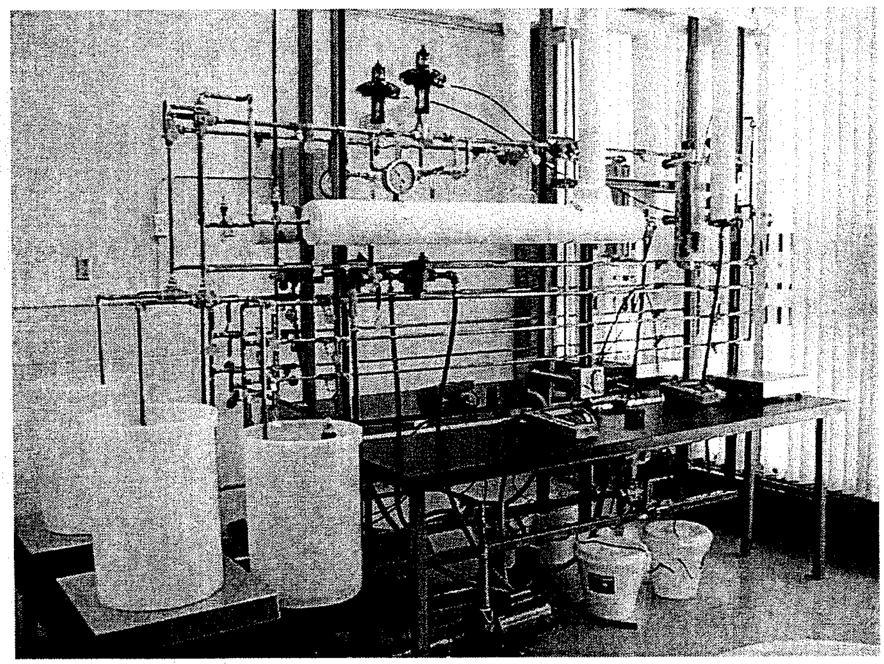
CM 3215

TRANSPORT LABORATORY

MANUAL



Department of Chemical Engineering
Michigan Technological University

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Acknowledgments

We are grateful to James and Sally Brozzo (MTU 1953) for their generous financial contribution to this new lab. Nam Kim and Kirk Schulz contributed in designing the initial draft of processes to be built. Dave Caspary developed the blue print and supervised installation process. The construction was performed by Jerry Norkol and Tim Gasperich. The initial operating part of the manual was contributed by Romulo Almedia, David Caspary, Nicholas Greenland, Jaya Yaddanapudi, Jason Keith, and Anna Siemionko.

Transport Laboratory

CM3215

Lecture 1

Introduction

Dr. Caneba
Chemical Engineering
Michigan Technological University

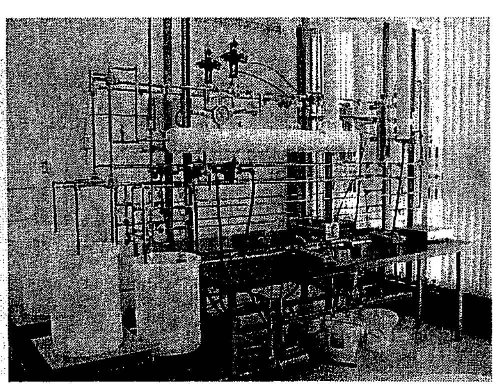
- **Instructors:** Dr. Caneba, Office:304B, Phone:7-2051, e-mail: caneba@mtu.edu; Dr. Co, Office:202G, Phone:7-2144, e-mail: tbco@mtu.edu
- **GTA**: Austin Bryan, Office:202O, e-mail:ambryan@mtu.edu
- **Lecture**: Rm. 102 Chem-Sci.
  - Monday 10:05-10:55
- **Lab periods**: Rm. 103 Chem-Sci.
  - Tuesday 9:05-10:55, 1:05-2:55, 3:05-4:55
  - Thursdays 2:05-3:55

What You Need:

- Textbooks: CM3110 and CM3120 are used for this course.
  - Geankoplis, Transport Process & Seperation Process Priciples
- Lecture Notes + Laboratory notes
- A laboratory notebook
- Approved safety glasses (chemstore)
- Can purchase 1-3 at the campus bookstore

Tentative Schedule

Week	Lecture Topics	Lab Experiments
1	Labor Day	Introduction, safety, report writing
2	Statistics	Constructing P&ID with Visio
3	Applied statistics I	Statistical analysis of data
4	Applied statistics II	Statistical experimental design
5	Fluid viscosity	Viscosity measurement
6	Fluid statics	Measurement of pressure
7	Flow measurement	Fundamentals of fluid mechanics
8	Friction loss in fluid systems	Friction losses in a piping system
9	Valves	Control valve characterization
10	Pumping system analysis	Construction of a system curve
11	Heat exchanger study	Heat transfer coefficient (HE)
12	Temperature measurement	System ID (TC dynamics)
13	Transient heat transfer	Heat transfer to a solid ball
14	In-class Final	On-line HTC and ΔT_{LM}



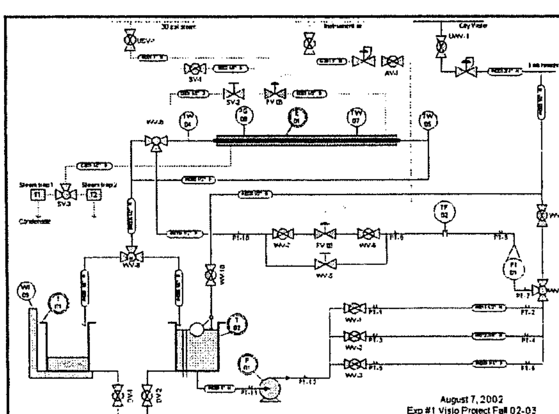


Figure 2. Transport Lab P&ID Visio Printout

Grade
- Scale
  - A: 100-92.00
  - AB: 91.99-88.00
  - B: 87.99-82.00
  - BC: 81.99-78.00
  - C: 77.99-72.00
  - CD: 71.99-68.00
  - D: 67.99-60.00
  - F: below 60
- Weight
  - Final exam: 20% (comprehensive)
  - Lab reports: 80%

Attendance

- Attendance is required:
  - lectures and your
  - designated laboratory period.

☒The course instructor (Dr. Kim) MUST approve excused absences in advance. Any unexpected or unapproved absence will result in the assignment of a zero for that particular laboratory period.

- **MEMORANDUM**
- **Date**: August 25, 2003
- **To**: John Q. Professor
- **From**: Frederick W. Flintstone
- **Re**: Construction of a P&ID using Visio™

Four key sections
- Introduction
- Experimental Data and Results
- Discussion
- Conclusion

- Length: 1 to 3 pages, short & concise. CM 3215 will be **2** pages, including figures.
- **Introduction**
  - Give an idea of the overall topic and purpose of the report.
  - Provide an overview of its contents
  - Orient readers to the report first

- **Experimental Data and Results**
  - Date you performed
  - Organize and present the collected data
    - Tables
    - Figures
  - Be quantitative (*stand alone*).

- **Discussion**
  - (Theory, method, procedure, and equipment). Give readers an idea of your approach:
    - A critical analysis of your data
    - A statistical analysis
    - Determination of uncertainties.
  - Give your reader an idea as to the quality of your data.
  - Provide an interpretive discussion of what your data means.

- **Conclusion**
  - In one or two sentence, present quantitative description as gleaned from
    - Experimental data and results
    - Discussion
  - Explain why you think those conclusions are valid

- **References**
  - David Beer & David McMurrey, A Guide to Writing as an Engineer
  - Sharon Gerson and Steven Gerson Technical Writing: Process and Product

MTU Safety and Environmental Policy

- Can be prevented:
  - Accidents
  - personal injury
  - damage to property or the environment
- Nothing is more important than
  - our safety
  - protection of the environment.
- Each of us is responsible
  - for their individual safety performance
  - for protection of the environment.

- Safety and environmental protection
  - must be an integral part of every job.
- Only through constant mutual effort/cooperation--> achieve these goals
- Signed by:
  - Curtis J. Tomptkins, Univ President
  - W. Kent Wray, Prov & Sr. VP Ac St Affairs
  - Fred W. Hensley, Sr. VP Adv & Marketing
  - Dale R. Tahtinen, VP Gov. Rel. & Sec. B of C
  - David D. Reed, VP for Research
  - William J. McGarry, VP for Administration

What to do if someone is hurt on campus

- **Life threatening**
  - call Public Safety at 1-2-3
  - ask for
    - an ambulance.
    - the fire department (if needed)
    - Public Safety officers (if needed)
- **Chemical spill**
  - the dispatcher will notify: Occupational Safety.

- **Non life threatening**
  - University employees:
    - Work-related injuries or illnesses: University Health Services: 487-2683
    - Non work-related: Personal physician
  - Students: the Health Center all types of medical care
  - Tell them what has happened UHS may be able to
    - Treat the victim
    - Send to the hospital.

- The victim should not drive.
  - the supervisor should
    - sign an authorization form
    - call ahead to notify of permission.
- Must fill out an incident investigation form (Safety Manual)
  - Supervisors: employees
  - Instructor: students in class

- For other incidents:
    - Chemical spills,
    - Property damage,
    - Near misses or
    - Environmental incidents,
  - Contact
    - Occupational Safety and Health Services: 487-2118
  - Fill out the required incident report form.
- At all other times
  - call Public Safety: 1-2-3.

General Safety Rules

- In designated areas you must wear:
  - Safety glasses.
  - Hard hats.
- When working with:
  - corrosive,
  - toxic,
  - hot, or
  - other hazardous materials

  Wear specified personal protective equipment

- An injury on departmental property

  loss of department property
  - report it to the Department Chair
  - report must be filed with the MTU Office of OSH Services
- Not allowed in departmental laboratories
  - Eating,
  - Drinking,
  - Chewing gum and
  - Use of tobacco products

- All laboratory personnel involved with laboratory activities,
  - Be familiar with:
    - the hazards of all the chemicals used in the laboratory
    - the coding system used to label containers and pipelines.

- Working alone in the laboratories during off-hours is discouraged.
  - 5 pm to 8 am
  - weekends
  - holidays

  - During these hours, assistance during an emergency would not normally be available.

Emergency procedure

- **General Emergency Procedure**
  - Dial:
    - 1-2-3 to call the MTU Public Safety.
    - 0 for the operator, if busy.
  - Report nature and location of accident
  - Identify yourself
  - Assist dispatched emergency personnel in locating accident.
  - Submit an accident report.

- **Evacuation Procedure**
  - If the fire alarm sounds,
  - All evacuate the building.
  - Emergency exit stairs:
    both ends of the building hallways
  - The loading dock: not an emergency exit.
  - Do not use the elevator.
  - Emergency exits: denoted by **lighted exit signs** posted on the ceilings.
  - Quickly, but calmly, vacate the building
  - After leaving the building move at least 100 feet away

- **Fires**
  - A clothing fire: use the safety shower
  - To put out fire: use the appropriate fire extinguisher
  - Shut down equipment, if time permits
  - Pull the fire alarm
  - Evacuate laboratory/building
  - Contact MTU Public Safety: dial 1-2-3
- **Smoke**
  - If smoke is visible, do not investigate!
  - Pull a fire alarm
  - Evacuate the building
  - Notify MTU Public Safety: dial 1-2-3

- **Chemical Spills**
  - SAFETY MANUAL (p. 69-76)
  - Department of Chemical Engineering, **SAFETY MANUAL**: For Faculty, Staff, and Students, Includes Chemical Hygiene Plan, August, 2003. Available in MTU Bookstore.

MEMORANDUM

Date: August 25, 2003

To: John Q. Professor

From: Frederick W. Flintstone

Re: Appropriate format for a technical memorandum

Introduction

All memos should have four key sections (when appropriate) which report on the experiment you performed in the laboratory. Memo's are frequently used in business calculations to give a brief description of the results of a project, and are often copied to a variety of different people at different levels within a company.

A memo is typically between 1 to 3 pages, and is short and concise. **The maximum allowable length for a memo report in CM 3215 will be 2 pages, including figures.**

Experimental Data and Results

This section should contain a graph or table that gives important results. This section should be *quantitative*, and should *stand alone*. Indicate the date you have performed the experiment.

Discussion

This section should include a critical analysis of your data, including statistical analysis and determination of uncertainties. You should give your reader an idea as to the quality of your data and provide an *interpretation* of what your data means.

Conclusion

This section should include a one or two sentence, ***quantitative*** description of your conclusion as gleaned from your experimental data, results, and discussion.

GUIDELINES ON GRAPHING

When putting together a graph of technical data, always use the following guidelines:

1. Size the graph appropriately.
2. Make sure to label your axes so that they are easily readable and give the appropriate units.
3. Use a key to label the different lines of your graph, or label data series.
4. Keep the tick marks and scale of your graph so that it reads out in standard, whole numbers. In Excel, you can select the minimum X and Y values to graph and can give the distance between ticks. This makes for a much more pleasing and useful graph.
5. Be sure to put an appropriate title on your graph.
6. Unless there is a specific reason, do not include horizontal or vertical lines on your graph. If you need a grid pattern, include that, but rarely are graphs needed with only horizontal or only vertical lines.
7. Remove the background graph color. In Excel, the gray background can be removed by right clicking on the graph area, selecting Format Plot Area, and select None under the pattern area.
8. Insert the appropriate trend lines where needed.
9. Always select the correct type of graph to represent your data. For most scientific applications, use an XY (Scatter Plot). Depending on the data, choose between:

    a. Scatter Points: Plots with varying or unknown trends or with noisy data.
    b. Scatter Points with Lines: Used to depict trends in clean or linear data.
    c. Scatter Points with smoothed Lines: Used to depict trends in noisy data.

MTU Safety and Environmental Policy

The Safety Policy of Michigan Technological University is based on the firm conviction that accidents which cause personal injury or damage to property or the environment can be prevented. No phase of University business or operation is of greater importance than the safety of our students, faculty, staff, and visitors, and protection of the environment.

Michigan Technological University will provide and maintain a safe and healthy environment at all locations and will establish operating practices designed to assure the safety of all.

Each students, faculty and staff is responsible for their individual safety performance and for protection of the environment. Each instructor/supervisor also has the responsibility to create a climate of safety and environmental awareness. Safety and environmental protection must be an integral part of every job. It is the responsibility of all to comply with safety rules and to work in such a manner as to prevent injuries to themselves, others and damage to the environment.

The prevention of accidents and the protection of the environment are in the best interest of all. Only through constant mutual effort and cooperation can we achieve these goals.

Signed by:
Curtis J. Tomptkins, University President
W. Kent Wray, Provost and Sr. VP for Academic and Student Affairs
Fred W. Hensley, Sr. VP for Advancement & Marketing
Dale R. Tahtinen, VP for Gov. Rel. & Sec. Board of Control
David D. Reed, VP for Research
William J. McGarry, VP for Administration

WHAT TO DO IF SOMEONE IS HURT

If an MTU employee, student or visitor becomes seriously ill or injured on campus, here is what you should do:

1. If the injury or illness is life threatening, or if you are in doubt, call Public Safety at 1-2-3 and ask for an ambulance. Be sure to let the dispatcher know if you need additional help, such as the fire department or Public Safety officers. In the event of a chemical spill, the dispatcher will notify Occupational Safety.

2. Work-related injuries or illnesses that require immediate care but are not life threatening should be referred to University Health Services (487-2683). Students may use the Health center for all types of medical care – University employees are treated there for work-related injury or illness only. Illnesses that are not work-related should be treated by your personal physician.

   Be sure to call University Health Services first, at 487-2683, and tell them what has happened. Health Services may be able to treat the victim, or they may recommend that the victim go to the hospital. In many cases, the victim should not drive. If an injured employee goes to Health Services, the supervisor should sign an authorization form or call ahead to notify staff that the victim has permission to receive treatment.

3. Supervisors must fill out an incident investigation form in the event of an employee accident or illness (a copy of this form is contained within this manual). For accidents involving a student in class, the instructor must complete the form.

For other incidents not involving injury, i.e. chemical spills, property damage, near misses or environmental incidents, contact Occupational Safety and Health Services at 487-2118, during normal working hours and then fill out the required incident report form. At all other times call Public Safety from a campus phone at 1-2-3.

