# INTRODUCTION

# TO

# CHEMICAL ENGINEERING LABORATORY I & II

Spring 2005

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Note: Materials about the other experiments will be provided by the TAs.

# INTRODUCTION TO THE CHEMICAL ENGINEERING LABORATORY

## Scope

Chemical Engineering Laboratory I and II provide the student with the opportunity to apply the theory learned in other courses to actual practice. Experiments in the laboratory are designed to illustrate the practical use of theoretical concepts. The equipment in the laboratory, while small in scale, is like industrial equipment. The problems posed (rate the performance of a piece of equipment, measure some properties, specify a piece of equipment based on tests, etc.) are like those which the student will encounter in his or her professional work.

The student uses various industrial type devices for measuring flow rate, temperature and composition of process streams. The student will also have practice in preparing and presenting engineering reports, both written and oral. The use of proper methods to prepare and present computations is emphasized. A reading materials section is provided for each experiment to refresh the related background knowledge. However, it is expected that library resources will be used as well to obtain the background information needed for a good understanding of the work at hand. The lecture portion of the course covers process engineering components which is background material needed in practical work.

In the first semester the laboratory experimental work covers transfer of heat, mass, and momentum whereas in the second semester the experimental work deals with the principles of thermodynamics and chemical reaction engineering. Specific objectives of the laboratory effort are to:

- Develop hands-on practical experience.
- develop critical engineering judgment and analytical ability by analyzing problems, developing and executing solutions, and evaluating results.
- evaluate the reliability of experimental data and gain an appreciation for limitations imposed by experimental technique.
- improve communication skills by preparing technical quality reports, both written and oral.
- experience the teamwork approach with its benefits and, at times, difficulties which result from coordinated effort by small groups.

## Laboratory Procedure

Students work in teams of two or more, **sharing equally in the work, and being equally responsible for understanding fully all aspects of that work.** Experiments are carried out during alternate weeks. Each team is assigned to a particular day of the week and on that day the team has exclusive use of the equipment assigned. There will be six experiments during the course of the semester. Every team will do each experiment, following a schedule distributed to them.

The laboratory work is divided into two parts, Pre-lab and Lab-week. Pre-lab runs to (but not including) the day assigned to the team as Lab-day. Lab-week begins with the assigned Lab-day, which is the day the experiment is carried out. Lab-week continues up to that day of the following week. Thus, for example, for a team assigned to the Wednesday laboratory, Pre-lab will run to Tuesday afternoon, which is the day preceding Lab-day. Lab-week runs until the following Wednesday afternoon. The cut-off time in the afternoons is 1:00. For those occasions when the cutoff time falls on a Sunday or a holiday, the cut-off time will be extended to 9:00 on the following schoolday morning.

Each experiment in this laboratory manual consists of the following five major parts:

- Introduction, represents an introductory information on the process involved.
- Theoretical Background, outlines the theoretical background related to the experiment.
- Equipment Description, refers to the particular piece of equipment that will be used, and its ancillaries, with drawings and other useful information (e.g. physical properties, calibration curves, etc.).
- Operating Procedure, gives special instructions, where necessary, on how the equipment is operated.
- Assignment, is structured similar to a request that an engineer's supervisor might make, to obtain operating or performance data on a particular piece of equipment in the plant. The Assignment does not tell the engineer HOW to do the work, nor does it give him instructions on how to operate the equipment. It is assumed that the engineer understands the job well enough to appreciate what needs to be done, and knows where to get the information needed.
- Results and Data Analysis Outline, provides an outline to present and analyze the result.
- References, a bibliography to be used for background information and study. All references are in Olin Library.
- Appendix-reading materials, refreshes the related background information and provides additional instructional or reference materials.

During **Pre-lab week** the team members must read their assigned experiment in the laboratory manual (this book). They will go to the laboratory to see, study, and understand the equipment they will use. The laboratory technician, the T/A responsible for that experiment, and the professor are all available for consultations. T/A's are assigned to the laboratory from 1:00 to 2:00 pm during Pre-lab week. T/A's will perform a trial operation and demonstrate the sequence of the operation of the experiment or its component. If some components are not ready to be operated, the T/A should go over it slowly and carefully. **For this matter, the students must be prepared before the pre lab.** They must have read the manual and prepared questions. It is the student's responsibility to ask the T/A questions about the experiment and its operation. The team may stay in the lab to absorb the covered information and to acquire more knowledge about the experiment and its operation. The lab is open Monday through Friday, 8 am to 5 pm, and the students can come any time to review their experiment. Team members will review and study the engineering principles involved, making use of textbooks from other courses, the provided reading materials and library references. Together they will plan their work and write a brief proposal in response to the Assignment. It is the student's responsibility to acquire a detailed knowledge about the experiment during the Pre-lab week.

The T/A will grade the proposal and review or discuss it with the team members before they start the experiment. This review assures that the team will not have overlooked or misunderstood something; there will not be a wasted laboratory period. Students will have the use of their proposal for reference while carrying out the experiment. It is not allowed to perform the experiment if either the pre-lab proposal is not submitted or is not reviewed with the T/A.

On the assigned **laboratory day** the **experiment** will be carried out, and data taken. It is expected that students come to the lab well prepared (performance grade will be given to each student). Data will be recorded on the forms provided by the laboratory. At the end of the day the data will be initialed by a T/A or the lab. technician, and the yellow carbon left with the lab. technician. During the days which follow the data will be reduced (i.e., computed) using the procedure outlined in the proposal. Graphs and tables summarizing the results will be prepared, and a report written.

T/As are assigned to be in the laboratory from 1:00 to 2:00 pm during the lab day. However, they are also available (office hours) from 2:00 to 5:00 pm during the lab day. They must notify the students where they will be and how they can be reached for questions, consultations, troubleshooting, etc.

The format, contents, and the grade distribution for both the proposal and the lab report are outlined in the following section.

