained. In general, the following correlations should be examined for your systems:

1. Correlate the level in the tank, H in inches, with the time of flow on arithmetic graph paper.

2. At the lowest flow rate, estimate the Reynolds number at the pipe exit.

3. Use Equation 1 or 2, whichever is applicable, and compare your measured data with the relationship by linearization.

4. Use linear regression analysis to determine the slope and compare the measured slope to the theoretical slope given by Equation 1 or 2.

Nomenclature

v = velocity at pipe exit, $\frac{\text{ft}}{\text{s}}$ or $\frac{\text{m}}{\text{s}}$

g = acceleration due to gravity, 32.2 $\frac{\text{ft}}{\text{s}^2}$ or 9.8066 $\frac{\text{m}}{\text{s}^2}$.

r_0 = radius of exit pipe, inches or feet.

L = length of exit pipe, inches or feet.

H_1 = height of liquid in tank initially, inches or feet.
H_2 = height of liquid in tank initially, inches or feet.

μ = viscosity, $\frac{\text{lb}_\text{m}}{\text{ft} \cdot \text{s}}$ or Pa.

ρ = density, $\frac{\text{lb}_\text{m}}{\text{ft}^3}$ or $\frac{\text{kg}}{\text{m}^3}$

r = radius of tank, ft or m.

N_{Re} = Reynolds number, dimensionless, $\frac{Dv\rho}{\mu}$.

D = inside pipe diameter, ft or m.

t_e = efflux time, sec.

References (Experiment 5)

1. Crosby, E.J., “Experiments in Transport Phenomena”, pp. 44-54, John Wiley & Sons, New York, N.Y. (1961).

2. Hanesian, D., “Chemical Engineering Laboratory Manual,” Second Printing, 1984.

F. *Experiment 6 : Fluid Flow and Friction Loss in Pipes and Fittings*

Introduction

The flow and behavior of fluids is important in many of the unit operations in process engineering. The behavior of a flowing fluid depends strongly on whether or not the fluid is under the influence of solid boundaries. In the regions where the influence of the wall is small, the shear stress may be negligible and the fluid may approach that of an ideal fluid, one that is incompressible and has zero viscosity. In this experiment, the characteristics of fluid flowing through pipes, pipe fittings, and three types of metering devices will be examined.

Experimental Objective

The purpose of this experiment is to study the measurement of fluid flow rates with various meters and to determine the friction effects of pipe expansion, pipe contraction, various pipe fittings, straight pipes, and the effect of pipe roughness factor.

Theory

When fluid moves through a closed channel, either of two distinct types of flow can be observed. The first type of flow, called laminar flow, generally occurs at lower velocities; the layers of the fluid slide by one another without the formation of eddies or swirls. The second type of flow, turbulent flow, generally occurs at higher velocities. The turbulent flow regime can be characterized by the presence of eddies and swirling.

Research has shown that the flow regime in tubes is not only a function of velocity but also of the tube diameter and the density and viscosity of the fluid. The regime of flow can be determined from the dimensionless Reynolds number:

$$N_{\mathrm{Re}} = \frac{Dv\rho}{\mu} \qquad (1)$$

The flow is laminar when N_{Re} is less than 2100 and turbulent when the Reynolds number is greater than 4000. When N_{Re} is in between, the flow is said to be in the transition region.

The length required to fully establish a developed velocity profile is called the entry length or transition length.

In the laminar flow regime the pressure drop relationship to the number of velocity heads can be shown by the Hagen-Poiseuille equation:

$$\Delta P = \frac{32LV\mu}{g_c D^2} \qquad (2)$$

For laminar flow only, the Fanning friction factor is equal to:

$$f = \frac{16}{N_{\mathrm{Re}}} = \frac{16}{Dv\rho/\mu} \qquad (3)$$

where f is the Fanning friction factor. The Blasius, Darcy Moody friction factor, f′, is equal to 4f.

As in the laminar flow regime, the friction factor in the turbulent regime depends on the Reynolds number. The Fanning friction factor, however, is not a simple function of the Reynolds number. The pressure drop in the turbulent regime is calculated using the following equation:

$$\frac{\Delta P}{\rho} = 4f\frac{L}{D}\frac{V^2}{2g_c} \qquad (4)$$

For fittings,

$$\frac{\Delta P}{\rho} = \phi\left(\frac{V^2}{2g_c}\right) \qquad (5)$$

where ϕ = number of velocity heads, and

$$\phi = 4\,f\,\frac{L_e}{D} \text{ and } \frac{L_e}{D} = \frac{\phi}{4f} \qquad (6)$$

Friction Loss in Expansion, Contraction, and Pipe Fittings

For straight pipes the friction losses can be calculated using the Fanning friction factor. Additional friction losses occur if the velocity of the flowing fluid changes in direction or magnitude. Further losses will occur if the path of the flowing fluid is obstructed by a valve or meter.

If the cross sectional area of a pipe enlarges very gradually, little or no extra losses are incurred. If the change is sudden, the additional losses are due to the eddies formed by the expanding jet. The following equation yields the friction losses:

$$h_{ex} = \frac{\left(V_1 - V_2\right)^2}{2\alpha g_c} = \left(1 - \frac{A_1}{A_2}\right)^2 \frac{V_1^2}{2\alpha g_c} = K_{ex}\,\frac{V_1^2}{2\alpha g_c} \qquad (7)$$

If the flow is laminar, $\alpha = 0.5$, and equals 1.0 for turbulent flow.

Similarly, when the cross sectional area of a pipe is suddenly reduced additional frictional losses occur. The losses can be calculated as follows:

$$h_c = 0.55\left(1 - \frac{A_2}{A_1}\right)\frac{v_2^2}{2\alpha g_c} = K_c\,\frac{v_2^2}{2\alpha g_c} \qquad (8)$$

If the flow is in the laminar regime, Equation 7 can be used with $\alpha = 0.5$ and $\alpha = 1.0$ for turbulent flow.

Pipe fittings and valves also contribute the frictional losses. The friction losses from fittings often exceed those from the interconnecting pipe. The friction loss for fittings and valves is given by the following equation:

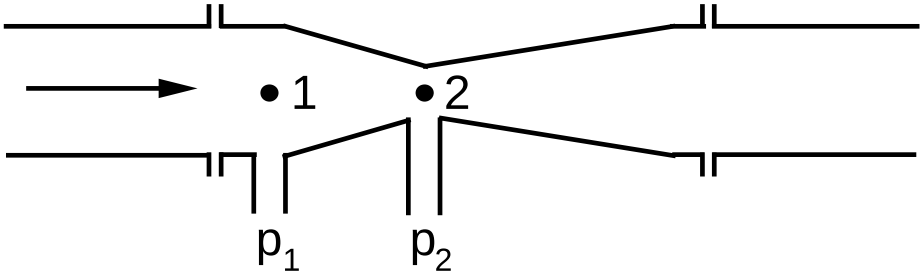
$$h_f = K_f \frac{v_1^2}{2} \qquad (9)$$

Measurement of Flow

Many different types of devices are used to measure the flow of fluids. Very widely used for fluid metering are the Pitot tube, venturi meter, orifice meter. A venturi meter is usually inserted directly into a pipeline as shown below (Figure 1).