Important Phone Numbers:

	Campus Phone	Outside
MTU Public Safety (Emergency):	1-2-3	
MTU Occupational Safety (non-emergency):	7-2118	487-2118
MTU Central Heating Plant:	7-2707	487-2707
MTU Dept. of Chemical Engineering:	7-3132	487-3132
Dave Caspary, Manager of Dept. Labs:	7-2022	487-2022
National Poison Control Center:	8-1-800-562-9781	1-800-562-9781
Houghton Fire Department:	8-482-1234	482-1234
Houghton Police:	8-482-2121	482-2121
Portage View Hospital:	8-487-7800	487-7800

General Safety Rules

All personnel must wear safety glasses in designated areas.
All personnel must wear hard hats in designated area.
All personnel must wear the specified personal protective equipment when working with corrosive, toxic, hot, or other hazardous materials.
Any individual sustaining an injury on departmental property must report it to the Chair of the Department of Chemical Engineering.
All accidents or incidents involving loss of department property must be reported to the Department Chair and a report must be filed with the MTU Office of Occupational Safety and Health Services.
Unsafe acts or conditions observed by any person on departmental property must be reported promptly to the Department Chair.
Alcoholic beverage, narcotics, hallucinogenic and other illegal drugs are not permitted on departmental property. Reporting to work under the influence of any of these substances is not allowed.
Firearms are not permitted on departmental property
Horseplay, fighting and running are not permitted on the departmental property.
Machinery and moving equipment must not be operated without the proper safety guards in place.
Danger areas must be roped off, barricaded or otherwise marked.
Only properly trained and authorized personnel are permitted to operate machines and equipment.
Eating, drinking, chewing gum and use of tobacco products is not allowed in departmental laboratories.
Laboratory floors must be kept dry, clean, and uncluttered at all times. Any spills should be cleaned up immediately using proscribed procedures and disposed of in an environmentally safe manner.
All laboratory personnel, including faculty, staff, students and all others involved with laboratory activities, are expected to be familiar with the hazards of all the chemicals used in the laboratory and with the coding system used to label containers and pipelines.
Working alone in the laboratories during off-hours (5 pm to 8 pm, on weekends, or on holidays) is discouraged. During these hours, assistance during an emergency would not normally available.

EMERGENCY PROCEDURE

This is essential when an accident or emergency occurs—a few seconds can make the difference between life and death. All departmental personnel should be familiar with emergency response procedures prior to the occurrence of an incident.

General Emergency Procedure

Dial 1-2-3 on any campus phone to call the MTU Public Safety. If busy, dial the operator.
Report nature and location of accident, and identify yourself.
Emergency personnel will be dispatched.
Assist emergency personnel in locating accident.
Submit an accident report.

Evacuation Procedure

All personnel are required to evacuate the building if the fire alarm sounds.
Emergency exit stairs are found on both ends of the building hallways. There are three exits to the Chemical Sciences and Engineering building. These are (1) at the south end of the building on the first floor, (2) between the first and basement levels at the northeast corner stairwell of the building, and (3) in the middle of the hallway on the first floor. The loading dock area is not an emergency exit.
Do not use the elevator as an evacuation route.
Emergency exits are denoted by lighted exit signs posted on the ceilings.
Quickly, but calmly, use the emergency exits to vacate the building.
After leaving the building move at least 100 feet away.

Fires

Use the safety shower to extinguish a clothing fire.
Shut down equipment, if possible and if time permits.
Use the appropriate fire extinguisher to put out fire if this can be done without endangering yourself.
Evacuate laboratory immediately and safely.
Pull the fire alarm located at the ends of each hallway.
Evacuate the building using the above evacuation procedure.
Contact MTU Public Safety by dialing 1-2-3 on any campus phone.

Smoke

If smoke is visible in the hallway or laboratory, and it is not obvious where it is coming from, do not investigate!
Pull a fire alarm located at either end of the hallway and evacuate the building.
Notify MTU Public Safety by dialing 1-2-3 on a campus phone.

Chemical Spills

See the detailed discussion in the section of this manual (p. 69-76).

Department of Chemical Engineering, **SAFETY MANUAL**: For Faculty, Staff, and Students, Includes Chemical Hygiene Plan, August, 2002. Available in MTU Bookstore, if interested.

Experiment 1. Preparation of a P&ID

Introduction

There are several types of engineering drawings that are commonly created in the engineering, design, construction, and operation of chemical processing equipment. Each drawing has a specific purpose and each is necessary to communicate information to others working on the same project.

A Block Flow Diagram is developed during the conceptual design phase of a project. This is a block diagram showing the major processing steps in the production of a chemical or product. The block flow diagram should include a material balance and rough equipment sizing to aid in developing an approximate capital cost estimate. The block flow diagram is used to help high-level decision makers understand the process being proposed and decide if the project warrants funding.

If a project is approved, the design progresses from the conceptual phase to the process design phase. During process design, alternative processing methods are considered and a best-fit solution is created. The process designers create a Process Flow Diagram (PFD) to identify the equipment, display energy and material balances, and define process control requirements. At this phase of the project the capital cost estimate is refined. The PFD is a two-dimensional schematic representation of the process. When process design is complete, the PFD and any supporting documentation are passed on to the detail design team.

The detailed engineering phase of a project is the final step before construction. A Piping and Instrument Diagram (P&ID or PID) begins to evolve from the PFD. The P&ID is a "connectivity" diagram, showing the relative location of all equipment, valves, and instrumentation. The P&ID shows line sizes, insulation, and references the appropriate instrument data sheet, and piping and equipment specifications. Like the PFD, the P&ID is also a 2-dimensional schematic. However, equipment is usually shown in relative size, shape, and physical orientation on a P&ID.

As the detailed design progresses, other types of drawings are created – loop drawings, fabrication drawings, equipment drawings, and installation detail drawings. Of this list the one drawing that has hierarchical priority over all other drawings and remains with the process from cradle to grave is the P&ID. As such, the P&ID is used to resolve any discrepancies that may arise during construction. The P&ID is said to be a "living document", used for daily operations, maintenance, and troubleshooting, and as such must be kept current throughout the life of the process.

A few important notes on P&ID's:

- The P&ID is normally part of the construction drawing set and is seen by contractors and supply, equipment, and instrumentation vendors. For this reason, never include any proprietary information about the process fluids, special process equipment features, material flow rates, or control logic information on a P&ID.

- A P&ID is not a substitute for a piping layout or isometric drawing and is never drawn to scale.
- As Bruce Lovelace of Dow Chemical Company stated, "The P&ID is the graphical table of contents to all other engineering documents that identify a process."

The Instrument Society of America (ISA) publishes a set of standard rules and symbols for construction of a P&ID. In this exercise we will create a P&ID of the flow loop in our Fundamentals of Chemical Engineering Laboratory, following the ISA standards. To help create this drawing, we have attached a copy of the completed drawing, a line schedule, a valve schedule, an equipment schedule, and an instrument schedule. A table of valve and equipment symbols and a table of instrumentation identification letters are also included.

At the completion of the exercise you should become familiar with the standard symbols, general rules for construction of a P&ID and become familiar with **Visio**™ drawing package.

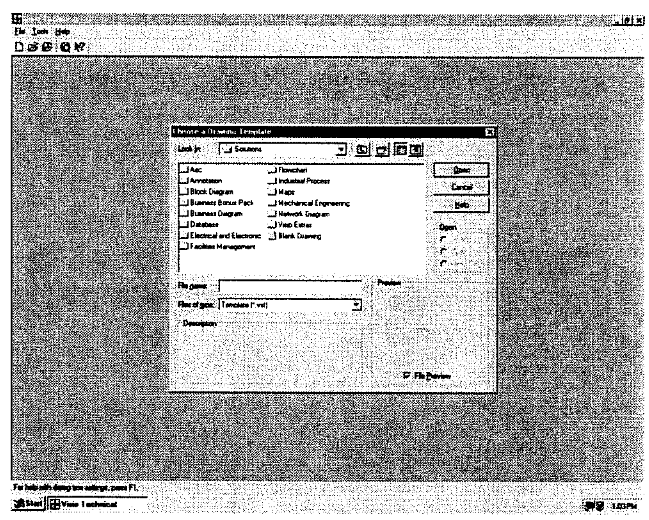
Construction of a proper P&ID is often required in Plant Design and UO Lab and in this laboratory experiment, you will use Visio™ to draw.

Experimental Procedure

1. Working with your laboratory partner, identify all of the major pieces of equipment in the process such as pump (P01), heat exchanger (E01), and control valves (FV03 & FV06). Refer to Figure 1.
2. (Optional) Using the tape measure, sketch the length (not given) and the size (given) of each pipe. Also measure distances between the hot pressure taps (for example: PT-1 and PT-2) on the straight pipes in your laboratory notebook.
3. Check the label with tags on all of the pieces of equipment and compare them to the P&ID.
4. Using Visio (as described below), make a scaled P&ID of the process in the laboratory.
5. If any piece of equipment is not shown in the P&ID, take a note of it.

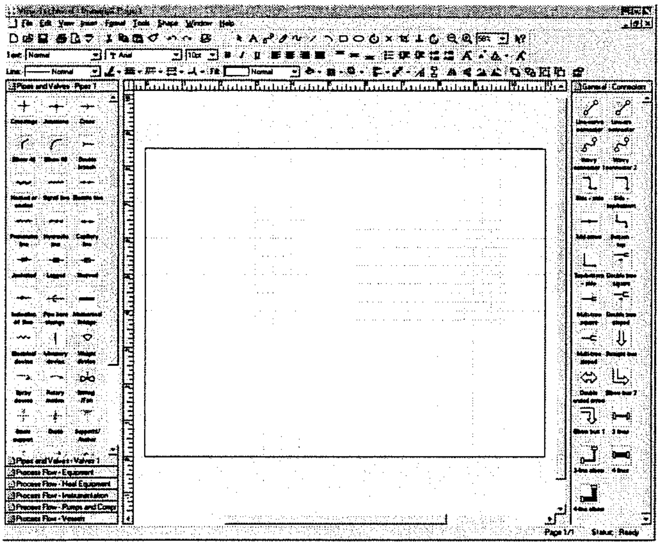
Construction of a P&ID using Visio

1. Log in to the any of the PC's in the computer labs.
2. Start-up Visio Technical 5.0.
3. The program will start and the screen below will appear.

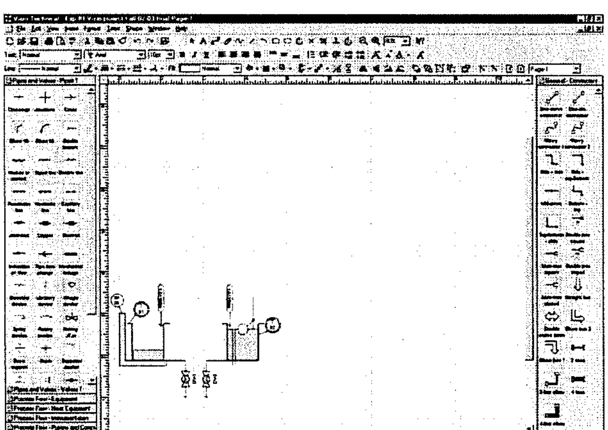


4. Select appropriate templates (example New -> Industrial Process -> Process Flow-All Stencils)

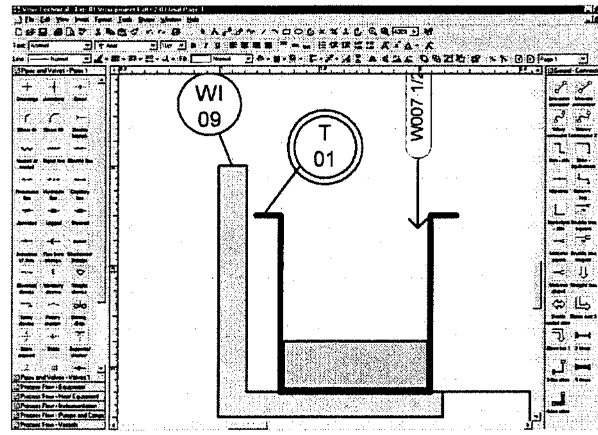
The following screen with a drawing board in the middle will appear



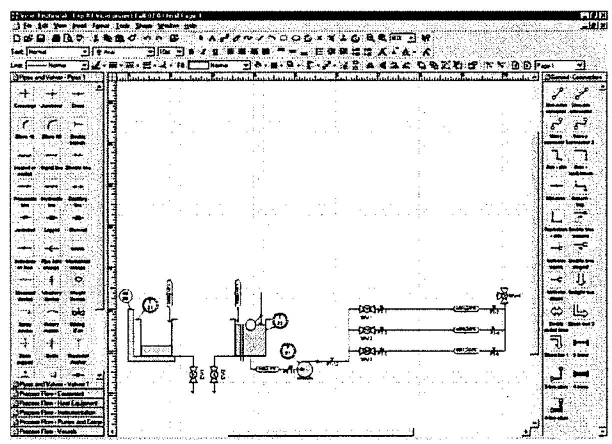
5. To select any of the right side templates simply click at its name
6. To inset an icon simply "drag and drop" the one you want. (If AutoCAD™ is used for this drawing, refer to master legends attached.)
7. The following 4 figures are given to guide you, using 80% Zoom Option as shown below.

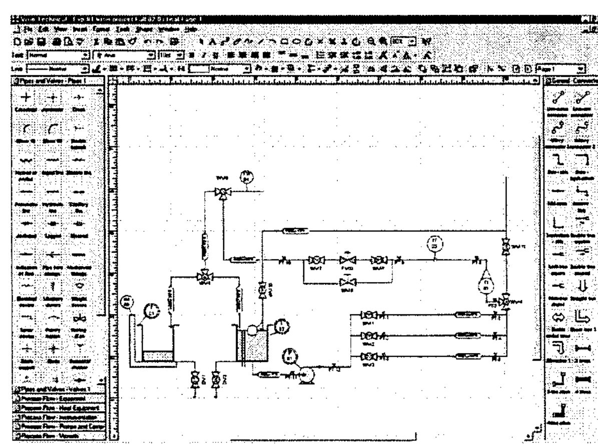


It is recommended to use 400 % zoom option to draw figures in detail (see below) and to use 80 % zoom option to construct an overall layout. These figures are made for Groups 2, 4, 6, and 8. (For those who belong to Gr 1, 3, 5, and 7 may use an alternative P&ID presented in Figure 3.)



8. Figure 1 shows one possible final drawing. Also see a printout in Figure 2.
9. Figure 4 shows some discrepancy between the icons of AutoCAD drawing and those of Visio.





Tips:

- Double click an icon and you will be able to label it.
- Right click on Icon and several options will appear. Explore these options.
- There are several Icons in your "toolbars". If you put your mouse pointer on it and wait for a few seconds a text box with a description of the icon will pop up.
- If you can't find the icon you want try different templates. Click on the "open stencil" Icon in the toolbar and several options will show up. There are a few directories available.
- If you can't find the appropriate icon, you can make your own drawings using this software package. You can draw lines, curves... by using icons from the toolbar.
- **If your drawing page is set to landscape, remember to also change the settings on the printer, otherwise it will print in 2 pages (File -> Page Setup -> Portrait)**

Also find the following attachments:

Master Legends
Identification Letters
  Meanings
  Notes
Piping Schedule
Valve Schedule
Instrument Schedule

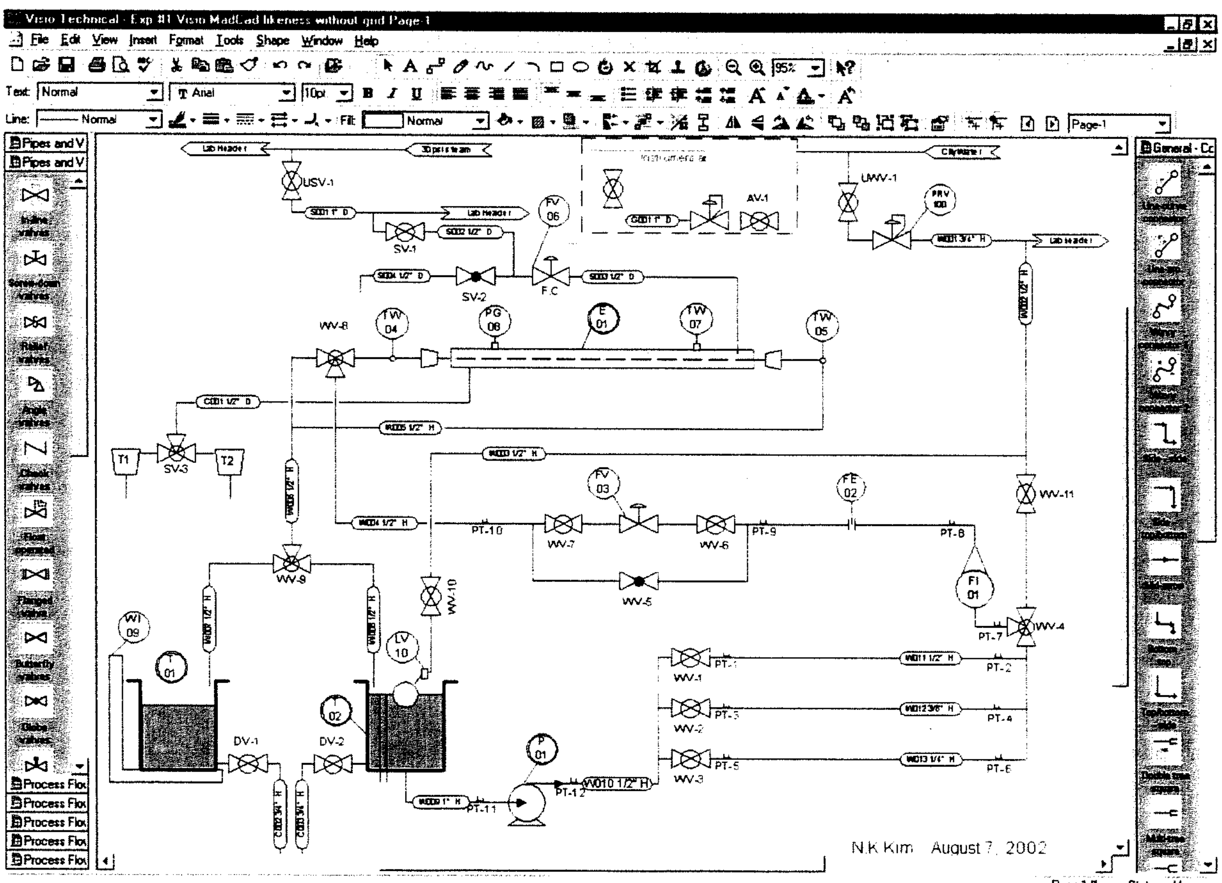


Figure 1. Transport Lab P&ID with Visio™

Report

Summarize your experience with Visio while you prepare a P&ID representing the process. Make sure you included all the parts of the process in your diagram. Make a comment on a new way or innovative approach.