There is a **penalty for tardiness**, for either the proposal or the report. **10% of the total points will be deducted from the grade.** Further, an experiment cannot be started until the proposal has been reviewed and approved by the T/A. A report that is one week or more late receives a **grade of zero.**

**Both proposals and reports are to be turned in to the Laboratory Technician, on or before the due date.** He will initial them with the date and time when he receives them. Proposals will be reviewed by the T/A before the start of the Lab-day, as indicated above. The grading will be done by the Monday following the day the material was turned in. Graded proposals and reports will be retained in the laboratory where they may be seen by their authors after the grades have been reviewed and recorded by the professor.

One experiment (date to be announced in advance) will be made orally or presented as a poster to a panel consisting of the T/A's and the professor.

Students will have the use of their proposal during Lab-week, for help in preparing the report for that experiment. Both the proposal and the report will be turned in together as specified in the following section. After grading, they will be available to the team that did the work, **but not to any other students**. All proposals and reports will be retained in the laboratory until graduation of the students who authored them. After graduation students may claim their work after assurances that the work will be used solely for the student's own reference, and will not be turned over to fraternity files, or any other such extra-curricular collections.

**Read the "Statement on Student Academic Integrity" which appears on the inside front cover of the Classroom Directory. Each student is bound by the rules detailed there. Violators will be dealt with severely.**

## Format, Grade Distribution, and Guidelines for Prelab Proposal and Final Report

The Contents and the grade distribution for the prelab proposal and the final report are summarized as follows:

I. Prelab Proposal Contents and Grade Distribution
II. Final Report Contents and Grade Distribution
III. Guidelines

### I. Prelab Proposal: Contents and Grade Distribution

The prelab proposal must consist of the following sections. It is graded on a 40 point basis. After it is graded, it must be included in the final report according to the order of the final report contents. The prelab proposal contents and its grade distribution are described below.

- **Cover Page**
- **Table of Contents**
- **Notation**
- **Introduction**
- **Objectives** ~~6~~ points
- **Experimental Set-up**
- **Experimental Procedure** ~~5~~ Points
- **Theory and Calculation Procedure** ~~23~~ points
  These points are distributed over the theory and calculation procedure subsections. More points are given to the subsections that involve more thinking or computing.
- **Data Collection**
  Identify what data need to be collected, how many data points are required for each set of operating conditions, and the range that each variable is expected to cover. Provide a sample data sheet. Specify the units of the data collected or measured.
- **References**
- **Overall Report** ~~6~~ points
  This grade is given based on the overall presentation of the pre lab report and the implementation of the guidelines and the experiment requirements.

**Total 40 points**

**Note:** Extra points will be deducted if you fail to submit a cover page, a table of contents, notation of variables, and a proper list of references.

## II. Final Reports: Contents and Grade Distribution

The final report is graded on a 60 points basis as outlined below. A graded version of the prelab proposal must be included according to the following order:

- **Cover page**
- **Abstract**
- **Table of Contents** ~~4~~ points
  Update the table of contents of the prelab proposal
- **Notation** (prelab proposal)
- **List of Figures**
- **List of Tables**
- **Introduction** (prelab proposal)
- **Objectives** (prelab proposal)
- **Experimental Set-up** (prelab proposal)
- **Experimental Procedure** (prelab proposal)
- **Theory and Calculation Procedure** (prelab proposal)
- **Results and Data Analysis** ~~42~~ points
  The points are distributed over the results and data analysis subsections. More points are given to the subsections that involve more thinking or computing. Each section is graded based on the requirements as outlined in the guidelines and the sample conclusions presented in Appendix A.

  40% for step by step calculations referenced on a spreadsheet. This represents the sample calculations presented in Appendix A.

  20% for results presentation (figures and tables)

  40% for discussion, data analysis, and utilizing statistical calculations, if any.

- **Conclusions** ~~5~~ points
- **Recommendations** **Extra Points**
  More constructive accomplishments in this part, extra points are granted.
- **References**
  Update the references of the prelab proposal.
- **Appendices**
  - **Appendix A - Sample Calculations**
    It is graded together with the results and data analysis section.

- **Appendix B - Spreadsheet Copies of the Processed Data and Calculations**
- **Appendix C - Raw Data Sheet**
- **Appendix D - Programs Used in Computing (if any)**
- **Overall Report**

This grade is given based on the overall presentation of the lab report and the implementation of the guidelines and the experiment requirements. This also includes, but is not limited to, the way the prelab sections are organized in the Final Report.

**~~9~~ points**

**Total ~~60~~ points**

**Note:** Extra points will be deducted if you fail to include the graded prelab proposal sections in the order above, cover page, table of contents, list of figures and tables, notation of variables, a proper list of references and appendices.

<u>Additional Grades</u>

- **Lab Performance Grade** **~~10~~ points**

  The T/A and professor will give a grade to each student during the lab day based on the preparation of doing the experiment, knowledge of its component and operation. It is important to emphasize that the T/A's will not operate the experiment for the students. They will only observe the students and, in the meantime, prevent any major wrong-doings.

## III. Guidelines

The guidelines for the final report and the prelab proposal are given below. The prelab proposal must be included after being graded. Both prelab and final report must be **TYPED** (except for sample calculations in which you may use clear hand writing). The title of each section must be typed bold in upper case letters while titles of subsections must be typed bold in lower case letters with first letter of each word in upper case. The text must be double spaced. Margins must be 1 inch.

**Extra points will be deducted for excessive verbosity and spelling errors.**

Note 1: Number the pages from Abstract to List of Tables in roman numerals (i, ii, iii, ...). Number the rest of the sections in Arabic numbers (1, 2, 3,...).

Note 2: Cite references in the following form when needed.
One author; (Underwood, 1995)
Two authors; (Smith and Van Ness, 1987)
More than two authors; (McCabe et al., 1985)

- **Cover Page:**
  An example of the format of the cover page is attached.

- **Abstract*** (1/2 page) (start on a new page)
  This should be a short and concise overview of the experiment, the significant results and the major conclusions.

- **Table of Contents*** (start on a new page)
  List all the contents with page number.

- **Notation*** (start on a new page)
  List definition and unit of symbols used. You must be consistent with units throughout your report (e.g. if you use SI units, use it for all the calculations involved in the report).