Figure 1

Venturi Flow Meter



The velocity at point 2, the throat, is given by the following equation:

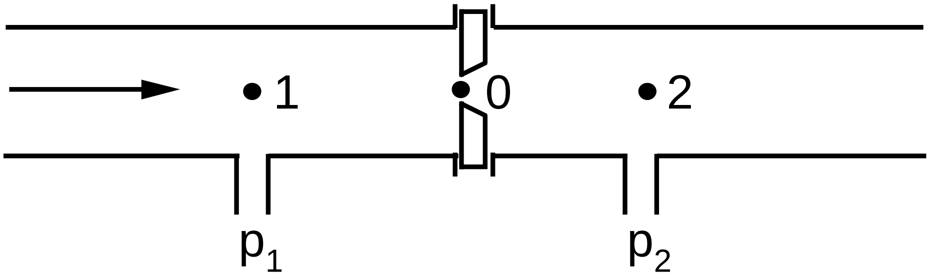
$$V_2 = \frac{C_v}{\sqrt{1-(D_2/D_1)^4}} \sqrt{\frac{2g_c(p_1-p_2)}{\rho}} \qquad (10)$$

where the venturi coefficient, C_v, is added to account for the small friction loss between points 1 and 2. The venturi coefficient is experimentally determined.

The orifice meter (Figure 2) has a larger pressure drop than the venturi meter, but it is much less expensive and easier to install. The head loss is greater due to the formation of eddies when the jet expands beyond the vena contracta (0).

Figure 2

Orifice Flow Meter



The equation for the orifice meter is similar to that of the venturi meter:

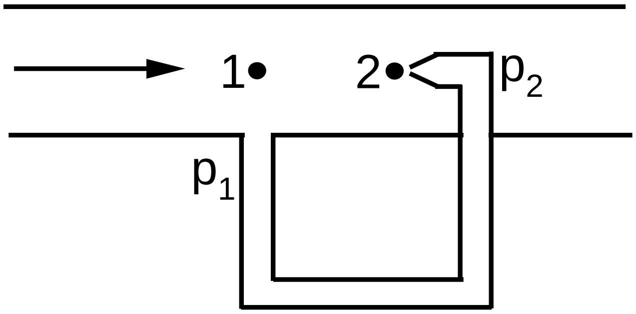
$$V_o = \frac{C_o}{\sqrt{1-\left(D_o/D_1\right)^4}}\sqrt{\frac{2g_c\left(p_1 - p_2\right)}{\rho}} \qquad (10)$$

As with the venturi meter, the orifice coefficient is experimentally determined.

The Pitot tube is shown in Figure 3.

Figure 3

Pitot Tube



The equation for the Pitot tube is:

$$V_1 = C_p \sqrt{\frac{2g_c\left(p_2 - p_1\right)}{\rho}} \qquad (11)$$

where C_p = Pitot tube coefficient and is generally very nearly equal to 1.0.

Procedure

CAUTION:

You will be working with water and electricity . . . Please use CAUTION when performing this experiment.

Operation of the Manometers

NOTE: Before beginning operation of the manometers, you should thoroughly read the Operation of the Self-Bleeding Manometers (Instruction Manual, Fluid Friction Apparatus, page 6 and page 12). Carefully study the diagram on page e and A1 in the Instruction Manual and understand why each of the valve operations described in the procedure are performed. Pay particular attention to the order of the valve operations. Once you understand basic manometer operation, continue with the procedure described below.

To connect a test probe to a pressure measurement point, push the tip of the test probe into the measurement point connector until it latches. Each measurement point on the apparatus is fitted with a self-sealing connection to prevent water leakage. Press the metal clip on the side of the connector to disconnect a test probe from a measurement point.

In operation, the connecting valves are set to the 90° position and the test probes are connected onto the required measurement points. Before going any further, make sure that all of the air bubbles in the system are purged into the tank via the vents in the body. This will ensure that the valve connection to the manometer remains sealed keeping the manometer fully primed. When all the air bubbles have been expelled, open the valve connecting the measurement point directly to the manometer. Before you remove the test probes, return the valve to the 90° position to seal the manometer.

Measuring the volumetric flow

The apparatus allows experiments to be run at low or high flow rates. Locate the remote sight gauge (Item 25, Instruction Manual, page 18) on the front of the service module. Note that this scale is divided into two zones corresponding to the volume above and below the step in the tank. The remote sight gauge measures the volume (liters) in the tank at any given time. The lower scale is to be used for low water flow rates; the upper scale is to be used for higher flow rates. A stilling baffle is used to reduce turbulence in the tank.

Before you start taking data, make sure that the volumetric tank is emptied by lifting the dump valve. To measure the water flow rate, close the dump valve, start the timer simultaneously, and measure the liquid volume in the tank. The flow rate is obtained by dividing the volume (liters) by the time (seconds). For each flow rate, make three runs and take the average to get the flow rate. Small volumes are measured on the lower portion of the scale monitoring the small tank volume beneath the step. Larger flow rates are measured on the upper scale corresponding to the main tank.

Commissioning and Bleeding the system (Instruction Manual, page 14)

The term bleeding describes the process by which air is purged from the system. Before starting the bleeding procedure make sure that the sump tank (23) is filled to about 80 mm from the top.

Close the inlet and outlet flow valves (V2 and V6). Plug the pump into the power outlet located behind the apparatus and start the pump. You will hear the motor when the pump is operating. Open the inlet flow valve (V2) and the outlet valve (V6) and observe that the water returns to the volumetric tank.

Open the dump valve so that the water returns to the sump tank. Open the air bleed valves (V3) located on the top right and top left side of the equipment. Open all the pipe valves in the system including the ball valve, the gate valve, and the globe valve. Filling all the pipes with water will ensure that all air is purged from all parts of the system.

After removing the air, close the two air bleed valves (V3). Close the outlet water flow valve (V6) and then the inlet flow valve (V2). This will keep the system completely free of air. Be sure to close the outlet water flow valve first followed by the inlet water flow valve. If the inlet flow valve is closed first, some water will drain out of the system creating air pockets; rebleeding may be necessary.

Data Analysis

Measure and graph the Fanning friction factor as a function of the Reynold's number and indicate the laminar flow regime, the transition region, and the turbulent regime.

Measure and perform an error analysis of the relative accuracy of the venturi flow meter and the orifice meter. Based on the meter geometries presented, postulate why the venturi meter might be more accurate and why its coefficient is different from that of the orifice meter.

Measure and graph the friction factors of each type of fitting. Calculate the equivalent length of straight pipe required to produce the same amount of frictional losses as each type of fitting.

(Your instructor will assign different experiments to be conducted. Consult your instructor for the experimental data analysis procedure.)

Note: Remember that you will be working with water and electricity. If you are uncertain about anything, DO NOT hesitate to consult your instructor or teaching assistant.