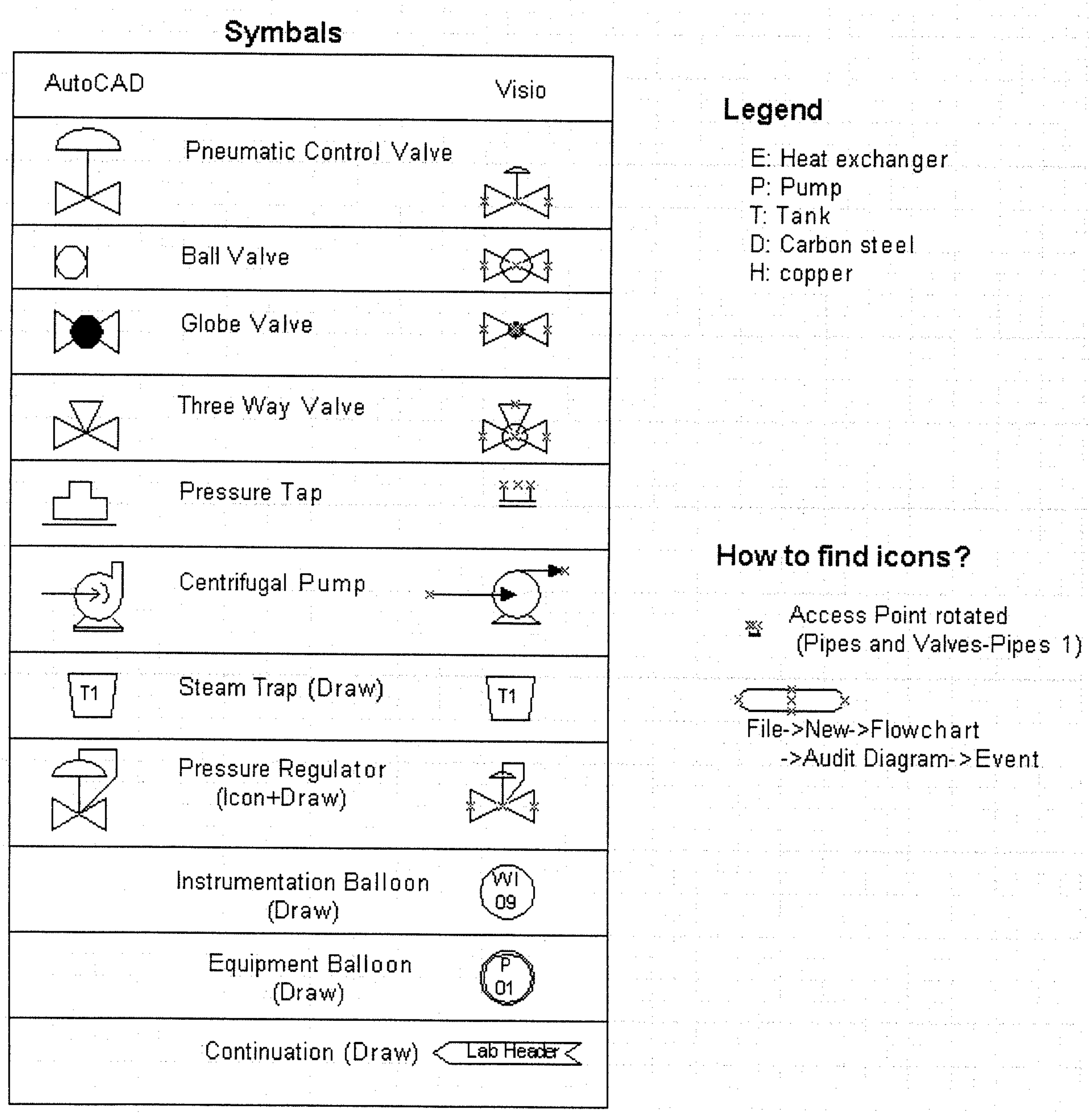


Figure 4. Icons used for Visio™ and AutoCAD™

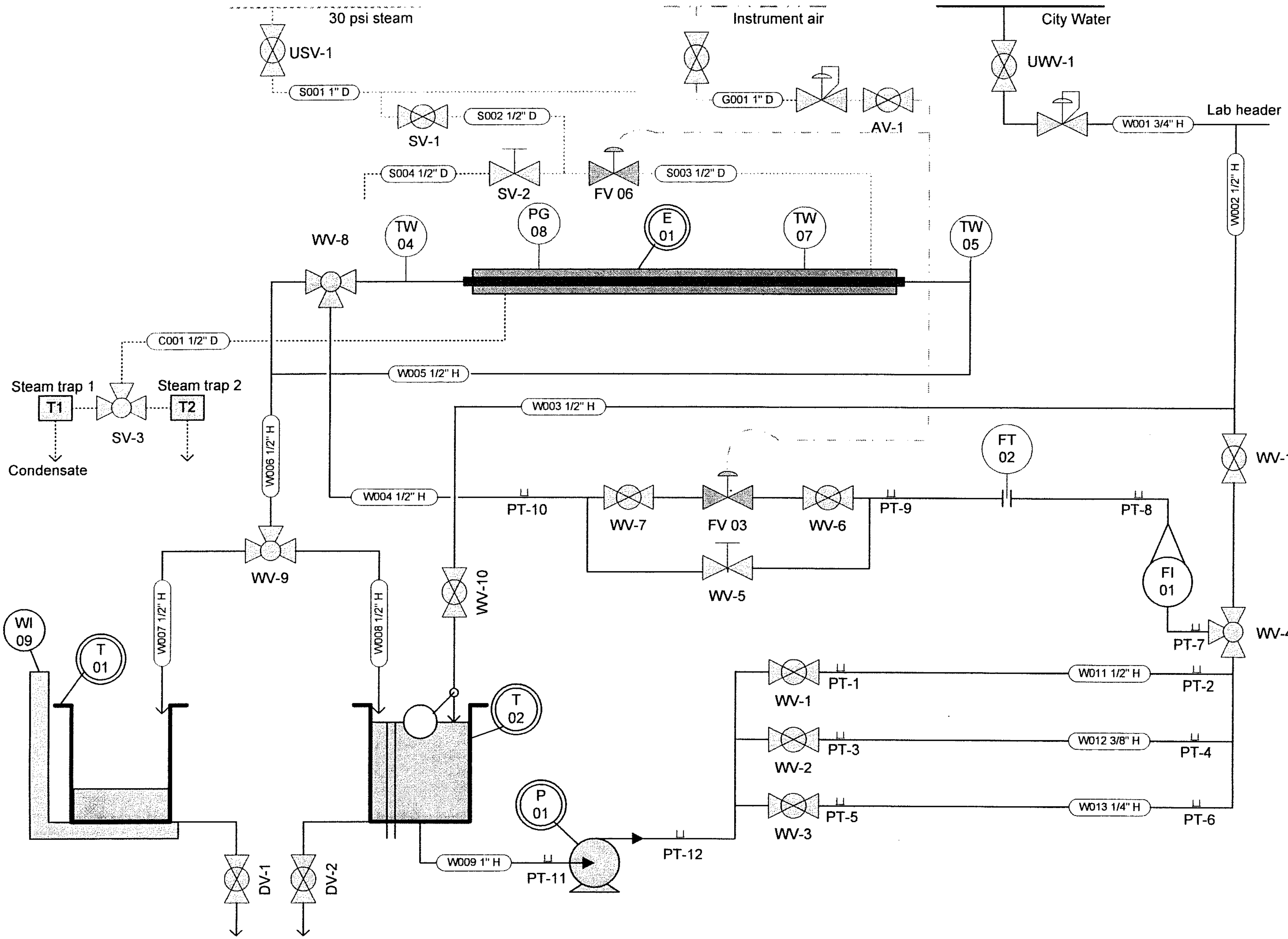


Figure 2. Transport Lab P&ID Visio Printout

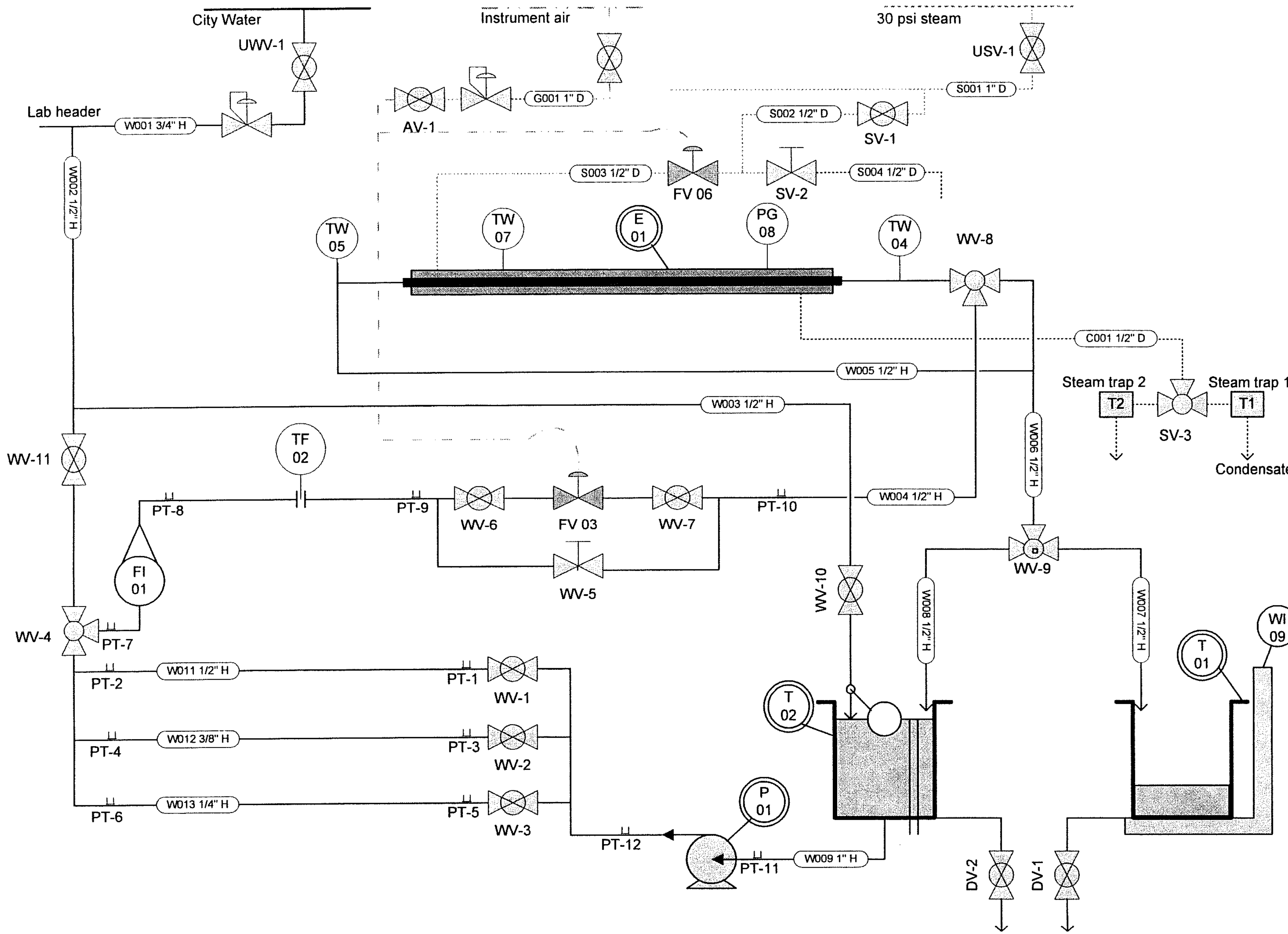


Figure 3. Transport Lab P&ID Visio Printout

Transport Laboratory

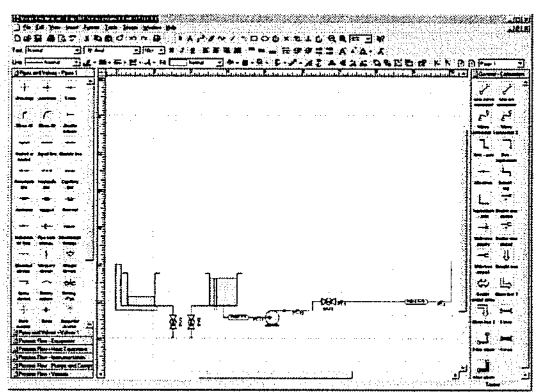
CM3215
Lecture 1 Supplement

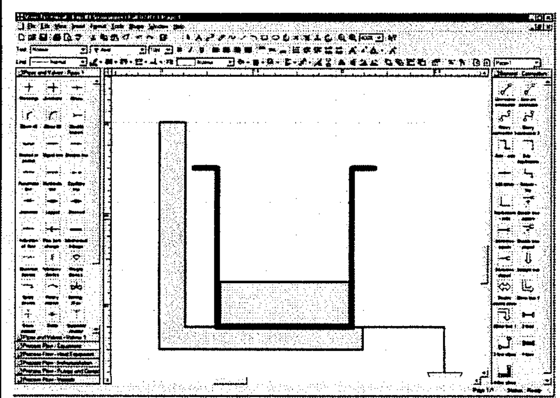
Using Visio

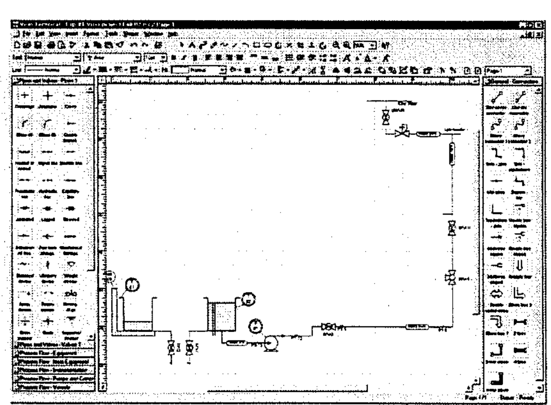
Nam K. Kim
Chemical Engineering
Michigan Technological University

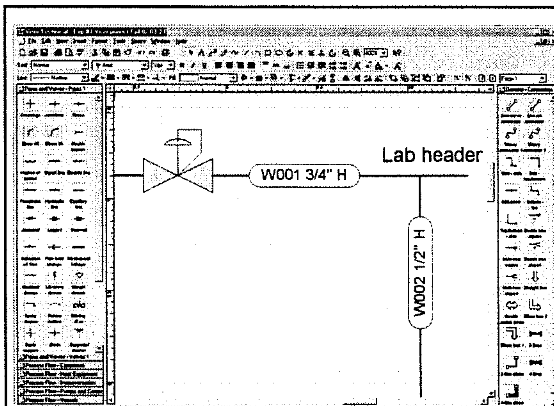
Usefull Suggestions

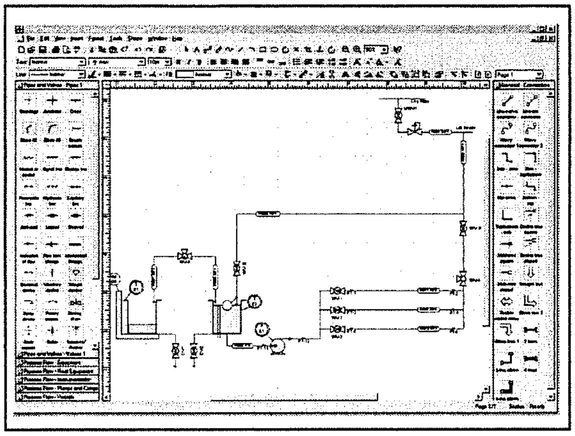
- ☒To present your P&ID in one sheet (8.5" by 11") pay attention to Grid and Rulers. Limit your drawing to 8.5" by 11" as shown on the x- and y-Rulers.
- ☒When the drawing is oversized, reduce it by the floowing steps:
  Page setup --> Page Size --> Same as printer size.
- ☒Move Zoom in and out from 35 % to 400 % (you can go up to 3000 %, if you want). You need 35 % for overall perspective and 400 % to draw in detail.