- **List of Figures*** (start on a new page)
  List all figures if any with figure number, caption and the page number specified as follows.

| | *Page* |
|---|---|
| Figure 1: The Effect of Gas Flow Rate on the Pressure Drop | 8 |

- **List of Tables** (continued after the list of figures, don't start on a new page)
  List all tables if any with table number, caption and the page number similar to the list of figures above.

* Should start on a new page

- **Introduction*** (1/2 - 1 page, start on a new page)
  This includes a brief discussion and outline of the purpose of the experiment's topic and the parameters to be measured or studied. It should also include the industrial importance.

- **Objectives** (1/2 page, continued after the introduction, <u>don't</u> start on a new page)
  List briefly the main objectives of the experiment (primarily deduced from the lab manual assignments of the experiment). Don't copy the assignments as they are.

- **Experimental Set-Up** (1/2 page, excluding figures, continued after the objectives, <u>don't</u> start on a new page).

  This includes a summary of the experimental set-up or facility that is used in the experiment. Discuss only the major part of the set-up and the process. The discussion must be supported with a schematic diagram of the facility. Refer to the course manual for detailed information.

- **Experimental Procedure** (1/2 - page, continued after the experimental set-up, <u>don't</u> start on a new page).

  Outline the step by step procedure to perform the experiment. Steps must be brief, informative and clear. You may refer to the course manual for the detailed procedure. In this section you must reflect your understanding of how to perform the experiment and the safety precaution that must be considered.

- **Theory and Calculation Procedure** (1 - 3 pages, continued after the experimental procedure, <u>don't</u> start on a new page).

  Summarize clearly the step-by-step procedure to estimate the parameters required. You must provide comments and a brief explanation for the calculations along with equations. For each equation or model or correlation used, you must cite the reference and the page number. Since you have a notation list, you don't need to define symbols again. If you need to use data or information extracted from tables and/or graphs, cite the reference and specify the table/graph number and page number. If you use programs provided by the laboratory, or library, or developed by you, outline the procedure for the calculations and equations used.

  This section reflects your understanding of the experiment and also helps to develop a good technical report.

- **Results and Data Analysis** (1 - 3 pages, excluding figures and tables, continued after the theory and calculation procedure, <u>don't</u> start on a new page).

  Divide this section into subsections based on assignments given in the lab manual. For each subsection, discuss the results and analyze the data. Use tables or graphs wherever necessary to present the data and the results. Cite references when needed.

- Be concise! This is where you demonstrate your understanding of the experiment, its purpose and results. It reflects your analytical ability.
- Discuss sources of error, disturbances in your results and trouble shooting.
- Include any statistical calculations such as regression, mean relative error, error bar, etc. wherever necessary.
- Use spreadsheets and computing packages to process the experiment data.
- Make the titles, subtitles and the subsections **bold**. Underline **only** the titles and the subtitles.

NOTE 3:

i. Tables and figures must be referred to by their numbers. They should be numbered in the order they appear in the text.

ii. Experimental data must be presented in scatter plots. Do not connect the data points with lines. If you want to demonstrate a trend which would help your discussion, use a French Curve and draw the trend as a dotted line.

iii. If you perform regression and want to plot both experimental data and a fitted line or curve, plot the data as symbols and predictions of models as lines in different formats.

iv. Make your graph clear and informative. Identify X and Y axes (name and units). Use clear legends to define your plots.

v. The caption of a figure should be below the figure while the caption of a table should be above it.

- **Conclusions** (1/2 page, continued after the results and data analysis, don't start on a new page).

  Summarize conclusions drawn based on results obtained, data analysis, equipment performance, etc. Be concise.

- **Recommendations** (continued after the conclusions, don't start on a new page).

  Summarize your recommendations, if any, and also your thoughts and ideas on all aspects of the experiment. You may also accomplish the following (Be concise).

  - Propose equipment modifications
  - Suggest more assignments
  - Propose an alternative experimental set-up for the subject
  - Suggest new experimental procedures

- **References**
  List only the references cited in your report. You must follow the format described in note 2 above.

- **Appendices**

- **Appendix A - Sample Calculations**
  Sample calculations must be provided for each subsection. Calculation steps can be hand written or typed.

  Select one or more experimental data points and identify the location(s) in the spreadsheet. Perform the required calculations leading to the presented results. You have to be consistent with units. Also you have to identify the reference, page number, figure number, table number etc. for each equation and/or parameter used. You should also include comments and a brief explanation of the calculation steps. **Points will be deducted** if your sample calculations are not clear and are hard to understand. Anyone not familiar with the experiment should be able to follow your report.

- **Appendix B - Spreadsheet Copies of the Processed Data and Calculations**

- **Appendix C - Raw Data Sheet**

- **Appendix D - Programs Used in Computations (if any)**

(Example for the format of the cover page)

Experiment #4
Prelab Proposal or Final Report
Day of the Prelab/Lab and the Date

**PRESSURE DROP IN A PACKED COLUMN**

**Nathan Green, Christopher Hugill, Keith Schreiber**

Submitted to
Professor Muthanna Al-Dahhan
Teaching Assistant Tariq Asrar

Chemical Engineering Laboratory - I
ChE 374
Fall 1994

## Laboratory Safety

Some of the laboratory experiments involve flammable materials, hazardous chemicals, moving machinery, and/or high temperatures. For this reason it is essential that certain precautions be observed.

All persons must wear **eye protection** at all times. Safety glasses will be loaned to anyone not wearing prescription glasses. Safety goggles or face shields must be worn over safety glasses or prescription glasses when handling chemicals. Users of contact lenses are urged to wear prescription glasses if possible as this eliminates the risk of severe eye irritation from accidental exposure to fumes. Contact lenses are in no sense protection against injuries to the eye. Instead, they aggravate problems resulting from exposure to irritating fumes and corrosive chemicals.

Note the location of **eye wash stations** and **safety showers**. Safety showers are the best emergency treatment for chemical spills or a person on fire. The victim is often disoriented in such a situation. Bystanders must take responsibility to help the victim, to lead him to the shower or eyewash, and help him. Standard procedure for eyewash is to hold they eyelids open with the fingers and rinse for fifteen minutes. The **emergency number (5-5555)** should be called immediately.