Nomenclature

N_{Re} = Reynolds number, dimensionless

D = inside pipe diameter, m or ft

ρ = fluid density, $\frac{\text{kg}}{\text{m}^3}$ or $\frac{\text{lb}_\text{m}}{\text{f}t^3}$

μ = fluid viscosity, Pa$s or $\frac{\text{lb}_\text{m}}{\text{f}t \cdot \text{s}}$

V = average fluid velocity, $\frac{\text{m}}{\text{s}}$ or $\frac{\text{ft}}{\text{s}}$

f = Fanning friction factor, dimensionless

g_c = conversion factor, $1\frac{\text{kg} \cdot \text{m}}{\text{N} \cdot \text{s}^2}$ or $32.174\frac{\text{l}b_m \cdot \text{f}t}{\text{l}b_f \cdot \text{s}^2}$

L = pipe length, m or ft

ϕ = number of velocity heads, dimensionless

L_e = the length of tube necessary to give the same frictional loss observed for the fitting, m or ft

h_{ex} = the friction loss of pipe expansion, $\frac{\text{J}}{\text{kg}}$ or $\frac{\text{lb}_\text{f} \cdot \text{ft}}{\text{lb}_\text{m}}$

K_{ex} = the expansion-loss coefficient = $(1 - \frac{A_1}{A_2})^2$

V_1 = the upstream velocity, $\frac{\text{m}}{\text{s}}$ or $\frac{\text{ft}}{\text{s}}$

V_2 = the downstream velocity, $\frac{\text{m}}{\text{s}}$ or $\frac{\text{ft}}{\text{s}}$

h_c = the friction loss of pipe contraction, $\frac{\mathrm{J}}{\mathrm{kg}}$ or $\frac{\mathrm{lb_f \cdot ft}}{\mathrm{lb_m}}$

K_c = the contraction-loss coefficient = $0.55(1 - \frac{A_1}{A_2})$, dimensionless

$\alpha = 1.0$ for turbulent flow; $\alpha = 0.5$ for laminar flow, dimensionless

h_f = the friction loss through a fitting, $\frac{\mathrm{J}}{\mathrm{kg}}$ or $\frac{\mathrm{lb_f \cdot ft}}{\mathrm{lb_m}}$

K_f = the loss coefficient for the fitting or valve, dimensionless

C_v = Venturi meter coefficient, dimensionless

V_o = the velocity in the orifice, $\frac{\mathrm{m}}{\mathrm{s}}$ or $\frac{\mathrm{ft}}{\mathrm{s}}$

D_o = the orifice diameter, m or ft

C_o = the orifice coefficient, dimensionless

C_p = the Pitot tube coefficient, dimensionless

p_1 = upstream pressure, $\frac{\mathrm{N}}{\mathrm{m}^2}$ or $\frac{\mathrm{lb_f}}{\mathrm{f}t^2}$

p_2 = downstream pressure, $\frac{\mathrm{N}}{\mathrm{m}^2}$ or $\frac{\mathrm{lb_f}}{\mathrm{f}t^2}$

G. *Experiment 7 : Agitation in Tanks*

Introduction

Agitation is fundamental to processing operations. Both heat and mass transfer are greatly influenced by agitation. Although agitation is an integral part of chemical processing, it is not amenable to rigid theoretical analysis.

Agitation can be defined as “the creation of a state of activity such as flow or turbulence apart from any mixing accomplished.” Mixing, however, is defined as “the intermingling of two or more different proportions of material resulting in the desired level of uniformity, either physical or chemical, in the final product.”

The rotation of an agitator in a confined liquid mass produces eddy currents. These are formed as a result of velocity differences within the liquid. High velocity streams coming in contact with lower velocity streams produce momentum transfer. Therefore, it is important to determine the energy requirements for such an operation.

Experimental Objective

The objectives of this experiment are to develop the power number versus the modified Reynold’s number in a baffled tank for various agitator configurations, and to develop the power requirement per gallon of fluid as compared with the modified Reynold’s number for several different paddle systems.

Theory

The power requirement for agitating a liquid in a tank is amenable to dimensional analysis. It is possible to relate the power required during agitation to the various parameters of the agitated fluid. Dimensional analysis is a technique used to express the behavior of a physical system in terms of the minimum number of independent variables.

Power consumed in a baffled tank is dependent on N, D_a, μ, g_c, and ρ. It is also assumed in this case that the other dimensions such as height of the liquid in the tank, diameter of the tank, and the number, size and dimensions of the baffles are strictly related to the agitator diameter.

By dimensional analysis, it can be shown that in a given baffled system:

$$\frac{Pg_c}{N^3 D_a^5 \rho} = f\left[\frac{D_a^2 N\rho}{\mu}\right] \qquad (1)$$

or

$$N_{p_0} = f\left(N_{\mathrm{Re}}\right) \qquad (2)$$

or the power number is a function of the modified Reynold's number.

A plot of N_{po} versus N_{Re} on log-log coordinates is commonly called a power curve. An individual power curve is only true for a particular geometrical configuration, but it is independent of vessel size.

If a power curve is available for a particular tank configuration, it may be used to calculate power for various agitator speeds, liquid viscosities and densities. Hence, studies on small scale equipment can be used in scale up to larger vessels if caution is observed in maintaining the correct geometries.

Procedure (Instruction Manual, pages 7-8, pages 13-14)

Turn drain cock to the horizontal (closed) position. Make sure that the drainage hose is positioned to empty the bucket. Fill the vessel with 15 liters of fresh water. Make sure the plug and socket are dry. Plug in the power supply. Do not turn on yet. Unhook the force balance and very carefully lift the agitator out of the vessel.

Find the turbine, locking collar and the paddles labeled 1-6. Begin with set of paddles labeled 1. Screw in the paddles so that the numbers are right side up and readable. Make sure that the paddles are secured tight enough not to fall off during agitation.

Put the locking collar on the shaft of the agitator making sure that the screw is against the flat side of the shaft. Tighten with a wrench or pliers so that the collar will not fall off midway through the experiment. Very carefully put the agitator back into the tank lining up the holes in the top with the bolts on the frame.

Rehook the force balance and place the settling block across the A-arm of the agitator. Line the top of the force balance up with the white around the frame. This is done by tightening and loosening the screws on the top of the apparatus behind the spring. Zero the force balance by holding the ball at the bottom of the balance and loosening the bolt on the side. Raise and lower the ball until the balance reads zero.

Turn on the power to the apparatus and remove the settling block. Raise the rpm in 25 rpm increments, being sure to give the system 20-30 seconds to stabilize before taking a reading and advancing to the next increment. Warning: the readings will be very small at first. Do not read them as zero; estimate to the best of your ability.

Keep taking readings until the A-arm becomes pinned (the arm has no further room for movement). Repeat the above steps for each of the numbered paddles, including use of the turbine, as time permits.

Data Analysis

Plot a graph on log-log paper of N_{po} versus N_{Re} for the turbine as well as for each paddle system used.

Plot a graph on log-log paper of horsepower / gallon versus N_{Re} for the turbine as well as for each paddle system used. This is known as a power requirement graph.

Figure 1 gives the dimensions of the agitation tank.