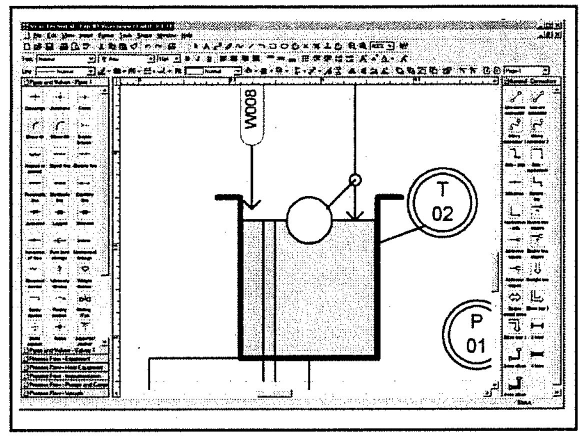


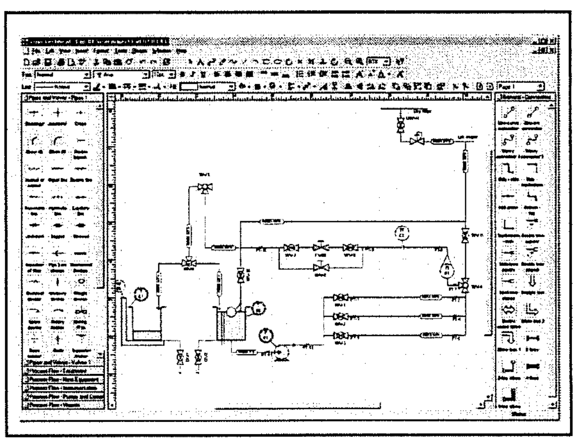


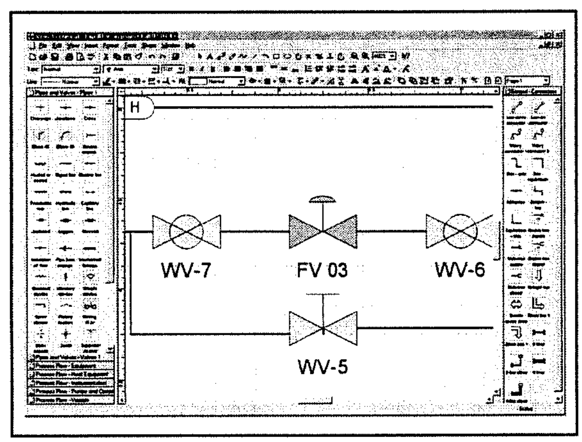


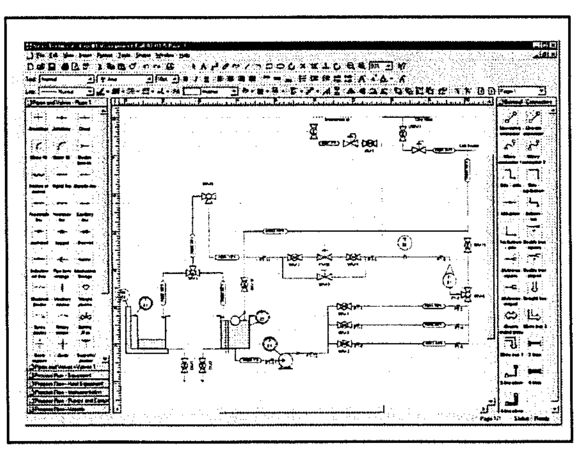


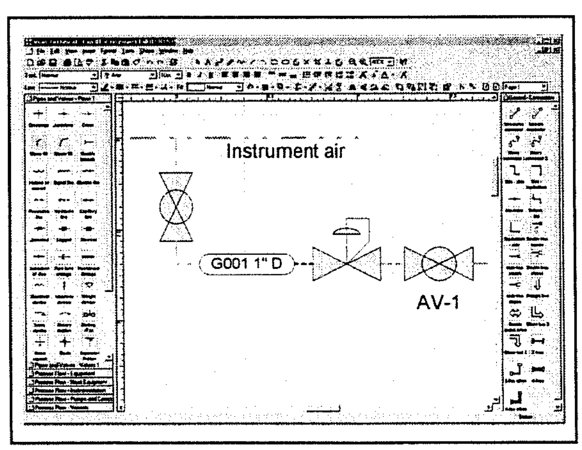


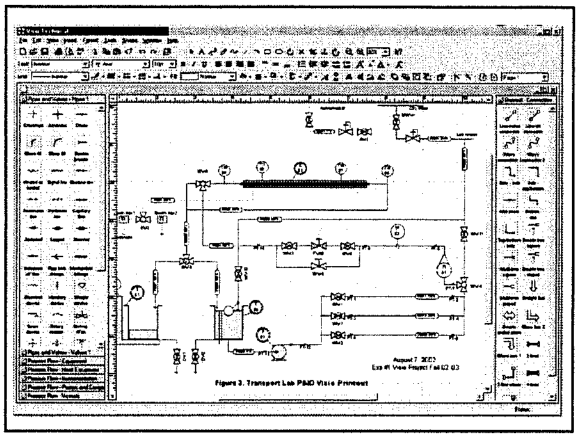

W008
T
02
P
01

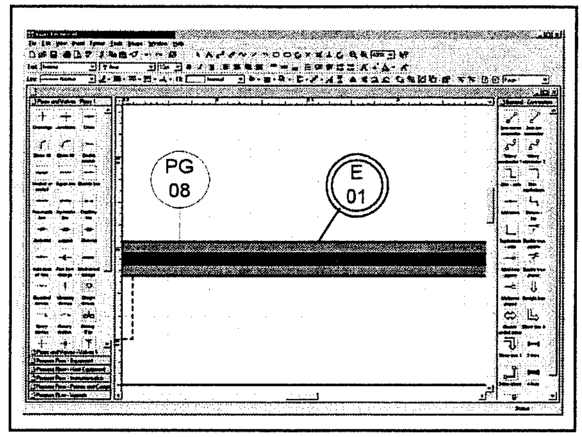


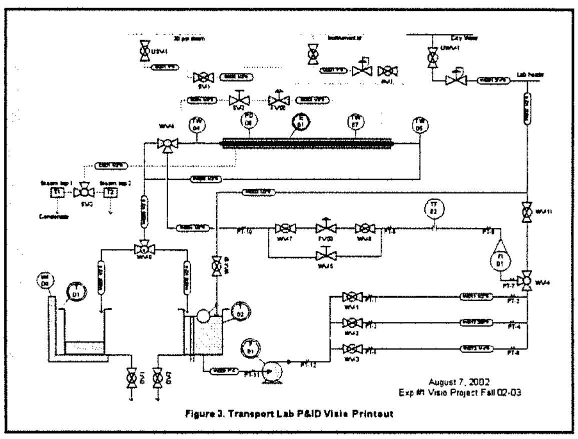

H
WV-7
FV 03
WV-6
WV-5

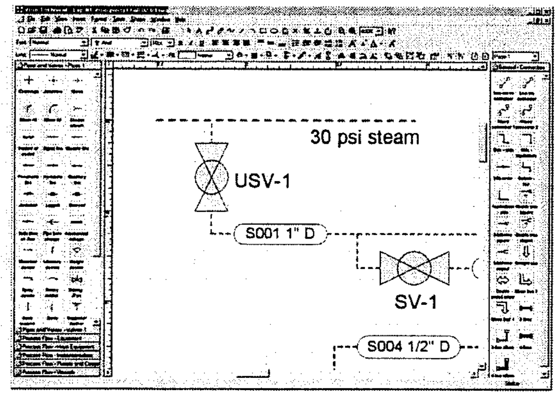



Instrument air
G001 1" D
AV-1



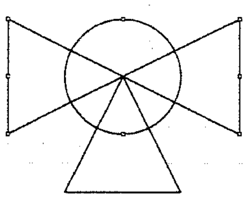

PG
08
E
01


City Water
Lab heater
August 7, 2002
Exp #1 Visio Project Fall 02-03
Figure 3. Transport Lab P&ID Visio Printout



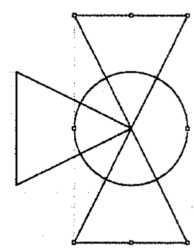
Some tricks to elaborate.

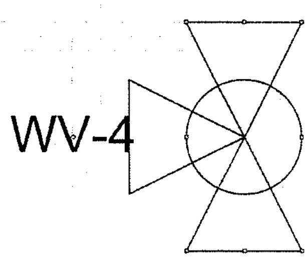
- ⌧Three-way valve
- ⌧Rotameter



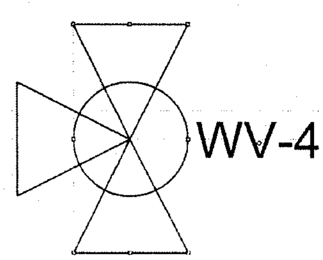
⌧The initial position We want to have the branch point to the left. So rotate right.

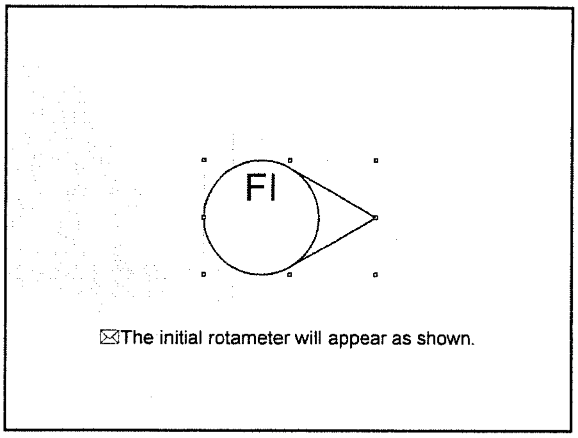
⌧Double click your cursor on the icon to write text.

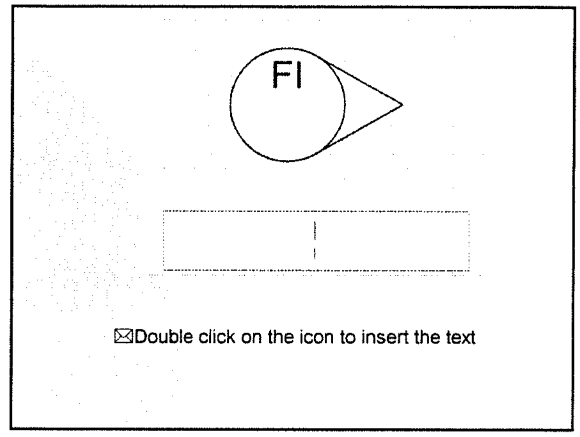


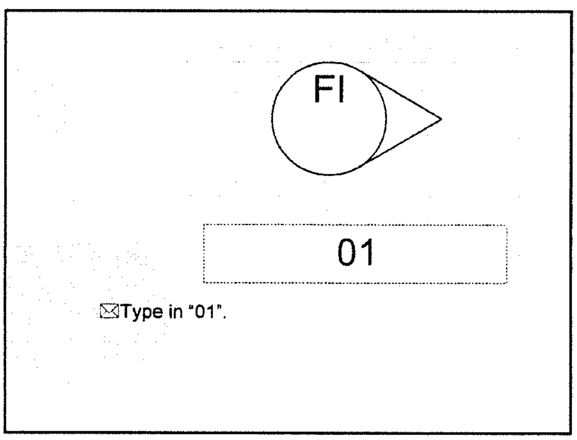


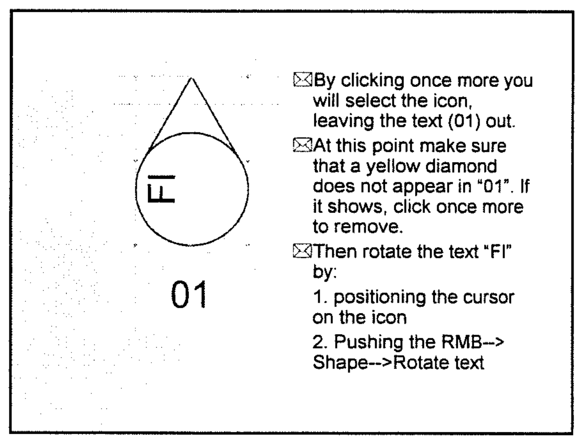
⌧But the text will appear on the left where piping should be connected. Move the text to the right side of the icon. By clicking once more on the icon notice that a small yellow diamond in the text will appear. Grab it (yellow) and drag to the right.

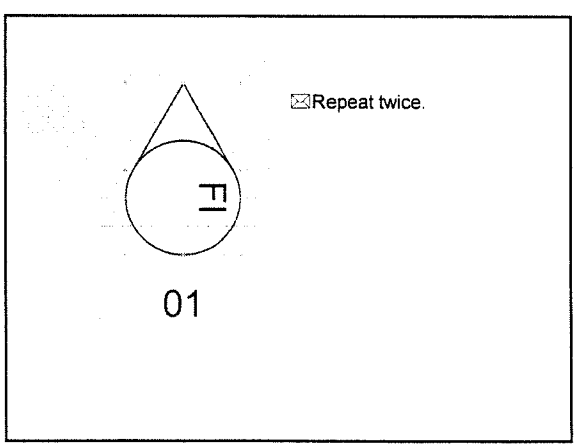


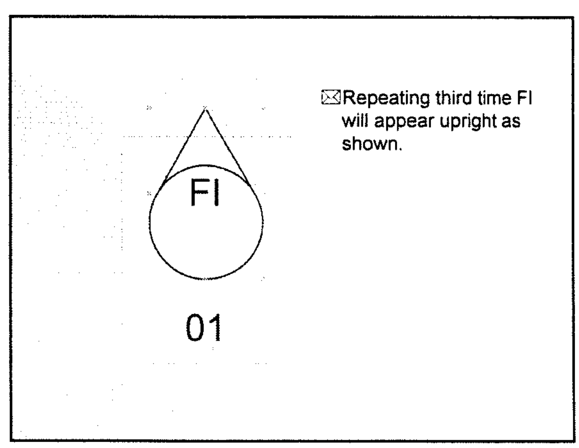

FI
⌧The initial rotameter will appear as shown.

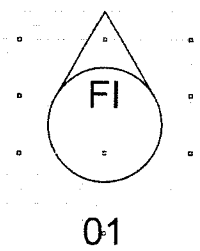

FI
⌧Double click on the icon to insert the text


FI
01
⌧Type in "01".

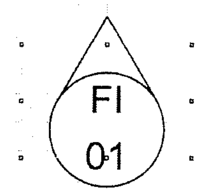

FI
01
⌧By clicking once more you will select the icon, leaving the text (01) out.
⌧At this point make sure that a yellow diamond does not appear in "01". If it shows, click once more to remove.
⌧Then rotate the text "FI" by:
1. positioning the cursor on the icon
2. Pushing the RMB--> Shape-->Rotate text


FI
01
⌧Repeat twice.


FI
01
⌧Repeating third time FI will appear upright as shown.



- Clicking once more on the icon, select the text "01". This is done when a small yellow diamond appear in the text "01". Grab the small yellow diamond and drag it into the icon as shown.



- Desired shape of Rotameter.

If the text is missing from the printout.

- If the text is missing from the printout, do the following:
  1. File --> Print --> Properties --> Document Options (double click) --> Print Text as graphics<Off> --> <On>
  2. Restore <On> to <Off> after finishing your job, because it tends to slow down the printer speed.

TABLE C-2
MEANINGS OF IDENTIFICATION LETTERS

This table applies only to the functional identification of instruments. Numbers in table refer to notes following.