**Hard hats** must be worn to protect against injury from structural members (head knockers) and against the remote possibility of an object falling from above. Adjust the hard hat to make sure it fits securely. A hat that falls off is no protection and can pose a danger to other workers and equipment as well.

**No open flames** are permitted without specific permission from the Instructor who will ascertain that the area is free of flammable liquid or vapor. No smoking is permitted in the laboratories at any time. Dry powder extinguishers are located in each laboratory. Larger units and fire hoses are located in the east and the west hallway on each floor.

**IN CASE OF FIRE: First dial the emergency number (5-5555) before trying to fight the fire. Do not hesitate to call the fire department. Remember, even the most disastrous fire starts small. No fireman has ever been known to complain because the fire was already out by the time he got there. Second, warn all other occupants of the lab. and evacuate the area. Only then should you try to fight the fire, and then only if you can do so safely. Remember, even the most disastrous fire starts small.**

**Warning:** If you use gloves, make sure to **thoroughly** clean the **inside** of the **gloves** and the **head band** of the face shield and the aprons before use.

All **accidents, injuries and "near misses"** are to be reported to the Professor so that prompt corrective action may be taken, and to improve safety in the future. Chemical spills should be reported immediately to the lab. technician so that appropriate cleanup action can be taken. This is especially critical in case of a mercury spill. The laboratory has a mercury vapor analyzer which is used to assure complete decontamination of a mercury spill.

**Eating and drinking** are not allowed in the laboratory. Avoid inhaling vapors from materials being processed, or from samples. Do not get chemicals on the hands, or spill chemicals on the body. Any such contamination must be washed off immediately. Examine samples only in a well-ventilated area. Dispose of samples only in approved, closed containers.

**Appropriate clothing** must be worn. There is always danger of brushing against a hot pipe or a projecting piece of metal. There is always the possibility of a spill of hot water or caustic chemical. Open grates are a hazard for fancy shoes. Therefore skirts, culottes and shorts are not permitted. Trousers or slacks must be worn instead. Impervious leather or rubber shoes must be worn. Open top shoes, running shoes with porous tops, sandals, or high heeled shoes are not permitted. *Hair longer than collar length must be tied up and worn under the hard hat.*

Piping and equipment are not to be used as a substitute for a ladder or platform at any time.

Failure to observe these safety rules will result in expulsion from the laboratory.

## Student Liability for Breakage

Students will be held responsible for damage or breakage resulting from negligence or careless handling. Failure to observe specific precautions noted in the text or posted near the equipment will constitute negligence. Normal wear and tear is, of course, excluded. The following procedure will be observed.

1. Before beginning an experiment, check the equipment for defects.

2. If it is possible to proceed without repairs or replacement, note any deficiencies on the data sheet and have the Teaching Assistant (T/A) sign the report to absolve you of responsibility for the damage. Otherwise request a replacement free of defects.

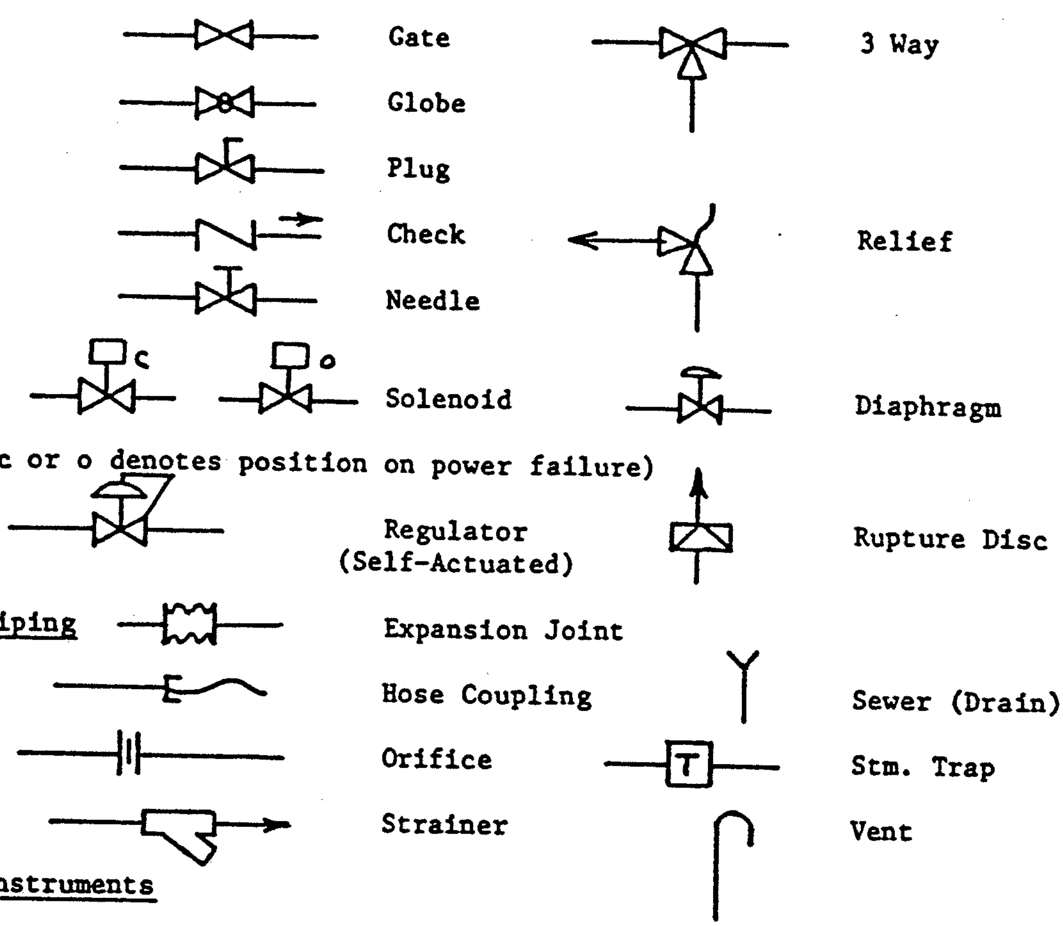
3. The TA will inspect the equipment at the end of the experiment and will note any new damage when signing the data.