Nomenclature

N = rpm of agitator, $\frac{\text{revs}}{\text{min}}$

D_a = diameter of paddle, m or ft

g_c = conversion factor, $1\frac{\text{kg}\cdot\text{m}}{\text{N}\cdot\text{s}^2}$ or $32.174\frac{\text{l}b_m\cdot\text{f}t}{\text{l}b_f\cdot\text{s}^2}$

P = Power (torque * rpm / 60), W or $\frac{\text{lb}_\text{f}\cdot\text{ft}}{\text{s}}$

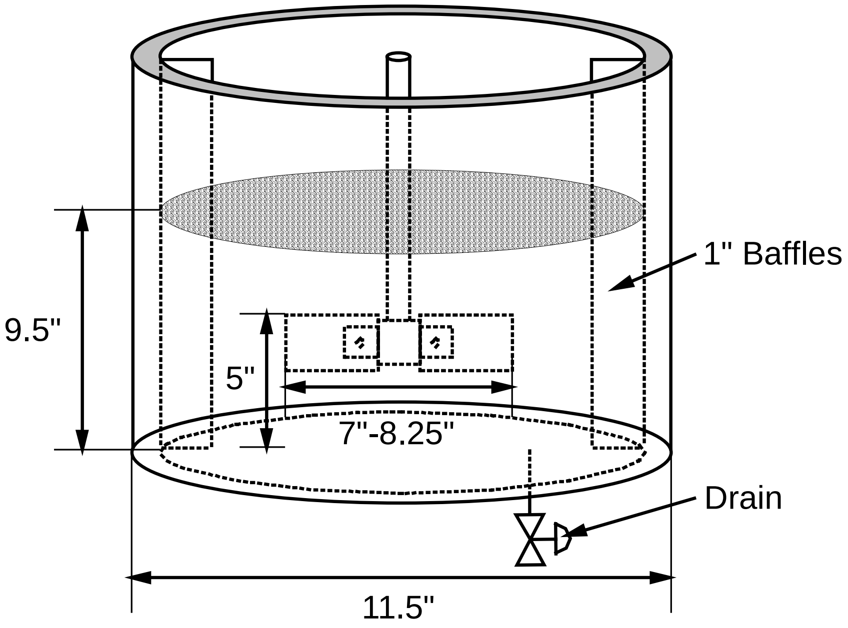
torque = force * torque-arm radius, J or $\text{lb}_\text{f}\cdot\text{ft}$

μ = viscosity, Pa·s or $\frac{\text{lb}_\text{m}}{\text{ft}\cdot\text{s}}$

ρ = density, $\frac{\text{kg}}{\text{m}^3}$ or $\frac{\text{lb}_\text{m}}{\text{f}t^3}$

Figure 1

Tank Dimensions



H. *Experiment 8 : The Concentric Tube Heat Exchanger*

Introduction

Heat transfer is the exchange of energy, in the form of heat, from one medium to another. Heat transfer is widely used in the process industry today due to the increasing cost of energy and the need to recover heat that might otherwise be lost. Industrial heat transfer is accomplished through the use of various heat exchangers. They are often used in combination with other unit operations, such as drying, distillation, fuel combustion, or evaporation.

Heat transfer takes place due to a temperature difference driving force inducing heat flow from the high to the low temperature region. There are three fundamental types of heat transfer: conduction, convection, and radiation.

Conduction, occurring in solids, liquids, and gases, is a transfer of energy of motion between adjacent molecules or the transfer of “free” electrons in metallic solids. Examples of this are heat transfer through walls of heat exchangers, heat treatment of steel forging, and the freezing of the ground during the winter.

Convection, occurring in solids, liquids, and gases, is the transfer by bulk transport and the mixing of warmer and cooler portions of macroscopic elements. Forced convection is where a fluid is forced to flow past a solid surface via a pump or some other mechanical means; natural convection is where the warmer or cooler fluid next to a solid surface causes a movement caused by a density difference in the fluid. Examples of convection are the heat loss from a car radiator, the boiling of water in a stirred pot, and the cooling of coffee by blowing on the surface.

The last type, radiation, is the transfer of energy through space by way of electromagnetic waves. Solids and liquids absorb the radiation that is transferred. Radiation is primarily important in the transfer of heat from the sun to the earth, microwave cooking, and the heating of fluids in coils of tubing inside a combustion furnace.

In operations that require the heating or cooling of a material, steam and/or cold water are the mediums of choice. They have the relatively high heat transfer coefficients, and are both readily available.

One of the most important types of exchanger is the continuous flow shell-and-tube exchanger. A shell-and-tube exchanger consists of a tube (in which the hot medium flows) and a shell which surrounds the tube (in which the cold medium flows). Heat transfer is accomplished by convection through one fluid, conduction through the tube wall, and then again by convection by the other fluid.

There are two types of flow that are encountered with shell-and-tube exchangers: parallel and countercurrent. In parallel flow, the hot medium in the tube flows in the same direction as the cold medium in the shell. In countercurrent flow, the flow in the tube is in the opposite direction as the flow in the shell. A simple variation of a shell and tube heat exchanger with numerous tubes is a concentric tube heat exchanger with one pipe inside a larger pipe.

The overall heat transfer coefficient, U_o, is a quantity that combines the effects of conduction and convection. These effects vary depending on the medium used, the contact area of the shell-and-tube, and the logarithmic mean of the temperature difference driving force.

Experimental Objective

The objective of this experiment is become familiarized with the concentric tube heat exchanger assuming steady-state conditions (the rate of heat transfer is constant with time) and to compare the overall heat transfer coefficient, U_o, at various flow rates for parallel and countercurrent flows.

Theory

For a shell-and-tube heat exchanger, the heat equation is:

$$Q_{avg} = U_o A_o \Delta T_{LM} \qquad (1)$$

The heat transfer rates are related by the equation:

$$Q_H = M_H C_p \Delta T = m_C c_p \Delta t = Q_C \qquad (2)$$

The heat transfer rates, Q_H and Q_C, should theoretically be equal, yielding 100% efficiency. When they are not equal, the efficiency or the percent closure can be calculated by:

$$\%\ \text{closure} = \left| \frac{Q_H - Q_C}{Q_H} \right| \qquad (3)$$

The log mean temperature difference, ΔT_{LM}, describes the relationship between the inlet and outlet temperatures (see figures 1 and 2).

Figure 1
Parallel Flow

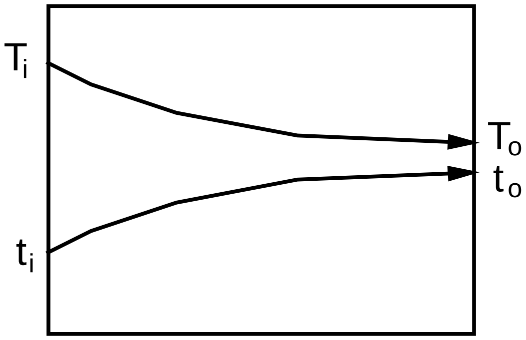
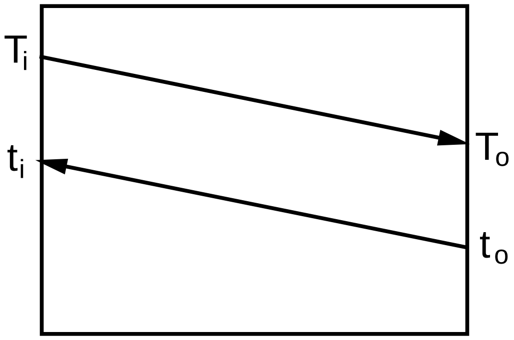


Figure 2
Countercurrent Flow



For parallel flow, ΔT_{LM} is calculated by the following equation,

$$\Delta T_{LM} = (T - t)_{LM} = \frac{(T_i - t_i) - (T_o - t_o)}{\ln \dfrac{(T_i - t_i)}{(T_o - t_o)}} \qquad (4)$$

For countercurrent flow, ΔT_{LM} is calculated by a similar equation,

$$\Delta T_{LM} = (T - t)_{LM} = \frac{(T_o - t_o) - (T_i - t_i)}{\ln \frac{(T_o - t_o)}{(T_i - t_i)}} \qquad (5)$$

Experimental values of U_o can be calculated from Equation 1.