	FIRST LETTER		SUCCEEDING LETTERS (3)		
	MEASURED OR INITIATING VARIABLE (4)	MODIFIER	READOUT OR PASSIVE FUNCTION	OUTPUT FUNCTION	MODIFIER
A	Analysis (5)		Alarm		
B	Burner Flame		User's Choice (1)	User's Choice (1)	User's Choice (1)
C	Conductivity (Electrical)			Control (13)	
D	Density (Mass) or Specific Gravity	Differential (4)			
E	Voltage (EMF)		Primary Element		
F	Flow Rate	Ratio (Fraction) (4)			
G	Gauging (Dimensional)		Glass (9)		
H	Hand (Manually Initiated)				High (7, 15, 16)
I	Current (Electrical)		Indicate (10)		
J	Power	Scan (7)			
K	Time or Time-Schedule			Control Station	
L	Level		Light (Pilot) (11)		Low (7, 15, 16)
M	Moisture or Humidity				Middle or Intermediate (7, 15)
N (1)	User's Choice		User's Choice	User's Choice	User's Choice
O	User's Choice (1)		Orifice (Restriction)		
P	Pressure or Vacuum		Point (Test Connection)		
Q	Quantity or Event	Integrate or Totalize (4)			
R	Radioactivity		Record or Print		
S	Speed or Frequency	Safety (8)		Switch (13)	
T	Temperature			Transmit	
U	Multivariable (6)		Multifunction (12)	Multifunction (12)	Multifunction (12)
V	Viscosity			Valve, Damper, or Louver (13)	
W	Weight or Force		Well		
X (2)	Unclassified		Unclassified	Unclassified	Unclassified
Y	User's Choice (1)			Relay or Compute (13,14)	
Z	Position			Drive, Actuate or Unclassified Final Control Element	

Note: Numbers in parentheses refer to specific explanatory notes on the next two pages.

From ISA S5.1/1975 (approved by ANSI)

NOTES FOR TABLE C-2
MEANINGS OF IDENTIFICATION LETTERS

1. A *user's choice* letter is intended to cover unlisted meanings that will be used repetitively in a particular project. If used, the letter may have one meaning as a first-letter and another meaning as a succeeding-letter. The meanings need be defined only once in a legend, or otherwise, for that project. For example, the letter *N* may be defined as *modulus of elasticity* as a first-letter and *oscilloscope* as a succeeding-letter.

2. The *unclassified* letter, *X*, is intended to cover unlisted meanings that will be used only once or to a limited extent. If used, the letter may have any number of meanings as a first-letter and any number of meanings as a succeeding-letter. Except for its use with distinctive symbols, it is expected that the meanings will be defined outside a tagging balloon on a flow diagram. For example, *XR-2* may be a *stress recorder*, *XR-3* may be a *vibration recorder*, and *XX-4* may be a *stress oscilloscope*.

3. The grammatical form of the succeeding-letter meanings may be modified as required. For example, *indicate* may be applied as *indicator* or *indicating*, *transmit* as *transmitter* or *transmitting*, etc.

4. Any first-letter, if used in combination with modifying letters *D* (differential), *F* (ratio), or *Q* (integrate or totalize), or any combination of them, shall be construed to represent a new and separate measured variable, and the combination shall be treated as a first-letter entity. Thus, instruments *TDI* and *TI* measure two different variables, namely, differential-temperature and temperature. These modifying letters shall be used when applicable.

5. First-letter *A* for *analysis* covers all analyses that are not listed in Table C-2 and are not covered by a *user's choice* letter. It is expected that the type of analysis in each instance will be defined outside a tagging balloon on a flow diagram.†

6. Use of first-letter *U* for *multivariable* in lieu of a combination of first-letters is optional.

7. The use of modifying terms *high*, *low*, *middle or intermediate*, and *scan* is preferred, but optional.

8. The term *safety* shall apply only to emergency protective primary elements and emergency protective final control elements. Thus, a self-actuated valve that prevents operation of a fluid system at a higher-than-desired pressure by bleeding fluid from the system shall be a back-pressure-type *PCV*, even if the valve were not intended to be used normally. However, this valve shall be a *PSV* if it were intended to protect against emergency conditions—i.e., conditions that are hazardous to personnel or equipment, or both, and that are not expected to arise normally.

   The designation *PSV* applies to all valves intended to protect against emergency pressure conditons regardless of whether the valve construction and more of operation place them in the category of the safety valve, relief valve, or safety-relief valve.

9. Passive function *glass* applies to instruments that provide an uncalibrated direct view of the process.

10. The term *indicate* applies only to the readout of an actual measurement. It does not apply to a scale for manual adjustment of a variable if there is no measurement input to the scale.

† *Readily recognized self-defining symbols such as pH, O_2, and CO have been used optionally in the past in place of first-letter A. This practice may cause confusion and misunderstanding particularly when the designations are printed by machines that use only uppercase letters.*

11. A *pilot light* that is part of an instrument loop shall be designated by a first-letter followed by succeeding-letter *L*. For example, a *pilot light* that indicates an expired time period may be tagged KL. However, if it is desired to tag a *pilot light* that is not part of a formal instrument loop, the *pilot light* may be designated in the same way or alternatively by a single letter *L*. For example, a running light for an electric motor may be tagged either *EL*, assuming that voltage is the appropriate measured variable, or *XL*, assuming that the light is actuated by auxiliary electric contacts of the motor starter, or simply *L*.

    The action of a *pilot light* may be accompanied by an audible signal.

12. Use of succeeding-letter *U* for *multifunction* instead of a combination of other functional letters is optional.

13. A device that connects, disconnects, or transfers one or more circuits may be either a *switch*, a *relay*, an on-off *controller*, or a *control valve*, depending on the application.

    If the device manipulates a fluid process stream and is not a hand-actuated, on-off block valve, it shall be designated as a *control valve*. For all applications other than fluid process streams, the device shall be designated as follows:

    A *switch*, if it is actuated by hand.

    A *switch* or an on-off *controller* if it is automatic and is the first such device in a loop. The term *switch* is generally used if the device is used for alarm, pilot light, selection, interlock, or safety. The term *controller* is generally used if the device is used for normal operating control.

    A *relay*, if it is automatic and is not the first such device in a loop, i.e., it is actuated by a *switch* or an on-off *controller*.

14. It is expected that the functions associated with the use of succeeding-letter *Y* will be defined outside a balloon on a flow diagram when it is convenient to do so. This need not be done when the function is self-evident, as for a solenoid valve in a fluid signal line.

15. Use of modifying terms *high*, *low*, and *middle or intermediate* shall correspond to values of the measured variable, not of the signal, unless otherwise noted. For example, a high-level alarm derived from a reverse-acting level transmitter signal shall be an *LAH* even though the alarm is actuated when the signal falls to a low value. The terms may be used in combinations as appropriate.

16. The terms *high* and *low*, when applied to positions of valves and other open-close devices, are defined as follows: *high* denotes that the valve is in or approaching the fully open position, and *low* denotes in or approaching the fully closed position.

Note: Words italicized correspond to entries in Table C-2.

8/17/2001
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Department of Chemical Engineering
Michigan Tech University

Piping Schedule
for
Fundamentals of CM Laboratory Apparatus

Line Number	Size	Pipe Spec.	From	To	Insulation	Product	Flowrate	Specific Gravity	Temp., deg. F
C001	1/2"	D	E-01	drain	1 1/2"Fiberglas	condensate	220 #/hr.	1	212
C002	1/2"	H	T-01	drain	none	City Water	3.5 GPM	1	120
C003	1/2"	H	T-02	drain	none	City Water	3.5 GPM	1	55
S001	1"	D	Utility Header	Room 103	1 1/2"Fiberglas	Steam	220 #/hr.	0.107#/cu.ft.	275
S002	1/2"	D	S001	S003/S004	1 1/2"Fiberglas	Steam	28 #/hr.	0.107#/cu.ft.	275
S003	1/2"	D	S002	E-01	1 1/2"Fiberglas	Steam	28 #/hr.	0.107#/cu.ft.	275
S004	1/2"	D	S002	drain	1 1/2"Fiberglas	Steam	28 #/hr.	0.107#/cu.ft.	275
W001	3/4"	H	Utility header	Room 103	none	City Water	25 GPM	1	55
W002	1/2"	H	W001	W013	none	City Water	3 GPM	1	55
W003	1/2"	H	W002	T-02	none	City Water	5 GPM	1	55
W004	1/2"	H	W002	W006	none	City Water	3.5 GPM	1	55
W005	1/2"	H	E-01	W006	none	City Water	3.5 GPM	1	120
W006	1/2"	H	E-01	W007/W008	none	City Water	3.5 GPM	1	120
W007	1/2"	H	W006	T-01	none	City Water	3.5 GPM	1	120
W008	1/2"	H	W006	T-02	none	City Water	3.5 GPM	1	55
W009	1"	H	T-02	P-01	none	City Water	3.3 GPM	1	55
W010	1/2"	H	P-01	W011	none	City Water	3.3 GPM	1	55
W011	1/2"	H	W010	W002	none	City Water	3.3 GPM	1	55
W012	3/8"	H	W010	W002	none	City Water	2.5 GPM	1	55
W013	1/4"	H	W010	W002	none	City Water	1.9 GPM	1	55

Key to Line Numbering	
C###	Condensate Line
S###	Steam Line
W###	Water Line

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Michigan Tech University

Valve Schedule for Fundamentals of CM Laboratory Apparatus

Valve Number	Size	Type	Brand	Body/Wetted Parts Material	Location or Line Number
AV-1	1/2" sweat	bv (ball valve)	Milwaukee	brass/316 SS	inst. air line
DV-1	1" NPT	bv	Hayward	PVC/PVC	C002
DV-2	1" NPT	bv	Hayward	PVC/PVC	C003
SV-1	1/2" NPT	bv	Apollo	brass/316 SS	S002
SV-2	1/2" NPT	globe	Milwaukee	brass/brass	S004
SV-3	1/2" NPT	3-way, bv	Kitz	brass/316 SS	C001
USV-1	1 1/2" NPT	bv	Apollo	brass/316 SS	steam header
UWV-1	1 1/4" sweat	bv	Apollo	brass/316 SS	cold water header
WV-1	1/2" sweat	full port bv	Milwaukee	brass/316 SS	W011
WV-2	1/2" sweat	full port bv	Milwaukee	brass/316 SS	W012
WV-3	1/4" NPT	full port bv	Milwaukee	brass/316 SS	W013
WV-4	3/4" NPT	3-way, bv	Kitz	brass/316 SS	W002
WV-5	1/2" NPT	needle valve	Swagelok	brass/316 SS	W004 bypass
WV-6	1/2" sweat	full port bv	Milwaukee	brass/316 SS	W004
WV-7	1/2" sweat	full port bv	Milwaukee	brass/316 SS	W004
WV-8	3/4" NPT	3-way, bv	Kitz	brass/316 SS	W006
WV-9	3/4" NPT	3-way, bv	Kitz	brass/316 SS	W007/W008
WV-10	1/2" sweat	full port bv	Milwaukee	brass/316 SS	W003
WV-11	1/2" sweat	full port bv	Milwaukee	brass/316 SS	W002

Key to Valve Numbering	
AV-##	Air Valve
DV-##	Drain Valve
SV-##	Steam Valve
USV-#	Utility Steam Valve
UWV-#	Utility Water Valve
WV-##	Water Valve

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Instrument Schedule for Fundamentals of CM Laboratory Apparatus

Loop Number	Element	Location of Device	Comments	Product	Flowrate	Specific Gravity	Temp., deg. F
01	FI-01	W004	Rotometer, dP=13"wc, 3/4"FNPT inlet and outlet	City Water	5.12 GPM	1	55
02	FE-02	W004	orifice assembly, 0.3 to 5.0 gpm, dP=100 inWC@5.0 gpm	City Water	5 GPM	1	55
03	FV-03	W004	Research Control Valve, 1/2" ato, 316SS, c-trim, linear	City Water	5 GPM	1	55
04	TW-04	W006	1/4" Thermocouple protection tube	City Water	---	1	55
05	TW-05	W005	1/4" Thermocouple protection tube	City Water	---	1	120
06	FV-06	S003	Research Control Valve, 1/2" ato, 316SS, d-trim, = %	Steam	28 lb/hr	0.107#/cu.ft.	275
07	TW-07	E-01	1/4" Thermocouple protection tube	Steam	---	0.107#/cu.ft.	275
08	PG-08	E-01	4" dial, 1/2" NPT stem, vac-0-30 psi, 316SS, silicone filled pressure gage	City Water	---	1	55
09	WI-09	on lower bench	0-50 Kg bench scale, +-2g, w/RS-232	City Water	5 GPM	1	55
10	LV-10	T-02	float valve	City Water	3.3 GPM	1	55
100	PRV-100	Lab Cold Water Header	Pressure reducing valve	City Water	25 GPM	1	55

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Equipment Schedule for Fundamentals of CM Laboratory Apparatus

Tag	Location of Device	Comments	Product	Flowrate	Specific Gravity	Temp., deg. F
E-01	Above branched piping circuit	Double-pipe Heat Exchanger, Shell-2"Sched. 40 C.S. pipe, Tube-3/8" o.d. type L copper tubing, 48" long.	City Water/ Steam	5.12 GPM	1	55
P-01	Below bench	3 gpm@71 ft. head, 1 1/4"x1", 120/240 VAC, 1ph., 1/2 hp open drip-proof motor	City Water	5 GPM	1	55
T-01	Below W007 outlet	Tank, 10 gallon, heavy wall PE, 18 3/4"h x 13" o.d.	City Water	5 GPM	1	55
T-02	Below W008 outlet	Tank, 10 gallon, heavy wall PE, 18 3/4"h x 13" o.d.	City Water	5 GPM	1	55

Key to Miscellaneous Identifiers	
PT-##	Pressure Tap
T#	Steam Trap

Transport Laboratory

CM3215
Lecture 4
Measurement of Viscosity

Nam K. Kim
Chemical Engineering
Michigan Technological University

Viscosity

- Defining Equation for dynamic or absolute viscosity

$$\tau_{yx} = -\mu \frac{dv_x}{dy}$$

τ_{yx}: shear stress between fluid layers in laminar flow, N/m2
μ: dynamic viscosity, Ns/m2
dv_x/dy: velocity gradient

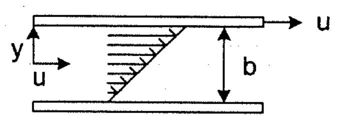
- The kinematic viscosity is defined by

$$\nu = \frac{\mu}{\rho}$$

ν: kinematic viscosity, Nsm/kg
ρ: fluid density, kg/m³

Two most common methods

- The rotating concentric cylinder method
- The capillary flow method
- Others: Perry's 4th Ed. 22-39.



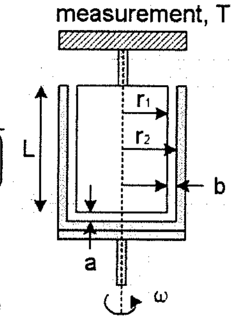
Measure the viscosity by measuring the force required to maintain the moving plate at constant velocity, u

The rotating concentric cylinder method

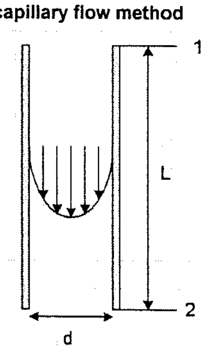
Torque measurement, T

$$\mu = \frac{T}{\pi \omega r_1^2 \left(\frac{2 L r_2}{b} + \frac{r_1^2}{2a} \right)}$$

- T: torque
- w: angular velocity
- L: length
- a, b: annular space



The capillary flow method



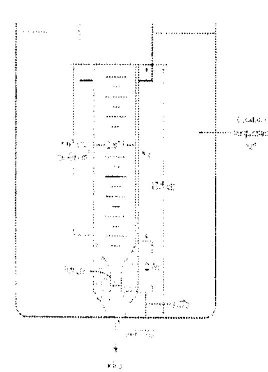
1. *Most common method.*

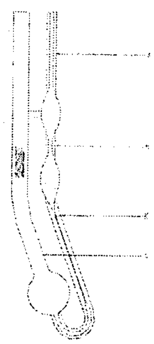
Measure of pressure drop in laminar flow through a capillary flow.

- Saybolt viscometer
- Cannon-Fenske viscometer

Saybolt viscometer

Time required for 60 ml to drain: an indicative of the viscosity of the sample





- **Cannon-Fenske viscometer**
  - Transparent liquids
  - Standard Test ASTM D 445 IP 71 and ISO 3104
- Viscometer No. 50 Y509
  - **Constant at 40 C 0.003821** mm^2/s^2, (cSt/s)
  - Constant at 100 C 0.003803 mm^2/s^2, (cSt/s)

- Viscosity of Sucrose Solutions
  - Perry Chem Eng Handbook (6th Ed. p. 3-254)

TABLE 3-315 Viscosity of Sucrose Solutions*

Viscosity in centipoises

Temp., °C.	Percentage sucrose by weight			Temp., °C.	Percentage sucrose by weight		
	20	40	60		20	40	60
0	3.818	14.52		50	0.974	2.506	14.06
5	3.166	11.60		55	0.887	2.227	11.71
10	2.662	9.830	113.9	60	0.811	1.950	9.87
15	2.275	7.496	74.9	65	0.745	1.785	8.37
20	1.967	6.223	56.7	70	0.688	1.614	7.18
25	1.710	5.206	44.02	75	0.637	1.467	6.22
30	1.510	4.398	34.01	80	0.592	1.339	5.42
35	1.336	3.776	26.62	85	0.552	1.226	4.75
40	1.197	3.261	21.30	90	.....	1.127	4.17
45	1.074	2.858	17.24	95	.....	1.041	3.73

*"International Critical Tables," vol. 5, p. 23. Bingham and Jackson, *Bur. Standards Bull.* 14, p. 59, 1919.