4. The TA will send a copy of all damage reports to the Professor so that an adequate inventory can be maintained.

This procedure is intended to provide a written record of defects to facilitate prompt repair and improve equipment reliability. It will also give each student an incentive to exercise reasonable care in the laboratory.

# COMMON FLOW SHEET SYMBOLS

**Valves**




**Instruments**

**Measured Variables**

| | | | | Suffix | |
|---|---|---|---|---|---|
| A | Analyzer | K | Time | Indicating | I |
| C | Conductivity | L | Level | Recording | R |
| D | Density | P | Pressure | Controlling | C |
| F | Flow | T | Temperature | Summing | Σ |

Example: FRC = Flow Recording Controller

**Auxiliary Devices**

| | | | |
|---|---|---|---|
| LG | Level Gage | PSV | Relief Valve |
| TW | Thermowell | PSE | Rupture Disc |
| TC | Thermocouple | | |

## Rotameter and Correction Factors

- **Rotameter**

The rotameter, an example shown below, has become one of the most popular flowmeters in industry. It consists essentially of a "float", which is free to move up or down in a vertical, slightly tapered tube having its small end down. The fluid enters the lower end of the tube and causes the float to rise until the annular area between the float and the wall of the tube is such that the pressure drop across this construction is just sufficient to support the float. Typically, the tapered is of glass and carries etched upon it a nearly linear scale on which the position of the float may be visually noted as an indication of the flow. Hence, the rotameter is a variable area flowmeter (area meters). The cross sectional area available for flow increases with the height of the rotameter.

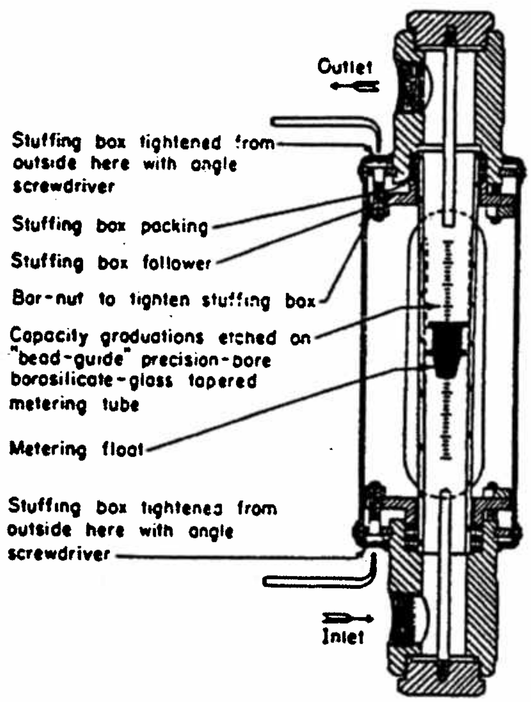
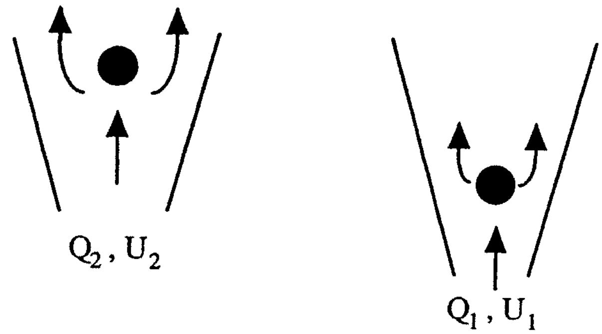



**FIG. 5-21** Rotameter.

The reading is a balance between the upward force of the flowing liquid and downward force of gravity acting on the float. Therefore, the force balance on the float is

$$float\ weight = Drag + Buoyancy$$

$$V_s \rho_s g = k_d \rho_f U^2 + V_s \rho_f g \tag{1}$$




$$Q_2 > Q_1$$
$$U_2 = U_1$$

where,

$V_s$ = *volume of the float*

$\rho_s$ = *density of the float*

$g$ = *gravity acceleration*

$k_s$ = *drag coefficient*

$\rho_f$ = *density of the fluid*

$U$ = *linear velocity through the cross sectional area available between the float and the tapered tube*

For a given fluid and a velocity (i.e. a volumetric flow rate), the forces of equation (1) are balanced. If the volumetric flow rate is increased, the linear velocity, U, increases if the float remains at its old height (position). Since the float weight and the buoyancy remain constant at the new volumetric flow rate and the force balance of eq (1) must maintain, the float is moved to a new height and a larger cross section area between the float and the tapered tube that produces a linear velocity equal to the previous one. In other words, the float height is adjusted (i.e. the cross section area between the float and the tapered tube) to maintain drag force constant.

$$U = \frac{Q}{A} \tag{2}$$

where,

$Q$ = *volumetric flow rate*

$A$ = *cross sectional area between the float and the tapered tube. A is proportional to the height of the float;* $A \propto h$ *and* $A = kh$

Therefore,

$$U = \frac{Q}{kh} = k_1 \frac{Q}{h} \tag{3}$$

where $k_1$ = *proportionality constant* $(1/k)$ substituting eq (3) into (1) yields

$$V_s\rho_s g = k_d k_1 \rho_f \left(\frac{Q}{h}\right)^2 + V_s\rho_f g \tag{4}$$

by solving for $\left(\frac{Q}{h}\right)^2$ and making $k_d k_1$ equal to a new constant $k_2$, yield

$$\left(\frac{Q}{h}\right)^2 = \frac{V_s\rho_s g - V_s\rho_f g}{k_2\rho_f} = \frac{V_s g}{k_2}\frac{(\rho_s - \rho_f)}{\rho_f} \tag{5}$$

Solving for $Q$ gives

$$Q = \sqrt{\frac{V_s g}{k_2}}\sqrt{\frac{(\rho_s - \rho_f)}{\rho_f}}\,h \tag{6}$$

for a given rotameter and float the term $\sqrt{\frac{V_s g}{k_2}}$ is a constant, hence

$$Q = k_3\sqrt{\frac{(\rho_s - \rho_f)}{\rho_f}}\,h \tag{7}$$

Equation (7) represents the relationship between the volumetric flow rate and the float height where the constant $k_3$ represents the characteristics of the rotameter (i.e. depends on the rotameter type).