Procedure

Be very careful, you're working with water and electricity. Before starting the experiment, study the apparatus and become familiarized with it. Make sure the tank is filled with water, the drain valves are fully closed, and the unit is plugged in.

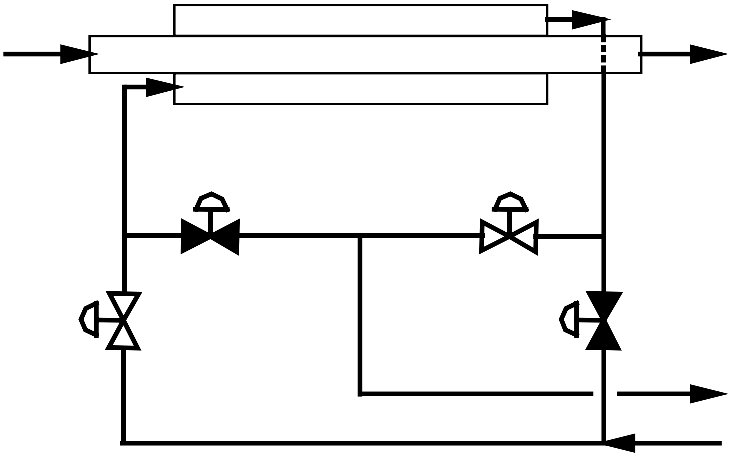
The system may require purging due to the presence air and therefore. In addition, the pump may need priming. Call the instructor for help.

Part 1 - Parallel Flow

Turn on the power switch and the water supply. Set the selector valves to the parallel flow position (see Figure 3).

Figure 3

Parallel Flow



Set the temperature controller to 60°C using the control knob on the front panel. Allow some time for the water to reach 60°C.

Open the hot water flow control valve and allow water to flow through the exchanger at 2.0 L/min. Set the cold water at different flow rates and record the following readings:

Note: After setting each cold water flow rate, allow the system to reach equilibrium by waiting at least 15 minutes before recording the temperature.

Cold Water Flow Rate (L/min)	$t_H$in (°C)	$t_H$mid (°C)	$t_H$out (°C)	$t_C$in (°C)	$t_C$mid (°C)	$t_C$out (°C)

Set the cold water flow rate constant at 1.0 L/min. Set the hot water at different flow rates and record the following readings:

Note: After setting each cold water flow rate, allow the system to reach equilibrium by waiting at least 15 minutes before recording the temperature.

Hot Water Flow Rate (L/min)	$t_H$in (°C)	$t_H$mid (°C)	$t_H$out (°C)	$t_C$in (°C)	$t_C$mid (°C)	$t_C$out (°C)

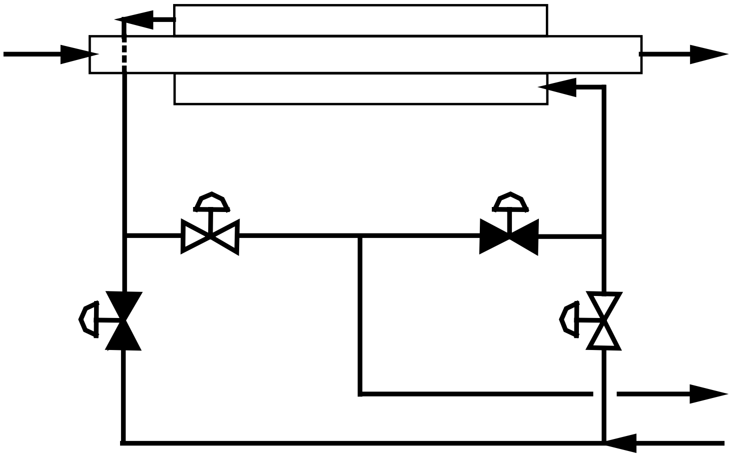
Power down the system before switching to countercurrent flow.

Part II - Countercurrent Flow

Set the selector valves to the countercurrent position (see Figure 4).

Figure 4

Countercurrent Flow



Set the temperature controller to 60°C.

Open the hot water flow control valve and allow water to flow through the exchanger at 2.0 L/min. Set the cold water at different flow rates and record the following readings:

Note: After setting each cold water flow rate, allow the system to reach equilibrium by waiting at least 15 minutes before recording the temperature.

Cold Water Flow Rate (L/min)	$t_H$in (°C)	$t_H$mid (°C)	$t_H$out (°C)	$t_C$in (°C)	$t_C$mid (°C)	$t_C$out (°C)

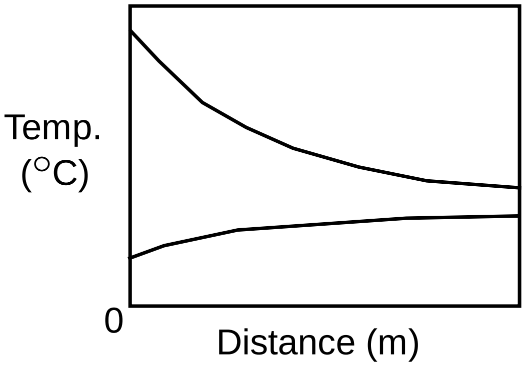
Set the cold water flow rate constant at 1.0 L/min. Set the hot water at different flow rates and record the following readings:

Note: After setting each cold water flow rate, allow the system to reach equilibrium by waiting at least 15 minutes before recording the temperature.