Example: Viscosity measurement

- 30 wt% sucrose solution
- at 40 C it took 7 minutes 26 seconds (= **446 s**)
- ν = 0.003821cSt/s (446 s) = 1.704 cSt
  - It comes from the individual viscometer as a "Birth certificate"
  - ν: kinematic viscosity in centi-Stoke [m^2/s]
- μ = νρ = 1.704 (1.12) = 1.91 cP [kg/ms]
  - μ: absolute viscosity in cP [kg/ms]
- ρ = to be measured [kg/m^3]

Units

- **Dynamic viscosity, μ**
  1 Ns/m^2 = 1kg/ms
  = 10 P = 1000 cP
  1 P = 100 cP
  = 0.1kg/ms
- **Kinematic viscosity, ν**
  1 m^2/s = 10^4 St
  1 St = 1 cm^2/s
  = 100 cSt = 10^{-4} m^2/s

- One use of the **Hagen-Poiseuille** equation is in determining the viscosity of a liquid by measuring the pressure drop and the velocity of the liquid in a capillary of known dimensions.

$$\mu = \frac{\pi(P_0 - P_L)R^4}{8QL}$$

Example: the capillary flow method

The liquid used has a density of 912 kg/m^3 and the capillary has a diameter of 2.222 mm and a length of 0.1585 m. The measured flow rate was 5.33E-7 m^3/s of liquid and the ***pressure drop*** 131 mm of water (density 996 kg/m^3). Neglecting end effects, calculate the viscosity of the liquid in Pa.s.

Given

$$Q = 5.33\times10^{-7}(m^3/s)$$

$$L = 0.1585(m)$$

$$R = \frac{2.222}{2}(mm)$$

$$= 1.111\times10^{-3}(m)$$

$$\mu = \frac{\pi(P_0 - P_L)R^4}{8QL}$$

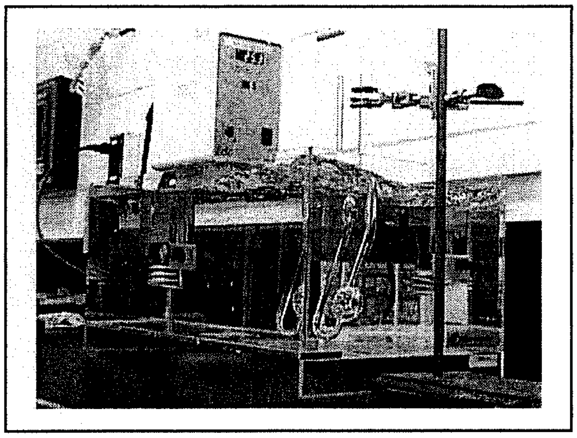
$$P_0 - P_L = 131(mm)10^{-3}(m/mm)996(\frac{kg}{m^3})9.807(\frac{m}{s^2})$$

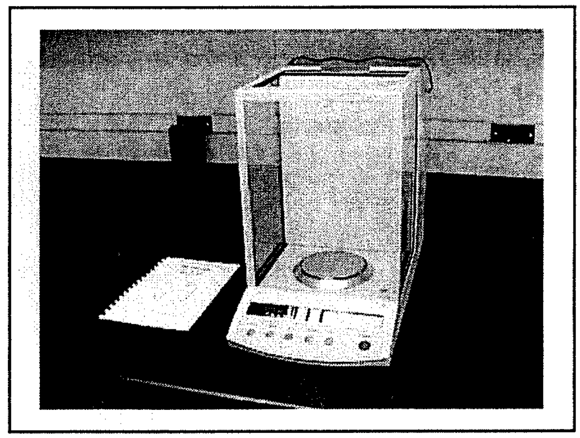
$$= 1279(\frac{kgm}{s^2})(\frac{1}{m^2}) = 1279(\frac{N}{m^2})$$

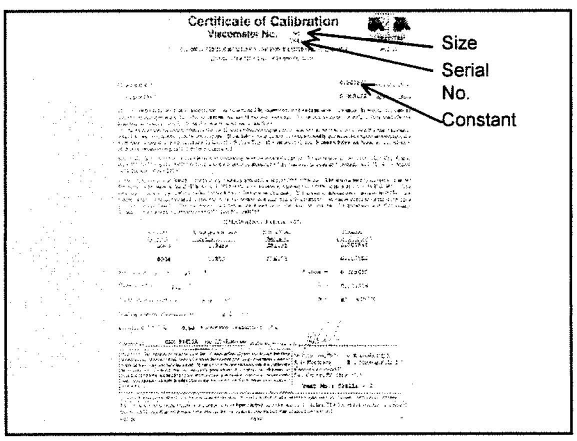
$$\mu = \frac{\pi(1279\frac{kgm}{s^2}\frac{1}{m^2})(1.111\times10^{-3}m)^4}{8(5.33\times10^{-7}\frac{m^3}{s})(0.1585m)}$$

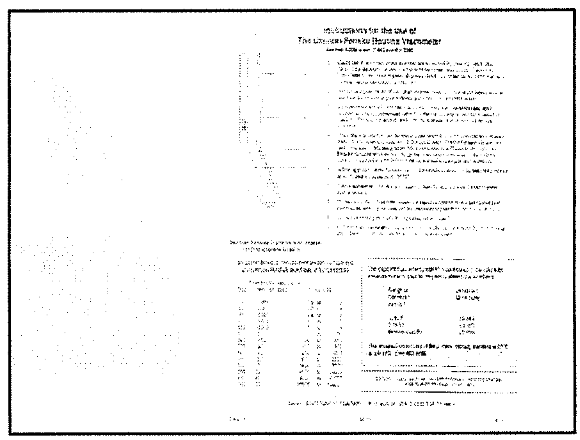
$$\mu = 9.058\times10^{-3}(\frac{kg}{ms})$$

$$[\frac{kg}{m^2}\frac{m}{s}\frac{s}{s}] = \frac{N}{m^2}s = Pa\cdot s$$



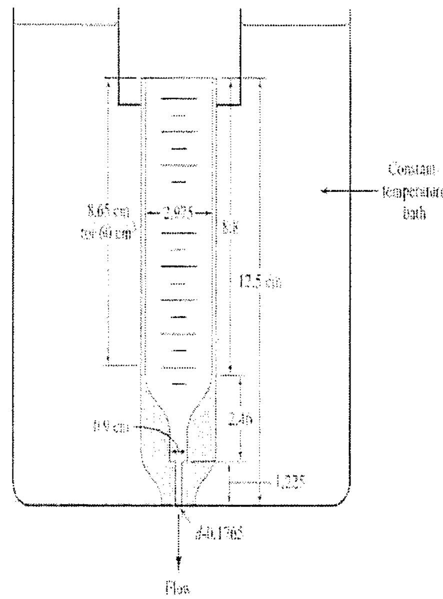



Certificate of Calibration
Size
Serial No.
Constant



- Saybolt viscometer
- Cannon-Fenske viscometer

- Saybolt viscometer
  Time required for 60 ml to drain: an indicative of the viscosity of the sample



- Viscosity of Sucrose Solutions
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TABLE 3-315 Viscosity of Sucrose Solutions*

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*"International Critical Tables," vol. 5, p. 23. Bingham and Jackson, *Bur. Standards Bull.* 14, p. 59, 1919.

Certificate of Calibration

Viscometer No. 50 Y541

Size

Serial No.

Constant

CANNON-FENSKE ROUTINE TYPE FOR TRANSPARENT LIQUIDS 1262.01

(Standard Test ASTM D 445, IP 71 and ISO 3104)

Constant at 40°C 0.003650 mm^2/s^2, (cSt/s)

Constant at 100°C 0.003632 mm^2/s^2, (cSt/s)

The viscometer constant at other temperatures can be obtained by interpolation or extrapolation. To obtain kinematic viscosity in mm^2/s(cSt) multiply the efflux time in seconds by the viscometer constant. To obtain viscosity in mPa·s (cP) multiply the kinematic viscosity in mm^2/s(cSt) by the density in grams per milliliter.
The above constants assume a value for the coefficient of thermal expansion typical to that for mineral oil, and that the viscometer was filled with test sample at room temperature. If the filling temperature T_F is substantially different than room temperature, the viscometer constant at test temperature T_T is $C_o (1 - B [T_T - T_F])$. The values of C_o and B shown below are based on a coefficient of thermal expansion typical to that for a mineral oil.

Kinematic viscosities of the standards used in calibrating were established in Master Viscometers as described in Ind. Eng. Chem. Anal. Ed. 16,708(1944), ASTM D 2162, and the Journal of Research of the National Bureau of Standards, Vol. 52, No. 3, March 1954, Research Paper 2479.

Kinematic viscosities are based on the primary viscosity standard, water, at 20°C (ITS-90). The internationally accepted value for the viscosity of water at 20°C (ITS-90) is 1.0016 mPa·s or kinematic viscosity is 1.0034 mm^2/s as listed in ISO 3666. The gravitational constant, g, is 980.1 cm/sec^2 at the Cannon Instrument Company. The gravitational constant varies up to 0.1% in the United States. To make this small correction in the viscometer constant, multiply the above viscometer constant by the factor [g(at your laboratory) /980.1]. The calibration data below are traceable to the National Institute for Standards and Technology. Temperature measurement traceable to NIST (Test No. 260470).

CALIBRATION DATA AT 40°C

Viscosity Standard	Kinematic Viscosity mm^2/s, (cSt)	Efflux Time Seconds	Constant mm^2/s^2, (cSt/s)
0003	1.0262	281.31	0.003648
0004	2.250	616.05	0.003652

Room Temp (approx.) 23 °C. Average = 0.003650

Charge (approx.) 7.2 ml. C_o = 0.003655

Driving fluid head (approx.) 9.0 cm. B = 83 x 10^{-6}/°C

Working diameter of lower reservoir 3.0 cm.

Constant at 100° C. is 0.50 % lower than the constant at 40° C.

Calibrated by SAB 538118 on 17-Aug-00 under supervision of [signature]

Please note: This calibration remains valid for 10 years unless (1) the viscometer has been damaged or (2) materials which chemically attack borosilicate glass (e.g., hydrofluoric acid or highly alkaline solutions) have been used. Nonetheless, it is recommended that the calibration be verified with kinematic viscosity standards periodically; if a change in calibration is indicated, carefully examine all sources of error, including especially temperature measurement since most apparent changes in calibration of the viscometer are due to errors in temperature measurement.

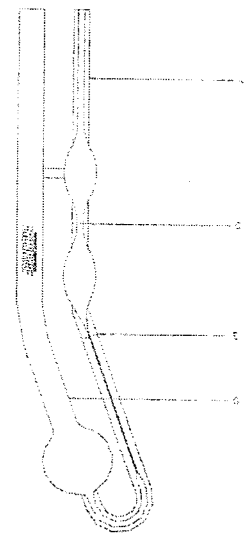
M. R. Hoover, Ph.D. M. K. Gerfin, C.Q.E.
K. O. Henderson R. E. Manning, Ph.D., P.E.
Cannon Instrument Co.
State College, PA 16804, USA

Test No.: 538118 - 2

The S.I. unit of kinematic viscosity is 1 meter squared per second, and is equal to 10^4 stokes. The S.I. unit of viscosity is 1 pascal second, and is equal to 10 poises. One centistokes is equal to one millimeter squared per second.

Instructions for the use of The Cannon-Fenske Routine Viscometer

See also ASTM D 445, D 446 and ISO 3105



1. Clean the viscometer using suitable solvents, and by passing clean, dry, filtered air through the instrument to remove the final traces of solvents. Periodically, traces of organic deposits should be removed with chromic acid or non-chromium cleaning solution.
2. If there is a possibility of lint, dust, or other solid material in the liquid sample, filter the sample through a sintered glass filter or fine mesh screen.
3. To charge the sample into the viscometer, invert the instrument and apply suction to tube G, immersing tube A in the liquid sample, and draw liquid to mark E. Wipe clean arm A, and turn the instrument to its normal vertical position.
4. Place the viscometer into the holder, and insert it into the constant temperature bath. A viscometer holder which fits the Cannon-Fenske Opaque viscometer and the Cannon-Manning Semi-Micro viscometer will also fit the Cannon-Fenske Routine viscometer. Align the viscometer vertically in the bath by means of a small plumb bob in tube G, if a self-aligning holder is not used.
5. Allow approximately 10 minutes for the sample to come to the bath temperature at 40°C and 15 minutes at 100°C.
6. Apply suction to tube A (or pressure to tube G) and draw the liquid slightly above mark C.
7. To measure the efflux time, allow the liquid sample to flow freely down past mark C, measuring the time for the meniscus to pass from mark C to mark E.
8. A check run may be made by repeating steps 6 and 7.
9. Calculate the kinematic viscosity in mm^2/s(cSt) of the sample by multiplying the efflux time in seconds by the viscometer constant.

Cannon-Fenske Routine Viscometer for Transparent Liquids

RECOMMENDED VISCOSITY RANGES FOR THE CANNON-FENSKE ROUTINE VISCOMETERS

Size	Kinematic Viscosity Range mm^2/s^2, (cSt/s)	mm^2/s, (cSt)
25	0.002	0.5 to 2
50	0.004	0.8 to 4
75	0.008	1.6 to 8
100	0.015	3 to 15
150	0.035	7 to 35
200	0.1	20 to 100
300	0.25	50 to 250
350	0.5	100 to 500
400	1.2	240 to 1200
450	2.5	500 to 2500
500	8	1600 to 8000
600	20	4000 to 20000
650	45	9000 to 45000
700	100	20000 to 100000

The expanded uncertainty with 95% confidence of the calibration measurements relative to the primary standard is as follows:

Range of Constants mm^2/s^2	Expanded Uncertainty
up to 5	±0.34%
5 to 50	±0.45%
Greater than 50	±0.69%

The assigned uncertainty of the primary viscosity standard at 20°C is ±0.17%. See ISO 3666.

THIS PRODUCT WAS CALIBRATED WITHIN A QUALITY SYSTEM WHICH IS REGISTERED TO ISO 9002.

CANNON INSTRUMENT COMPANY P. O. BOX 16 STATE COLLEGE, PA 16804

Experiment 4. Viscosity measurement

Pre-laboratory Assignment

Read the MSDS Sheets on sucrose (and glycerol, if used). Be prepared to take a quiz on the hazards and handling of these chemicals.

Introduction

Viscosity is one of the primary fluid properties, which is used in the design and analysis of chemical processing equipment. Viscosity is also dependent on fluid composition and temperature, and both variables must be taken into account when performing design calculations. In order to understand the relationships between fluid viscosity, temperature, and composition, viscosity measurements will be made of a series of sucrose (and/or glycerol) solutions of different concentration. Additionally, each group will examine the viscosity at an elevated temperature for a selected concentration.

Theory: Lecture notes.

Experimental Procedure

[ ] Sucrose [ ] Glycerol [ ] __________

1. Receive a Canon-Fenske viscometer from the GTA and inspect it for cleanliness.
2. Make up 100 grams of a x wt % solution:

Group	x wt %	Remark
Gr 1	60	200*
Gr 2	40	100
Gr 3	20	50
Gr 4	50	200
Gr 5	30	100
Gr 6	10	50
Gr 7	65	200
Gr 8	45	100
All	0	50

*There are 3 different sizes of viscometers available in the lab: 200 for viscous fluids and 50 for less viscous fluids. Each of these viscometers has its own birth certificate with unique viscometer constant. Identify your viscometer with a serial number imprinted on the gauge and its certificate. Ask instructor for this.

3. Determine the viscosity of this solution using the instructions for the viscometer attached. Be sure to do enough trials to get a statistically significant data set.
4. Your GTA will assist you with preparation of constant temperature water-bath and different composition of your solutions. Using the water baths in the laboratory, measure the viscosity of your solution at the given temperature (for example, 40 C and/or 60 C). Write your viscosity values along with the Group number and the water-bath temperature on the whiteboard so that it will be available for other groups to use. An example of data collection and computation is shown in Figure 1.
5. Dispose the solution properly. Ask instructor for details.
6. Clean the viscometer thoroughly using an appropriate solution. Carefully dry the viscometer with filtered compressed air. You must return the clean viscometer to GTA for inspection. This must be done without exception.