Usually, the rotameters are calibrated by the manufacturer for common fluids before they are used in any application. The calibration data or curve provide a relationship between the volumetric flow rate and the float position (i.e. height) for a given float and tapered tube.

- **Correction factors**

  Usually, the rotameters are calibrated with water for liquid volumetric flow rate measurements and are calibrated with air at standard conditions (atmospheric pressure and room temperature) for gas volumetric flow rate measurements. Therefore, to obtain the true volumetric flow rate, the indicated flow rate based on the calibration data must be corrected for liquids other than water and for gases other than air and/or for conditions other than the standard ones.

* **Correction Factor for Liquids**

The rotameters used to measure liquids flow rates, are usually calibrated for water, which has a specific gravity of 1.0 and a viscosity of 1.0 centistoke. Reasonable variations in viscosity (up to 5 - 20 centistokes) of the fluid through the instrument do not have a significant influence on the actual flow rate compared to the calibrated one. The density of the liquid measured will, however, affect the actual (true) flow rate. Therefore, for any liquid other than water ( the calibrated liquid) the volumetric flow rate evaluated from the calibration curve or the rate of full scale must be corrected.

The volumetric flow rate of water when the float is at $h_1$ height can be evaluated using equation (7).

$$Q_{w,\ calibration} = k_3 \sqrt{\frac{\rho_s - \rho_w}{\rho_w}} \quad h_1 \tag{8}$$

Suppose the same rotameter is employed to measure the flow rate of another liquid. The liquid flow rate is then adjusted until the float reaches the same height ($h_1$). In this case, the actual volumetric flow rate is different and evaluated using also equation 7.

$$Q_{L,\ actual} = k_3 \sqrt{\frac{\rho_s - \rho_L}{\rho_L}} \quad h_1 \tag{9}$$

where $Q_L$ is the actual liquid volumetric flow rate by dividing equation (9) and (8) yields

$$\frac{Q_{L,\ actual}}{Q_{w,\ calibration}} = \frac{\sqrt{\frac{\rho_s - \rho_L}{\rho_L}}}{\sqrt{\frac{\rho_s - \rho_w}{\rho_w}}}$$

$$Q_{L,\ actual} = \sqrt{\frac{(\rho_s - \rho_L)\rho_w}{(\rho_s - \rho_w)\rho_L}} \quad Q_{w,\ calibration} \tag{10}$$

In general, equation (10) represents the corrected flow rate equation for liquids and the correlation factor is:

$$\text{correction factor for liquids (C.F.)} = \sqrt{\frac{(\rho_s - \rho_L)\rho_w}{(\rho_s - \rho_w)\rho_L}} \tag{11}$$

If the calibration liquid is water as usual and the float is stainless steel, then:

$$\rho_w = 1.0 \quad g/cm^3$$
$$\rho_s = 8.02 \quad g/cm^3$$

The correction factor for such specific case is

$$C.F.\ (liquid) = \sqrt{\frac{8.02 - \rho_L}{(8.02 - 1)\,\rho_L}} = \sqrt{\frac{8.02 - \rho_L}{7.02\,\rho_L}} \tag{12}$$

- **How to measure the actual flow rate**

If you have a rotameter with either a calibration curve or a rate of full scale for water and you want to measure the flow rate of a liquid, the actual liquid volumetric flow rate is evaluated as follows:

- Take the float reading (the float height or the scale reading) where the liquid is passing through.
- Use the water calibration curve or a rate of full scale for water to evaluate the water volumetric flow rate at the same float position as if <u>water</u> passing through.
- Calculate the actual liquid flow rate at this position (the position of the float where the liquid is passing through) as follows:

$$Q_{L,\,actual} = \sqrt{\frac{8.02 - \rho_L}{7.02\,\rho_L}}\; Q_{w,\,calibration} \tag{13}$$

* **Correction Factor for Gases**

The rotameters used to measure gases flow rates, are usually calibrated for air at standard conditions (atmospheric pressure and room temperature). Therefore, for air at any other pressure and temperature and/or for other gases at standard conditions or other conditions, the volumetric flow rate evaluated from the calibration curve or the rate at full scale must be corrected.

The volumetric flow rate of air at standard conditions $(T_{stand}, P_{stand})$ when the float is at $h_1$ height can be evaluated using eq (7)

$$Q_{air,\,calibration} = k_3 \sqrt{\frac{\rho_s - \rho_{air}}{\rho_{air}}}\; h_1 \tag{14}$$

For air and gases in general the gas density would be neglected compared to the float density, i.e.

$$\rho_s - \rho_{air} \approx \rho_s \tag{15}$$

Therefore, eq. (14) becomes

$$Q_{air,\,calibration} = \sqrt{\frac{\rho_s}{\rho_{air}}}\; h_1 \tag{16}$$

Suppose the same rotameter is employed to measure the flow rate of another gas or/and at different conditions of pressure and temperature (T, P). The gas flow rate is adjusted until the float reaches the same height ($h_1$). In this case, the actual volumetric flow rate is

$$Q_{g,\,actual} = \sqrt{\frac{\rho_s}{\rho_g}}\; h_1 \tag{17}$$

Dividing eq. (17) and (16) yield,

$$\frac{Q_{g,\,actual}}{Q_{air,\,calibration}} = \sqrt{\frac{\frac{\rho_s}{\rho_g}}{\frac{\rho_s}{\rho_{air}}}} \tag{18}$$

$$Q_{g,\,actual} = \sqrt{\frac{\rho_{air}}{\rho_g}}\; Q_{air} \tag{19}$$

Assuming ideal gases:

$$\rho_g = \frac{P\,M_{wtg}}{R\,T} \tag{20}$$

$$\rho_{air} = \frac{P_{standard}\,M_{wt\,air}}{R\,T_{standard}} = \frac{P_{st.}\,M_{wt\,air}}{R\,T_{st.}} \tag{21}$$