Hot Water Flow Rate (L/min)	$t_H$in (°C)	$t_H$mid (°C)	$t_H$out (°C)	$t_C$in (°C)	$t_C$mid (°C)	$t_C$out (°C)

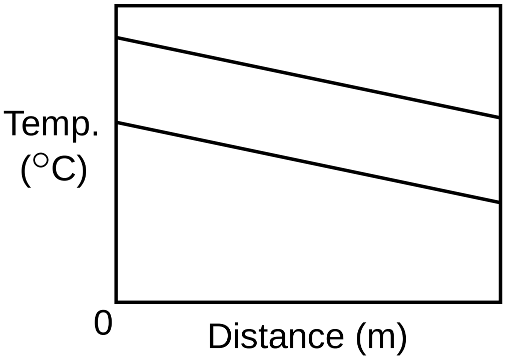
Graph the following from the experimental data obtained:

Figure 5



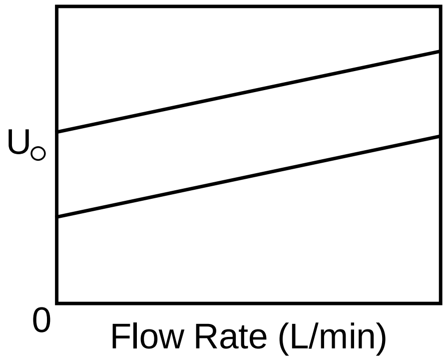
Temperature vs. Distance
for Parallel Flow

Figure 6



Temperature vs. Distance
for Countercurrent Flow

Figure 7



U_O vs. Flow Rate
for Parallel and Countercurrent Flow

Basic Data

water at 60°C	water at 20°C
$\rho = 983.24\ \mathrm{kg/m^3}$	$\rho = 998.23\ \mathrm{kg/m^3}$
$C_p = 4.187$ kJ/kg K	$c_p = 4.185$ kJ/kg K

Use the following equations to calculate the ΔT and Δt for the inlet and outlet fluid temperatures:

$\Delta T = T_i - T_o$ and $\Delta t = t_o - t_i$

Nomenclature

T_i = Temperature of the hot fluid going in, °C

T_o = Temperature of the hot fluid going out, °C

t_i = Temperature of the cold fluid going in, °C

t_o = Temperature of the cold fluid going out, °C

ΔT = Temperature difference between the inlet and outlet temperature of the hot stream, °C

Δt = Temperature difference between the outlet and inlet temperature of the cold stream, °C

M_H = Flow rate of the hot fluid, $\frac{L}{min}$ or $\frac{kg}{s}$

m_C = Flow rate of the cold fluid, $\frac{L}{min}$ or $\frac{kg}{s}$

Q_H = Heat transfer rate of the hot fluid, $\frac{kJ}{s}$

Q_C = Heat transfer rate of the cold fluid, $\frac{kJ}{s}$

Q_{avg} = Average heat transfer rate $\frac{Q_H + Q_C}{2}$, $\frac{kJ}{s}$

$\Delta T_{LM} = (T - t)_{LM}$ = Log mean temperature difference, °C

U_o = Overall heat transfer coefficient, $\frac{W}{m^2 \cdot {}^oC}$

C_p = Heat capacity of the hot fluid, $\frac{kJ}{kg \cdot {}^oC}$

c_p = Heat capacity of the cold fluid, $\frac{kJ}{kg \cdot {}^oC}$

ρ = Density of the fluid, $\frac{kg}{m^3}$

A_o = Area of the heat transfer surface, m^2

I. *Experiment 9 : Fixed and Fluidized Beds*

Introduction

The upward flow of fluid through a bed of particles is an important process occurring in nature and in industrial operations. When fluid passes at a high velocity upward through a solid bed such that the fluid phase is continuous and the solid phase is discontinuous, a phenomenon called fluidization occurs. This phenomenon takes place naturally in “quick sand” and can often be advantageous for industrial applications. Fluidized beds are extensively used as chemical reactors because of the good heat transfer contact and because the bed, once fluidized, will flow and can be pumped just like a fluid. One example is the fluid catalytic cracking reactor used in refineries to “crack” higher molecular weight hydrocarbons into the smaller molecules used for the gasoline fraction. Fluidized bed reactors are also used in pollution prevention to reduce potentially harmful side reactions at the front end of a process.

The apparatus used in this experiment was designed to allow the study of the characteristics of flow through both fixed and fluidized beds of solid particles. The unit is made for the simultaneous study of air and water systems in order to show the differences between “aggregative” or non-uniform fluidization and “particulate”, or smooth, uniform fluidization.

“Particulate” fluidization occurs when fluidization is smooth and large bubbling is not observed. This kind of fluidization should be observed when water is used as the fluid medium. Of course, in most solid-fluid systems, this particular kind of fluidization does not take place. Non-uniform or “aggregative” fluidization occurs when the fluid is a gas and the velocity is in excess of that required for fluidization. When this happens, large bubbling and “channeling” of the gas is observed. This more common kind of fluidization should be observed when air is used as the fluid medium. In long, narrow fluidized beds, the phenomenon of “slugging” can occur at high gas velocities. The gas bubbles coalesce and become large enough to cover the entire cross-section of the column. Slugging is undesirable because it causes severe entrainment problems.

It is important to note that the test columns on the apparatus are wide enough so that bubbling can be observed without the risk of slugging.

Experimental Objective

The purpose of this experiment is to determine the pressure drop through a fixed and fluidized bed, verify the Carmen-Kozeny equation, observe the onset of fluidization, to determine the point of minimum fluidization, and to measure the effect of superficial fluid velocity on bed height. This is to be done twice, once with water and once with air.

Theory

Fixed Beds

The pressure drop suffered by the gas in flowing through a bed of packed solids is the result of viscous-energy losses and kinetic-energy losses. Hence, by considering both of these sources of energy loss, Ergun has correlated the pressure drop for any single fluid flowing through a packed bed, including the flow of gases through dry, random packing of the type considered here, by the relation given in Foust (2)

$$-\left(\frac{\Delta P}{L}\right)\left(\frac{D_p g_c}{\rho_v v^2}\right)\left(\frac{\varepsilon^3}{1-\varepsilon}\right) = 150\left(\frac{1-\varepsilon}{N_{Re}}\right) + 1.75 \qquad (1)$$

A log-log plot of Equation (1) (left side versus N_{Re}) for air flowing over dry packing should result in a slope of -1 at low N_{Re}, and a constant value of 1.75 at high N_{Re}.

When the packing has a shape different from spherical, an effective particle diameter may be used:

$$D_p = \frac{6V_p}{A_p} = \frac{6(1-\varepsilon)}{A_s} \qquad (2)$$

The porosity, ε, which is the fraction of total volume that is void is defined as:

$$\varepsilon = \frac{\text{volume voids}}{\text{volume of entire bed}} = \frac{\text{volume of entire bed} - \text{volume of particles}}{\text{volume of entire bed}}$$

$$= \frac{\pi \frac{D^2}{4} L - \frac{\text{weight of all particles}}{\text{particle density}}}{\pi \frac{D^2}{4} L} \qquad (3)$$

A_S and ε are characteristics of the packing. Experimental values of ε are ordinarily easy to determine from Equation (3) but A_S for non-spherical particles is usually more difficult to obtain. Values of A_S and ε are normally tabulated for the most common commercial packing in the various references. A_S for spheres may be readily computed from the volume and surface area of a sphere.

Fluidized Beds

Many factors are important in fluidization. A few of the more important are;

1. properties of solid

2. properties of fluid

3. bed geometry

4. fluid flow rate

5. type of fluid distribution

6. vessel internals, screens, baffles, heat exchangers

In this experiment, the pressure drop characteristics of a fluidized bed are studied as a function of fluid velocity. The solid particles are ballotini and the fluidizing medium is air or water. The bed of solid particles is of uniform size; multi particle size fluidization is not studied.

At low gas velocities, the pressure drop characteristics are those of a fixed bed and the Ergun (1, 2, 3, 4) Equation applies.