Data analysis

(1) Means and standard deviations for each concentration

(2) Data published in the literatures or handbooks

(3) Generate a plot of viscosity versus solution concentration

(4) Regression lines with R^2 values

(5) Solution density

Report

In your report, discuss the effects of concentration (type of compound: sucrose versus glycerol, if used), temperature on viscosity, and density on viscosity. For more details refer to a typical grade sheet that may be used by the instructor. Your lab report is due at the beginning of your next lab session.

Table 1. An example of data collection

Target		Values obtained at C			Published	Error
Conc		MTU data			Viscosity	
%	Trials	Kine. Visc	Density	cP	cP	%
0	1					
	2					
	3					
10	1					
	2					
	3					
20	1					
	2					
	3					

Fisher Scientific

Back to Sucrose (Crystalline/NF)

Material Safety Data Sheet
D(+)-Sucrose

ACC# 22174

Section 1 - Chemical Product and Company Identification

MSDS Name: D(+)-Sucrose
Catalog Numbers: S71203, S71204, BP220 1, BP220 10, BP220 212, BP220-1, BP220-10, BP220-212, BP2201, BP22010, BP220212, NC9486117, S3, S3-12, S3-212, S3-500, S312, S3212, S5 3, S5 500, S5-3, S5-500, S53, S5500
Synonyms: Beet sugar, cane sugar, maple sugar, saccharose, sugar
Company Identification:
Fisher Scientific
1 Reagent Lane
Fairlawn, NJ 07410
For information, call: 201-796-7100
Emergency Number: 201-796-7100
For CHEMTREC assistance, call: 800-424-9300
For International CHEMTREC assistance, call: 703-527-3887

Section 2 - Composition, Information on Ingredients

CAS#	Chemical Name	Percent	EINECS/ELINCS
57-50-1	Sucrose	100	200-334-9

Section 3 - Hazards Identification

EMERGENCY OVERVIEW

Appearance: white. **Caution!** May cause eye and skin irritation. Maycause respiratory and digestive tract irritation.
Target Organs: None.

Potential Health Effects

Eye: Dust may cause mechanical irritation.
Skin: Low hazard for usual industrial handling.
Ingestion: Ingestion of large amounts may cause gastrointestinal irritation.
Inhalation: Excessive inhalation may cause minor respiratory irritation.
Chronic: No information found.

Section 4 - First Aid Measures

Eyes: Flush eyes with plenty of water for at least 15 minutes, occasionally lifting the upper and lower lids. Get medical aid.
Skin: Get medical aid if irritation develops or persists.
Ingestion: Get medical aid if irritation or symptoms occur.
Inhalation: Remove from exposure to fresh air immediately. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. Get medical aid if cough or other symptoms appear.
Notes to Physician: Treat symptomatically and supportively.
Antidote: None reported.

Section 5 - Firefighting Measures

General Information: Wear appropriate protective clothing to prevent contact with skin and eyes. Wear a self-contained breathing apparatus (SCBA) to prevent contact with thermal decomposition products.
Extinguishing Media: For small fires, use dry chemical, carbon dioxide, water spray or alcohol-resistant foam.
Autoignition Temperature: Not available.
Flash Point: Not available.
NFPA Rating: Not published. Explosion Limits, Lower: Not available. Upper: Not available.

Section 6 - Accidental Release Measures

General Information: Use proper personal protective equipment as indicated in Section 8.
Spills/Leaks: Vacuum or sweep up material and place into a suitable disposal container.

Section 7 - Handling and Storage

Handling: Use with adequate ventilation. Minimize dust generation and accumulation.
Storage: Store in a cool, dry, well-ventilated area away from incompatible substances.

Section 8 - Exposure Controls, Personal Protection

Engineering Controls: Use adequate ventilation to keep airborne concentrations low.
Exposure Limits

Chemical Name	ACGIH	NIOSH	OSHA - Final PELs
Sucrose	10 mg/m3	total: 10 mg/m3 TWA; respirable dust: 5 mg/m3 TWA	total dust: 15 mg/m3 TWA; respirable fraction: 5 mg/m3 TWA

OSHA Vacated PELs: Sucrose: total dust: 15 mg/m3 TWA; respirable fraction: 5 mg/m3 TWA

Personal Protective Equipment
Eyes: Wear appropriate protective eyeglasses or chemical safety goggles as described by

OSHA's eye and face protection regulations in 29 CFR 1910.133 or European Standard EN166.
Skin: Wear appropriate gloves to prevent skin exposure.
Clothing: Wear appropriate protective clothing to minimize contact with skin.
Respirators: Follow the OSHA respirator regulations found in 29CFR 1910.134 or European Standard EN 149. Always use a NIOSH or European Standard EN 149 approved respirator when necessary.

Section 9 - Physical and Chemical Properties

Physical State: Solid
Appearance: white
Odor: odorless
pH: Not available.
Vapor Pressure: Not available.
Vapor Density: Not available.
Evaporation Rate:
Viscosity: Not available.
Boiling Point: Not available.
Freezing/Melting Point:190.00 - 192.00 deg C
Decomposition Temperature: Not available.
Solubility: 1970 G/L WATER (150C)
Specific Gravity/Density: Not available.
Molecular Formula:C12H22O11
Molecular Weight:

Section 10 - Stability and Reactivity

Chemical Stability: Stable.
Conditions to Avoid: Incompatible materials, excess heat.
Incompatibilities with Other Materials: Strong oxidizers.
Hazardous Decomposition Products: Carbon monoxide, carbon dioxide.
Hazardous Polymerization: Has not been reported.

Section 11 - Toxicological Information

RTECS#:
CAS# 57-50-1: WN6500000
LD50/LC50:
CAS# 57-50-1:
Oral, rat: LD50 = 29700 mg/kg;
Carcinogenicity:
CAS# 57-50-1:
ACGIH: A4 - Not Classifiable as a Human Carcinogen
Epidemiology: No data available.
Teratogenicity: No data available.
Reproductive Effects: No data available.
Neurotoxicity: No data available.

Mutagenicity: No data available.
Other Studies: No data available.

Section 12 - Ecological Information

Ecotoxicity: Not available.
Environmental Fate: Not available.
Physical/Chemical: Not available.
Other: Not available.

Section 13 - Disposal Considerations

Dispose of in a manner consistent with federal, state, and local regulations.
RCRA D-Series Maximum Concentration ofContaminants: None listed.
RCRA D-Series Chronic Toxicity ReferenceLevels: None listed.
RCRA F-Series: None listed.
RCRA P-Series: None listed.
RCRA U-Series: None listed.

Section 14 - Transport Information

	US DOT	IATA	RID/ADR	IMO	Canada TDG
Shipping Name:	No information available.	No information available.	No information available.	No information available.	No information available.
Hazard Class:					
UN Number:					
Packing Group:					

Section 15 - Regulatory Information

US FEDERAL

TSCA
CAS# 57-50-1 is listed on the TSCA inventory.
Health & Safety Reporting List
None of the chemicals are on the Health & Safety Reporting List.
Chemical Test Rules
None of the chemicals in this product are under a Chemical Test Rule.
Section 12b
None of the chemicals are listed under TSCA Section 12b.
TSCA Significant New Use Rule
None of the chemicals in this material have a SNUR under TSCA.
SARA

Section 302 (RQ)

None of the chemicals in this material have an RQ.

Section 302 (TPQ)

None of the chemicals in this product have a TPQ.

SARA Codes

CAS # 57-50-1: acute, flammable.

Section 313

No chemicals are reportable under Section 313.

Clean Air Act:

This material does not contain any hazardous air pollutants. This material does not contain any Class 1 Ozone depletors. This material does not contain any Class 2 Ozone depletors.

Clean Water Act:

None of the chemicals in this product are listed as Hazardous Substances under the CWA. None of the chemicals in this product are listed as Priority Pollutants under the CWA. None of the chemicals in this product are listed as Toxic Pollutants under the CWA.

OSHA:

None of the chemicals in this product are considered highly hazardous by OSHA.

STATE

CAS# 57-50-1 can be found on the following state right to know lists: Pennsylvania, Minnesota, Massachusetts.

California No Significant Risk Level: None of the chemicals in this product are listed.

European/International Regulations

European Labeling in Accordance with EC Directives

Hazard Symbols:

Not available.

Risk Phrases:

Safety Phrases:

WGK (Water Danger/Protection)

CAS# 57-50-1: 0

Canada

CAS# 57-50-1 is listed on Canada's DSL/NDSL List.

This product has a WHMIS classification of Not controlled..

CAS# 57-50-1 is not listed on Canada's Ingredient Disclosure List.

Exposure Limits

CAS# 57-50-1: OEL-AUSTRALIA:TWA 10 mg/m3 OEL-BELGIUM:TWA 10 mg/m3 OEL-FRANCE:TWA 10 mg/m3 OEL-UNITED KINGDOM:TWA 10 mg/m3 OEL IN BULGA RIA, COLOMBIA, JORDAN, KOREA check ACGIH TLV OEL IN NEW ZEALAND, SING APORE, VIETNAM check ACGI TLV

Section 16 - Additional Information

MSDS Creation Date: 1/09/1995

Revision #8 Date: 12/12/1997

The information above is believed to be accurate and represents the best information currently available to us. However, we make no warranty of merchantability or any other warranty, express or implied, with respect to such information, and we assume no liability resulting from its use. Users should make their own investigations to determine the suitability of the information for their particular purposes. In no way shall Fisher be liable for any claims, losses, or damages of any third party or for lost profits or any special, indirect, incidental, consequential or exemplary damages, howsoever arising, even if Fisher has been advised of the possibility of such damages.

Please reduce your browser font size for better viewing and printing.

MSDS *Material Safety Data Sheet*

From: Mallinckrodt Baker, Inc.
222 Red School Lane
Phillipsburg, NJ 08865

MALLINCKRODT J.T.Baker

24 Hour Emergency Telephone: 908-859-2151
CHEMTREC: 1-800-424-9300

National Response in Canada
CANUTEC: 613-996-6666

Outside U.S. and Canada
Chemtrec: 202-483-7616

NOTE: CHEMTREC, CANUTEC and National Response Center emergency numbers to be used only in the event of chemical emergencies involving a spill, leak, fire, exposure or accident involving chemicals.

All non-emergency questions should be directed to Customer Service (1-800-582-2537) for assistance.

GLYCEROL

MSDS Number: G4774 --- ***Effective Date: 02/25/99***

1. Product Identification

Synonyms: 1,2,3-propanetriol; glycerin; glycol alcohol; glycerol, anhydrous
CAS No.: 56-81-5
Molecular Weight: 92.09
Chemical Formula: $C_3H_5(OH)_3$
Product Codes:
J.T. Baker: 2135, 2136, 2140, 2142, 2143, 4043, M778
Mallinckrodt: 5092, 5093, 5100

2. Composition/Information on Ingredients

Ingredient	CAS No	Percent	Hazardous
Glycerin	56-81-5	90 - 100%	Yes

3. Hazards Identification

Emergency Overview

CAUTION! MAY CAUSE IRRITATION TO SKIN, EYES, AND RESPIRATORY TRACT. MAY AFFECT KIDNEYS.

J.T. Baker SAF-T-DATA(tm) Ratings (Provided here for your convenience)

Health Rating: 1 - Slight
Flammability Rating: 1 - Slight
Reactivity Rating: 0 - None

Contact Rating: 1 - Slight
Lab Protective Equip: GOGGLES; LAB COAT
Storage Color Code: Orange (General Storage)

Potential Health Effects

Inhalation:
Due to the low vapor pressure, inhalation of the vapors at room temperatures is unlikely. Inhalation of mist may cause irritation of respiratory tract.
Ingestion:
Low toxicity. May cause nausea, headache, diarrhea.
Skin Contact:
May cause irritation.
Eye Contact:
May cause irritation.
Chronic Exposure:
May cause kidney injury.
Aggravation of Pre-existing Conditions:
Persons with pre-existing skin disorders or eye problems or impaired liver or kidney function may be more susceptible to the effects of the substance.

4. First Aid Measures

Inhalation:
Remove to fresh air. Get medical attention for any breathing difficulty.
Ingestion:
Induce vomiting immediately as directed by medical personnel. Never give anything by mouth to an unconscious person. Get medical attention.
Skin Contact:
Immediately flush skin with plenty of water for at least 15 minutes. Remove contaminated clothing and shoes. Wash clothing before reuse. Thoroughly clean shoes before reuse. Get medical attention if irritation develops.
Eye Contact:
Immediately flush eyes with plenty of water for at least 15 minutes, lifting upper and lower eyelids occasionally. Get medical attention if irritation persists.

5. Fire Fighting Measures

Fire:
Flash point: 199C (390F) CC
Autoignition temperature: 370C (698F)
Slight fire hazard when exposed to heat or flame.
Explosion:
Above flash point, vapor-air mixtures are explosive within flammable limits noted above.
Fire Extinguishing Media:
Use any means suitable for extinguishing surrounding fire. Water spray may be used to extinguish surrounding fire and cool exposed containers. Water spray will also reduce fume and irritant gases.
Special Information:
In the event of a fire, wear full protective clothing and NIOSH-approved self-contained

breathing apparatus with full facepiece operated in the pressure demand or other positive pressure mode.

---

6. Accidental Release Measures

Ventilate area of leak or spill. Wear appropriate personal protective equipment as specified in Section 8. Contain and recover liquid when possible. Collect liquid in an appropriate container or absorb with an inert material (e. g., vermiculite, dry sand, earth), and place in a chemical waste container. Do not use combustible materials, such as saw dust. Do not flush to sewer!

---

7. Handling and Storage

Keep in a tightly closed container, stored in a cool, dry, ventilated area. Protect against physical damage. Isolate from incompatible substances. Containers of this material may be hazardous when empty since they retain product residues (vapors, liquid); observe all warnings and precautions listed for the product.

---

8. Exposure Controls/Personal Protection

Airborne Exposure Limits:
For Glycerin Mist:
- OSHA Permissible Exposure Limit (PEL):
Total Dust: 15 mg/m3 (TWA);
Respirable Fraction: 5 mg/m3(TWA).
- ACGIH Threshold Limit Value (TLV):
10 mg/m3
Ventilation System:
A system of local and/or general exhaust is recommended to keep employee exposures below the Airborne Exposure Limits. Local exhaust ventilation is generally preferred because it can control the emissions of the contaminant at its source, preventing dispersion of it into the general work area. Please refer to the ACGIH document, *Industrial Ventilation, A Manual of Recommended Practices*, most recent edition, for details.
Personal Respirators (NIOSH Approved):
If the exposure limit is exceeded and engineering controls are not feasible, a half facepiece particulate respirator (NIOSH type P95 or R95 filters) may be worn for up to ten times the exposure limit or the maximum use concentration specified by the appropriate regulatory agency or respirator supplier, whichever is lowest.. A full-face piece particulate respirator (NIOSH type P100 or R100 filters) may be worn up to 50 times the exposure limit, or the maximum use concentration specified by the appropriate regulatory agency, or respirator supplier, whichever is lowest. Please note that N filters are not recommended for this material. For emergencies or instances where the exposure levels are not known, use a full-facepiece positive-pressure, air-supplied respirator. WARNING: Air-purifying respirators do not protect workers in oxygen-deficient atmospheres.
Skin Protection:
Wear protective gloves and clean body-covering clothing.
Eye Protection:
Use chemical safety goggles. Maintain eye wash fountain and quick-drench facilities in work area.

9. Physical and Chemical Properties

Appearance:
Clear oily liquid.
Odor:
Odorless.
Solubility:
Miscible in water.
Specific Gravity:
1.26 @ 20C/4C
pH:
(neutral to litmus)
% Volatiles by volume @ 21C (70F):
0
Boiling Point:
290C (554F)
Melting Point:
18C (64F)
Vapor Density (Air=1):
3.17
Vapor Pressure (mm Hg):
0.0025 @ 50C (122F)
Evaporation Rate (BuAc=1):
No information found.

10. Stability and Reactivity

Stability:
Stable under ordinary conditions of use and storage.
Hazardous Decomposition Products:
Toxic gases and vapors may be released if involved in a fire. Glycerin decomposes upon heating above 290C, forming corrosive gas (acrolein).
Hazardous Polymerization:
Will not occur.
Incompatibilities:
Strong oxidizers. Can react violently with acetic anhydride, calcium oxychloride, chromium oxides and alkali metal hydrides.
Conditions to Avoid:
Heat, flames, ignition sources and incompatibles.