Substituting eqs. (20) and (21) into (19) gives

$$Q_{g,\,actual} = \sqrt{\frac{\frac{P_{st}M_{wt\,air}}{R\,T_{st}}}{\frac{P\quad M_{wt\,g}}{R\,T}}}\; Q_{air,\,calibration} \tag{22}$$

$$Q_{g,\,actual} = \sqrt{\frac{P_{st}T}{P}\;\frac{M_{wt\,air}}{T_{st}M_{wt\,g}}}\; Q_{air,\,calibration} \tag{23}$$

In general, equation (23) represents the corrected flow rate equation for gases and the correction factor is:

$$\textit{correction factor for gases (C.F.)} = \sqrt{\frac{P_{st}T}{P}\;\frac{M_{wt\,air}}{T_{st}M_{wt\,g}}} \tag{24}$$

- How to measure the actual flow rate

If you have a rotameter with either calibration curve or a rate of full scale for air at standard condition $(T_{standard}, P_{standard})$ and you want to measure the flow rate of another gas or air at temperature $(T)$ and pressure $(P)$ and/or another gas at standard conditions, the actual gas flow rate is evaluated as follows:

- Take the float reading (The float height or the scale reading) where the gas is passing through.
- Use the air calibration curve or a rate of the full scale to evaluate the air volumetric flow rate at the same float position as if air at standard conditions passing through.
- Measure the rotameter outlet pressure and temperature.
- Calculate the actual gas flow rate at this position (the position of the float where the gas is passing through) as follows (eq. 23):

$$Q_{g,\ actual} = \sqrt{\frac{P_{St}T}{P}\ \frac{M_{wt\ air}}{T_{St}M_{wt_g}}}\ Q_{air,\ calibration}$$

**Note:** The same procedure is used for the air at pressure and/or temperature different than the standard ones used for the calibration.

- **Rotameter's Reading**

The following figures demonstrate how to read the rotameters with various types of floats.

- How to measure the actual flow rate

If you have a rotameter with either calibration curve or a rate of full scale for air at standard condition $(T_{standard}, P_{standard})$ and you want to measure the flow rate of another gas or air at temperature $(T)$ and pressure $(P)$ and/or another gas at standard conditions, the actual gas flow rate is evaluated as follows:

- Take the float reading (The float height or the scale reading) where the gas is passing through.
- Use the air calibration curve or a rate of the full scale to evaluate the air volumetric flow rate at the same float position as if air at standard conditions passing through.
- Measure the rotameter outlet pressure and temperature.
- Calculate the actual gas flow rate at this position (the position of the float where the gas is passing through) as follows (eq. 23):

$$Q_{g,\,actual} = \sqrt{\frac{P\,T_{standard}\,M_{wt\,g}}{P_{standard}\,T\,M_{wt\,air}}}\;Q_{air,\,calibration}$$

**Note:** The same procedure is used for the air at pressure and/or temperature different than the standard ones used for the calibration.

- **Rotameter's Reading**

The following figures demonstrate how to read the rotameters with various types of floats.