As the gas velocity increases, a maximum pressure drop is reached. The particles begin adjusting to minimize the resistance to flow, the bed begins to expand and there is a slight down turn in pressure drop. The point of maximum pressure drop is the point of minimum fluidization.

Further increases in gas velocity fluidize the bed, the pressure drop rises very slightly until, eventually, slugging and entrainment occur.

At the point of minimum fluidization,

$$\left(\begin{array}{c}\textbf{the upward}\\ \textbf{drag force}\end{array}\right) = \left(\begin{array}{c}\textbf{weight of particles}\\ \textbf{in the bed}\end{array}\right)$$

$$\left(\begin{array}{c}\textbf{the pressure}\\ \textbf{drop across the}\\ \textbf{bed}\end{array}\right)\left(\begin{array}{c}\textbf{cross}\\ \textbf{sectional}\\ \textbf{area}\end{array}\right) = \left(\begin{array}{c}\textbf{volume}\\ \textbf{of bed}\end{array}\right)\left(\begin{array}{c}\textbf{fraction of}\\ \textbf{solids}\end{array}\right)\left(\begin{array}{c}\textbf{specific}\\ \textbf{weight of}\\ \textbf{solids}\end{array}\right)$$

Thus,

$$(\Delta P)(S) = W = (SL_{mf})(1-\varepsilon_{mf})\left[(\rho_s - \rho_v)\frac{g}{g_c}\right] \qquad (4)$$

or

$$\frac{(\Delta P)}{L_{mf}} = (1-\varepsilon_{mf})(\rho_s - \rho_v)\frac{g}{g_c} \qquad (5)$$

If Equation 5 is combined with Equation 1 then v_{mf} can be calculated by trial and error from the quadratic equation:

$$\frac{1.75}{\phi_s \varepsilon_{mf}}\left(\frac{D_p v_{mf} \rho_v}{\mu}\right)^2 + \frac{150(1-\varepsilon_{mf})}{\phi_s^2 \varepsilon_{mf}^3}\left(\frac{D_p v_{mf} \rho_v}{\mu}\right) = \frac{D_p^3 \rho_v (\rho_s - \rho_v) g}{\mu^2} \qquad (6)$$

Wen and Yu (5) have shown that for many systems, Equation 8 simplifies to:
For small particles

$$v_{mf} = \frac{D_p^2(\rho_s - \rho_v)g}{1650\mu}, \quad N_{Re_{mod}} < 20 \qquad (7)$$

For large particles

$$v_{mf}^2 = \frac{D_p(\rho_s - \rho_v)g}{24.5\rho_v}, \quad N_{Re_{mod}} > 1000 \qquad (8)$$

Procedure (Read Instruction Manual, pages 7-8, pages 13-14)

Do not touch the sump tank in the rear of the unit. It has been adjusted so that the amount of water needed to do the experiment is already there. Wait until your instructor(s) is present before starting the unit. When finished using the unit, unplug it.

Before turning on the water pump, make sure that the manometer reads zero. If it does not, adjust the level accordingly. Once this is done, switch on the water pump.

Starting at zero, adjust the water flow rate from the flow meter in increments of 0.1 L/min up to 1.6 L/min. Report the height of the bed, the manometer reading, and the state of the bed.

Turn off the pump and reset the manometer.

Three trials are to be done using the water test column. When completed, run three trials using the air test column. Note: The air flow rate is to be adjusted in increments of 1.0 L/min up to 16.0 L/min.

Data Analysis

1. On log-log graph paper, plot the pressure drop (y-axis) versus the average superficial velocity (x-axis). All three water trials should be on the same graph; repeat for the air trials. Graphs for the water and air trials must be handed in separately.

2. On regular graph paper, plot the bed height versus the average superficial velocity for the water and air trials separately.

3. Using data from both graphs, determine the minimum fluidization velocities of both water and air.

4. On log-log graph paper, plot the left side of Equation (1) {y-axis} versus [$(1-\varepsilon) / N_{Re}$] {x-axis}. The graph should show a slope of 1 at low N_{Re} and a constant slope of 1.75 at high N_{Re}.

Basic Data

Packing: Ballotini (Coarse grade {in water column})
(Fine grade {in air column})
Approximate density (coarse) = 1.754 g/ml
Approximate density (fine) = 1.821 g/ml
Approximate size (coarse) = 485 microns
Approximate size (fine) = 267 microns

Conversion factors (Pressure): 1 atm = 1.01325×10^5 Pa
1 atm = 33.932 feet of H_2O

$$1\ \mathrm{N/m^2} = 1\ \mathrm{Pa}$$

Nomenclature

D_p = hydraulic particle diameter (not to be confused with diameter of packing), ft or m.

g_c = conversion factor, $32.174 \frac{lb_m \cdot ft}{lb_f \cdot s^2}$ or $1.0 \frac{kg \cdot m}{N \cdot s^2}$

ΔP = pressure drop across the bed, $\frac{lbs}{ft^2}$ or Pa.

L = bed height, ft or m

ρ_V = gas density, $\frac{lb_m}{ft^3}$ or $\frac{kg}{m^3}$.

ε = bed porosity (void fraction), dimensionless

N_{Re} = Reynolds number, $\frac{D_p v \rho_v}{\mu}$, dimensionless

μ = gas viscosity, $\frac{lbs}{ft\ hr}$ or Pa·s.

S = cross sectional area of column, ft^2 or m^2

w = mass of bed, lb_m or kg

ρ_S = particle density, $\frac{lb_m}{ft^3}$ or $\frac{kg}{m^3}$

g = gravitational constant, $32.2\ \frac{ft}{s^2}$ or $9.81\ \frac{m}{s^2}$

v = superficial gas velocity, $\frac{ft}{s}$ or, $\frac{m}{s}$ based upon empty column cross sectional area

A_S = interfacial area of packing per unit of packing volume, $\frac{ft^2}{ft^3}$ or $\frac{m^2}{m^3}$.

d_p = particle diameter, ft or m

D = inside diameter of column, ft or m

$N_{Re_{mod}}$ = average modified Reynolds number based on superficial vapor velocity and hydraulic particle diameter $\frac{D_p G_v}{\mu}$, dimensionless

V_p = particle volume, ft^3

A_p = particle surface area, ft^2

ϕ_s = sphericity

Subscripts

o = initial conditions

mf = minimum fluidization

References

1. Kunii, D., and Levenspiel, O., “Fluidization Engineering”, John Wiley & Sons, Inc., New York, N.Y. (1969).

2. Foust, A.S. et al., “Principles of Unit Operations”, Second Edition, John Wiley & Sons, Inc., New York, N.Y. (1980).

3. Geankopolis, C.J., “Transport Processes and Unit Operations,” Third Edition, Prentice Hall, Englewood Cliffs, New Jersey (1993).

4. McCabe, W.L., Smith, J.C., Harriot, P., “Unit Operations of Chemical Engineering,” Fifth Edition, McGraw Hill Inc., New York, New York (1993).