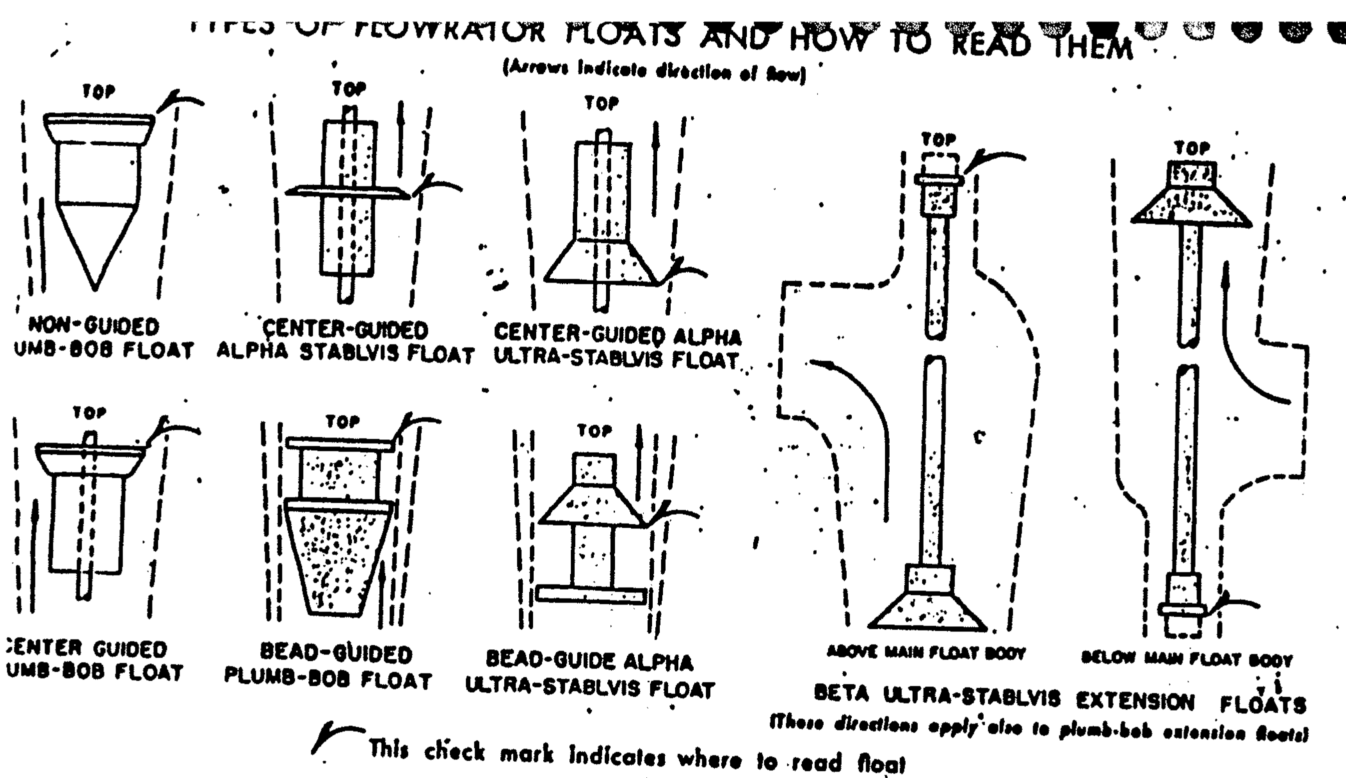



ILLUSTRATION 8

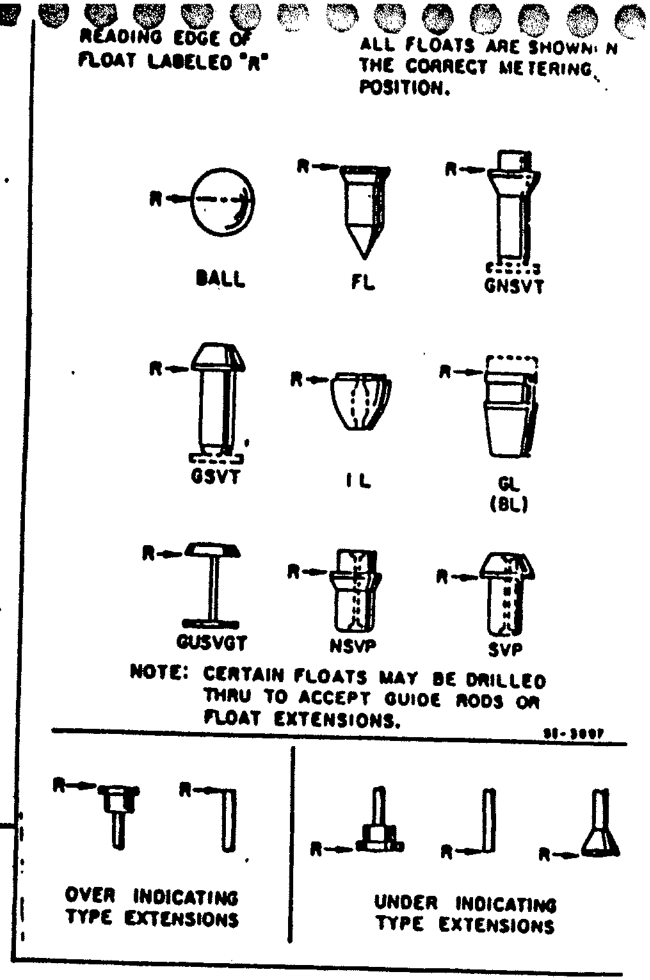



FIGURE 8 FLOAT READING EDGES

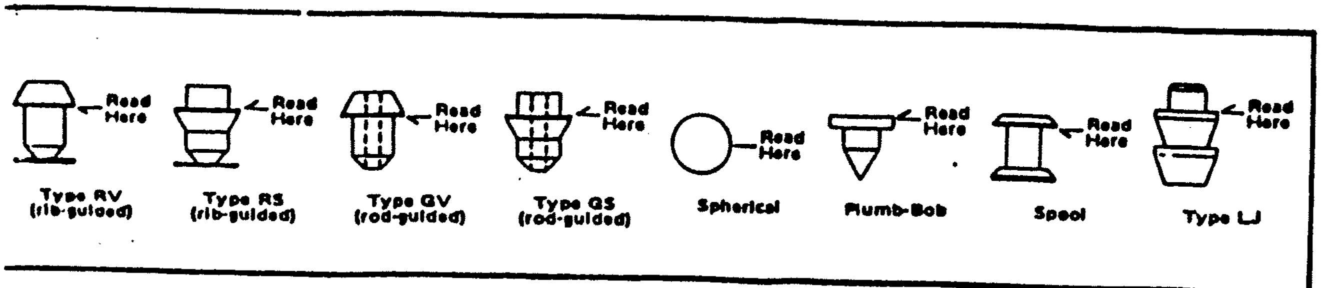



Figure 3-1. Float Types

## Material and Energy Balances

Everyone is familiar with the equation

$$input - output = accumulation$$

It is necessary to know the magnitude of each stream entering the process, and each stream leaving. The reason is that we use these magnitudes to design and operate the equipment. What size pipe do we need for this stream? How big a pump? What flow of cooling water will we need for the condenser? And so on.

When a process is operating at steady state, there should be neither accumulation, nor its negative, depletion. However, our measurements generally show some, one way or the other. Small amounts can perhaps be accounted for by inaccuracies in measuring the flows of mass or energy. However, it is quite possible for a process to show a gain or loss in mass because of a leak the engineer was unaware of. This, in fact, is one important reason for doing a material balance. It can call attention to leaks that otherwise might not have been detected.

Sometimes depletions are called "losses". For example, a cooling tower will show a loss in mass of circulating water because of evaporation to the atmosphere. Or a distillation column will show a loss in thermal energy which is presumed to be losses by radiation and convection from the surface of the column. After summing the measured inputs and outputs the difference is designated as the loss. It is important, however, that the value assigned be **reasonable.**

**What is "reasonable"?** We can always expect some discrepancies due to limitations on the precision and accuracy of the measurements that go into the computation. But those discrepancies should not exceed amounts that can be accounted for by such errors in measurement.

We can make estimates of losses that cannot be measured directly. For example, it is quite possible to calculate an estimate, from the operating conditions, of the loss of water from a cooling tower. It is quite possible, from the size of a distillation column, its insulation, and its operating temperature, to estimate the energy loss by radiation and convection. The losses assigned to such throwaway categories, when doing a material and energy balance, must always be checked for reasonableness by comparing them with estimated values. Else one may overlook a leaking valve, or a faulty flow indicator, or some other detail that needs correction, or the fact that the system was not really at steady state. Indeed, it might be that an error has crept into the calculations. (Oh no! Of course not! I never make a mistake, do I? Do I?).

Doing the material and energy balance is simple enough. One starts with a sketch of the essential elements of the system being studied, draws a boundary line around it, identifies each stream crossing the boundary and takes the necessary data to determine its value. If one needs a refresher, the subject is covered in detail in part 2 of Felder and Rousseau (1978). Once the mass flow rates of the streams are found, it is a simple matter to find the energy balance from the temperature and physical properties of the streams. This subject, too, is covered in part 3 of Felder and Rousseau (1978).