5. Wen, C.Y. and Yu, Y.H., AIChE Journal, 12, 610, (1966).

J. *Experiment 10 : Temperature Measurement*

Introduction

The measurement of temperature is very crucial in everyday life. People take their body temperature which could be an indicator of illness, cars have a gauge that can monitor the temperature of the engine so that the car doesn't overheat, and certain foods need to be cooked to a specific temperature before being eaten.

As in everyday life, the measurement of temperature is also vital in industry. Temperature is most often used as a monitoring and correction device. A temperature sensor can alert workers that the temperature of a vessel is too high therefore preventing explosions. In process industries, the ability to maintain temperature also means maintaining control of the input and the output. This is very important in industry because most companies have a daily quota or specifications that they need to adhere to and they cannot afford mistakes. Due to the high cost of energy, ensuring that the optimal conditions for the situation are maintained is not only efficient, but cost-effective as well.

Experimental Objective

The objective of this experiment is to measure temperature using various types of temperature measuring devices such as:

- Mercury-in-glass thermometer
- Vapor pressure thermometer
- Bi-metal thermometer
- Thermocouple thermometer
- Chromel-alumel
- Copper-constantan
- Platinum resistance thermometer
- Thermistor thermometer

In addition, students will be exposed to the concept of relative humidity using a whirling hygrometer.

Theory

The measurement of the temperature of a substance (solid, liquid, or gas) is a measure of the average kinetic energy the body possesses because of molecular motion. It is difficult to measure this energy directly and therefore, very often some physical property of the material is measured which depends upon temperature. For example, in a mercury thermometer, a column of mercury increases in height because as the mercury is heated, it expands, the density decreases, the volume increases, and since the walls contain the mercury, it rises in height. We use this change in volume as a measure of temperature. In a resistance thermometer, the electrical resistance of the conductor changes with temperature and hence, a measure of the change in resistance becomes a measure of the change in temperature, and indirectly a measure of the change in kinetic energy. Similarly, a change in voltage between two dissimilar wires connected together results from a change in temperature from a thermocouple. A change in spectra of emitted radiation is used to measure temperature with a pyrometer.

As discussed earlier in this manual (page 10-11), temperature is measured in degrees of Fahrenheit, Celsius (Centigrade), Kelvin, and sometimes Rankin. Although Fahrenheit and Celsius are the most commonly used in industry, the absolute degrees Kelvin and Rankin are used. The basis of these scales is the boiling and freezing points of water at sea level and at 1 atm (See Table 1).

Table 1

	^oC	**^oF**	**^oK**	**^oR**
Boiling Water	100	212	373.15	671.7
Melting Ice	0	32	273.15	491.7
Absolute Zero	-273.15	-459.7	0	0

There are calculations that automatically calculate the conversion, but the following equations can be used to convert form one unit to another very easily (See Table 2).

Table 2

Units Desired	**Conversion Equation**
Fahrenheit	32 + 1.8 * (°C)
Celsius/Centigrade	1 / 1.8 * (°F - 32)
Rankin	(°F) + 459.67
Kelvin	(°C) + 273.15

Procedure

Temperature will be measured using various instruments using the Armfield HT2-B Temperature Measurement Bench with or without the Armfield HT2-13 Temperature Data Logger. The Armfield Temperature Bench provided is designed to introduce various techniques and equipment for temperature measurement. The various thermometers provided are:

Mercury-in-glass Thermometer: Best used to measure the temperature of liquid; on one end is a bulb filled with mercury, there is a scale which starts slightly below zero and goes up in increments of ten degrees, and the end of the scale, the units are given in °C. Care needs to be taken when handling this because it can be easily broken and mercury is toxic. If one should break, please notify the instructor immediately because there is a special clean-up procedure for mercury.

Bi-metal thermometer: Best used to measure the temperature of air or some other gas; it is a round dial that gets hung in the environment that needs to measured. There are two scales on the face - the inside scale reads °C in increments of ten and the outside scale reads °F in increments of ten. Be careful when handling after being heated because the surface gets very hot.

Vapor Pressure Thermometer: Having a similar face as that of the bi-metal air thermometer, the scale starts at higher temperatures. It is already located in the platen and there is no need to remove it unless removing the platen from its holder. (Caution: The platen gets very hot so please use handles when removing or placing.)

Whirling Hygrometer: Best used to determine the relative humidity, this is used to get a more accurate temperature reading when using a damp sensor. It is made up of two thermometers; one is for the dry bulb temperature and the other is the wet bulb temperature. Both are in °C and basically look like smaller versions of a regular mercury-in-glass thermometer. The thermometer with the wick on it is to be wet before using. Please be careful so that no one gets hurt. To interpret these readings, please talk to the instructor for the slide calculator of the hygrometric charts.

Platinum Resistance Thermometer: This is installed on the bench and before a measurement is taken, the platinum resistance probe needs to be plugged in. This allows that the temperature reading will show up on the digital readout. This thermometer is calibrated to give an accurate temperature to a resolution of 0.1 °C over the range of -150 to +200 °C.

Thermistor Thermometer: Like the platinum thermometer, this is already installed on the bench and needs to be hooked up to a thermistor probe before using. It also reads as a digital readout. This thermometer is calibrated to give measurements of temperature to a resolution of 0.1 °C over the range of 0 to 100 °C.

Thermocouple Thermometer: This is also installed on the bench and the thermocouple probe needs to be plugged in, but it does have the same kind of plug as the others. Instead of having one socket, it has red and black leads attached. This probe can get plugged into the millivolt meter where it will read a voltage or it can be plugged into the respective colored sockets that are numbered 1-6. Leads are provided so that a connection can be made so that a temperature reading as well as a voltage reading can be done. This is primarily used to determine surface temperatures.

Chromel/Alumel and Copper/Constantan Thermocouples: These are to be plugged into various outlets on the bench to allow for a voltage reading and a temperature reading. They are used to take temperatures of liquids and gases. Thermocouples are used to show that two dissimilar metals can affect the temperature reading. Two different kinds of thermocouples have been provided and they will initially produce different temperature and voltage readings. The thermocouples have all been labeled. Observe that all the thermocouple tips are not the same. Pleas read the experiment entirely so that the right thermocouple is used.

When using this equipment, please make sure that you know how to use it and to use it safely. Please clean and dry all equipment when not in use before placing it back into the storage box.

The Armfield Instruction manual details the experimental procedure to follow for the various experiments. These are:

- Experiment A - Mercury-in-glass thermometer
- Experiment B - Vapor Pressure Thermometer
- Experiment C - Bi-metal Thermometer
- Experiment D - Thermocouple Thermometers
  - Chromel-Alumel
  - Copper-Constantan
- Experiment S - Platinum Resistance Thermometer
- Experiment T - Thermistor Thermometer
- Experiment X - Whirling Hygrometer

If time permits, the instructor may assign other experiments beyond the seven basic experiments that are required.

Data Analysis

Compare the temperatures measured with the various thermometers. Record the wet bulb and dry bulb temperatures and determine the relative humidity in the laboratory. Using the psychrometric charts determine the

- Absolute Humidity
- Dew Point
- Humid Volume
- Specific Enthalpy
- Enthalpy Deviation

References

1. Felder, R. M., and Rousseau, R. W., “Elementary Principles of Chemical Processes”, Second Edition, John Wiley and Sons, New York, New York (1986).