11. Toxicological Information

Oral rat LD50: 12,600 mg/kg. Investigated as a mutagen, reproductive effector.

```
--------\Cancer Lists\------------------------------------------------------
                                        ---NTP Carcinogen---
Ingredient                              Known    Anticipated     IARC Category
------------------------------------    -----    -----------     -------------
```

Glycerin (56-81-5)	No	No	None

12. Ecological Information

Environmental Fate:
When released into the soil, this material is expected to readily biodegrade. When released into the soil, this material is not expected to evaporate significantly. When released into water, this material is expected to readily biodegrade. This material is not expected to significantly bioaccumulate. When released into the air, this material may be moderately degraded by reaction with photochemically produced hydroxyl radicals. When released into the air, this material may be removed from the atmosphere to a moderate extent by wet deposition.
Environmental Toxicity:
This material is not expected to be toxic to aquatic life.

13. Disposal Considerations

Whatever cannot be saved for recovery or recycling should be managed in an appropriate and approved waste disposal facility. Processing, use or contamination of this product may change the waste management options. State and local disposal regulations may differ from federal disposal regulations. Dispose of container and unused contents in accordance with federal, state and local requirements.

14. Transport Information

Not regulated.

15. Regulatory Information

--------\Chemical Inventory Status - Part 1\---------------------------------

Ingredient	TSCA	EC	Japan	Australia
Glycerin (56-81-5)	Yes	Yes	Yes	Yes

--------\Chemical Inventory Status - Part 2\---------------------------------

Ingredient	Korea	--Canada-- DSL	--Canada-- NDSL	Phil.
Glycerin (56-81-5)	Yes	Yes	No	Yes

--------\Federal, State & International Regulations - Part 1\----------------

Ingredient	-SARA 302- RQ	-SARA 302- TPQ	------SARA 313------ List	------SARA 313------ Chemical Catg.
Glycerin (56-81-5)	No	No	No	No

--------\Federal, State & International Regulations - Part 2\----------------

Ingredient	CERCLA	-RCRA- 261.33	-TSCA- 8(d)

Glycerin (56-81-5)	No	No	No

Chemical Weapons Convention: No TSCA 12(b): No CDTA: No
SARA 311/312: Acute: Yes Chronic: Yes Fire: No Pressure: No
Reactivity: No (Pure / Liquid)

Australian Hazchem Code: No information found.
Poison Schedule: No information found.
WHMIS:
This MSDS has been prepared according to the hazard criteria of the Controlled Products Regulations (CPR) and the MSDS contains all of the information required by the CPR.

---

16. Other Information

NFPA Ratings: Health: **1** Flammability: **1** Reactivity: **0**
Label Hazard Warning:
CAUTION! MAY CAUSE IRRITATION TO SKIN, EYES, AND RESPIRATORY TRACT. MAY AFFECT KIDNEYS.
Label Precautions:
Avoid breathing mist.
Avoid contact with eyes, skin and clothing.
Keep container closed.
Use with adequate ventilation.
Wash thoroughly after handling.
Label First Aid:
If inhaled, remove to fresh air. Get medical attention for any breathing difficulty. In case of contact, immediately flush eyes or skin with plenty of water for at least 15 minutes. Get medical attention if irritation develops or persists.
Product Use:
Laboratory Reagent.
Revision Information:
MSDS Section(s) changed since last revision of document include: 8.
Disclaimer:
****

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Prepared by: Strategic Services Division
Phone Number: (314) 539-1600 (U.S.A.)

Transport Laboratory

CM3215
Lecture 5
Measurement of Pressure

Nam K. Kim
Chemical Engineering
Michigan Tech University

Pressure

$$P = \frac{F}{A}$$

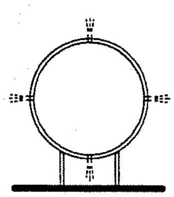
- A woman wearing high heels give higher pressure to floors than she would with flat heels. (Force upon the area)
  Weight = 140 lb; Area of the heel = 0.12 in^2
  Pressure = 1,170 lb/in^2

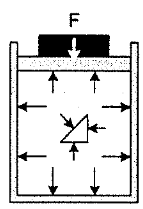
$$P = \frac{F}{A} = \frac{140}{0.12} = 1{,}170$$

- **Fluid pressure**

☒The forces exerted by a fluid on the wall of its container must always act ***perpendicular*** to the wall.

☒Fluids exert pressure in **all** direction



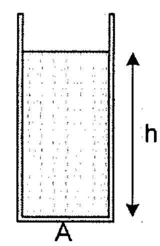


- At any particular depth in a fluid, the pressure is the same in all direction. If this were not true, the fluid would flow under the influence of a resultant pressure until a new condition of equilibrium was reached.

$$W = DV = DAh$$

$$P = \frac{W}{A} = Dh = \rho g h$$

where W = weight of the fluid; D = weight density of the fluid; P = pressure at the depth *h*; ρ = mass density.



☒Example.

The water pressure in a certain home is 100 lb/in^2. How high must the water level in a reservoir be above the point of release in the home?

P=(100 lb/in^2)(144 in^2)/(1 ft^2) = 14,400 lb/ft^2

Solving for ***h***

h = P/D = 14,400 lb/ft^2/62.4 lb/ft^3 = 230 ft

☐Absolute pressure (P_{abs})

= gauge pressure (P_g) + atmospheric pressure (P_{atm})

P_{atm} at sea level

= **14.7** lb/in^2 or **1.01325E5** N/m^2 (=Pascal)

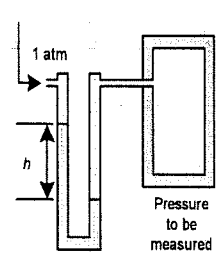
A common device for measuring gauge pressure

- *Open-tube manometer*

☒Example.

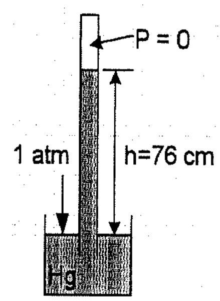
The mercury manometer is used to measure the pressure of a gas inside a tank. The gauge pressure is 36 cm of Hg (=h).

What is the absolute pressure?



- P = Dh= ρgh = (13.6g/cm^3)(980 cm/s^2)((36+76) cm) =1.49E6 dynes/cm^2 = 21.6 lb/in^2 = 1.47 atm

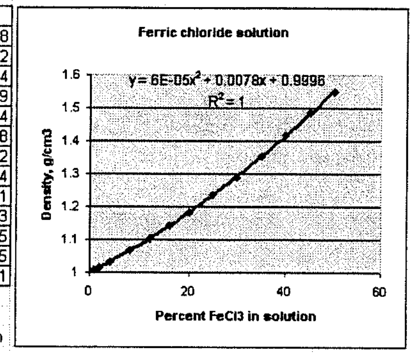
- Measuring the atmospheric pressure



Perry's (4th) Table 3-70 Ferric Chloride Solution (20 C)

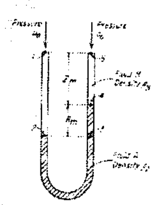
%	g/cm3
1	1.0068
2	1.0152
4	1.0324
8	1.0669
12	1.104
16	1.1418
20	1.182
25	1.234
30	1.291
35	1.353
40	1.4175
45	1.485
50	1.551

% FeCl3 concentration



Measurement of Pressure

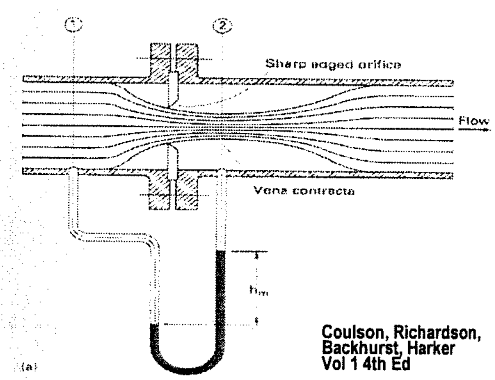
- The manometer operates on the principle of relating **rate of flow** to **pressure drop** across a restriction (orifice) require a pressure measurement.
- A conduit filled with a fluid (a 50 wt% solution of $FeCl_3$, its density ρ=1.55 gm/cm³)
- Bernoulli's equation with no friction loss



$$\Delta\frac{\langle v\rangle^2}{2}+g\Delta z+\frac{\Delta P}{\rho}=0$$

$$\frac{\Delta P}{\rho}+g\Delta z=0$$

$$\Delta P=p_a-p_b=\frac{g}{g_c}R_m(\rho_A-\rho_B)$$
$$=-\rho g(z_4-z_3)$$



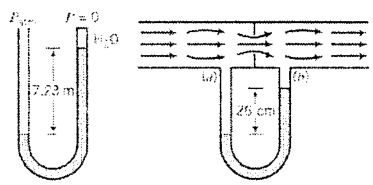
Coulson, Richardson, Backhurst, Harker Vol 1 4th Ed

☒A manometer shown is used to measure the pressure drop across an orifice. Liquid A is *mercury* (ρ = 13,590 kg/m³) and fluid B flowing through the orifice and filling the manometer leads, is *brine* (ρ = 1260 kg/m³). When the pressure at the taps are equal, the level of mercury in the manometer is 0.9 m below the orifice taps. Under operating conditions, the gauge pressure at the upstream tap is 0.14 bar; the pressure at the downstream tap is 250 mm Hg below atmospheric. What is the reading of the manometer in millimeters? (McCabe 1993)

$$\Delta P=p_a-p_b=\frac{g}{g_c}R_m(\rho_A-\rho_B)$$
$$=-\rho g(z_4-z_3)$$

$$g_c=1$$
$$p_a=0.14\times10^5=14{,}000(Pa)$$
$$p_b=z_b\frac{g}{g_c}=\frac{-250}{1000}\frac{9.80665}{1}13{,}590$$
$$=-33{,}318(Pa)$$
$$14{,}000+33{,}318=R_m(9.80665)(13{,}590-1260)$$
$$R_m=0.391(m)=391(mm)$$

⇩ A fluid of unknown density is used in two manometers--one sealed end, the other across the orifice in a water pipeline. The readings shown here are obtained on a day when barometric pressure is 756 mm Hg. What is the pressure drop from point (a) and point (b)? Felder & Rousseau Problems 3.43



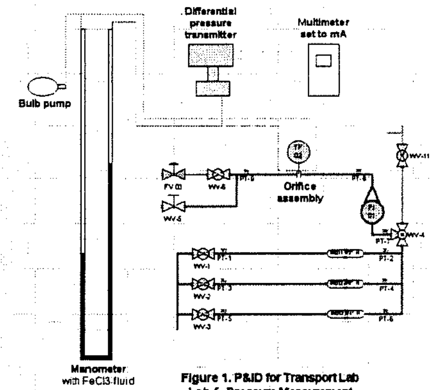
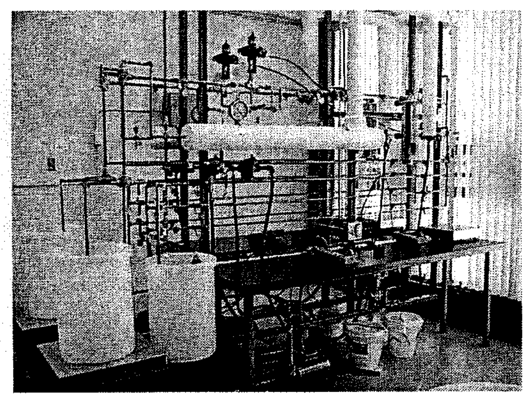
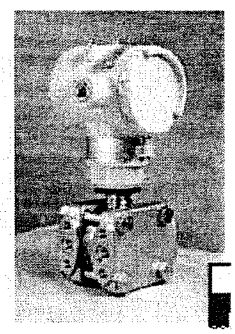
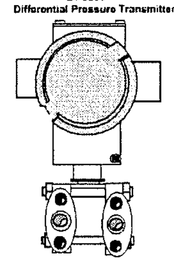


Figure 1. P&ID for Transport Lab Lab 5. Pressure Measurement

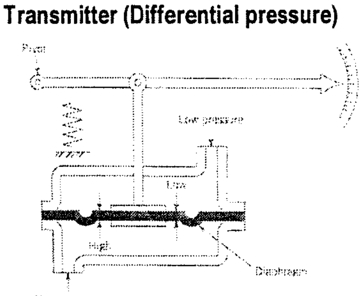


Honeywell ST3000 Differential Pressure Transmitter
Fac Cal: 0 - 100 inH_2O (-40 to 125 C)



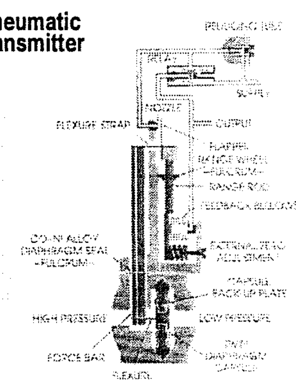


DP Transmitter (Differential pressure)



- Smith and Corripio, *Principles and Practice of Automatic Process Control*, 2nd Ed., Wiley (C-2 Flow sensors)
- Output: **Dial gauge**

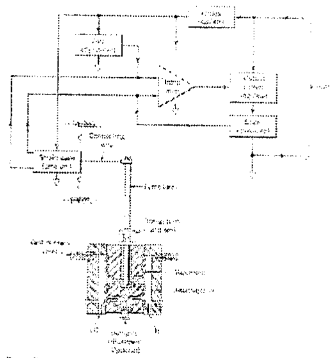
Pneumatic transmitter



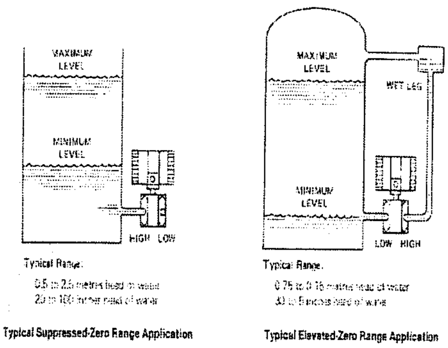
- Smith and Corripio, *Principles and Practice of Automatic Process Control*, 2nd Ed., Wiley (C-6 Transmitters)
- ☐ Output signal: 3 to 15 psig

Electronic DP Transmitter

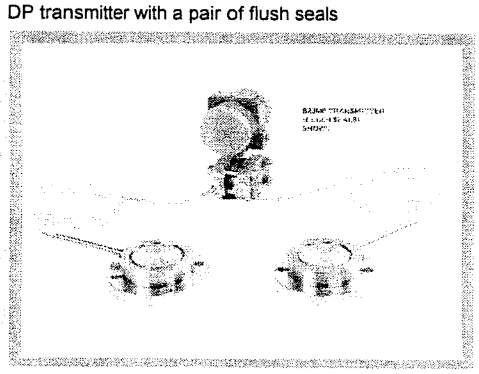
- Smith and Corripio, *Principles and Practice of Automatic Process Control*, 2nd Ed., Wiley (C-6 Transmitters)
- ☐ Output signal: 4 to 20 mA (or 0 - 5 V)



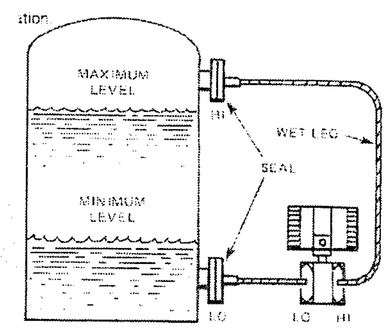
☐ **Installation** of a DP transmitter

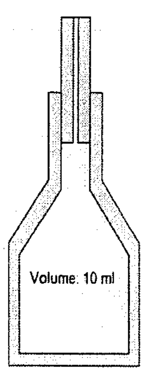


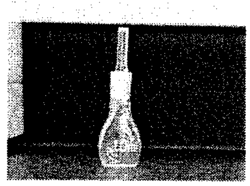
- DP transmitter with a pair of flush seals



- Installation of a DP transmitter with flush seals







☒Pycnometer

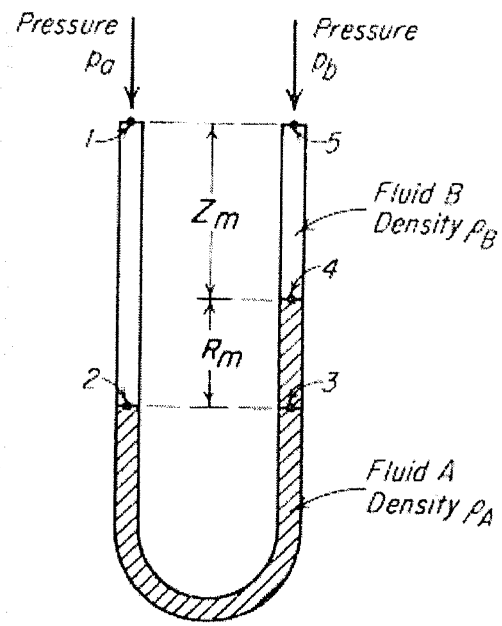
- A glass or metal container with a precisely determined volume, used for determining both the density of liquids and dispersion or by simply weighing the defined volumes.

☒**175 Blue Fluid**

- Manufacturer: Meriam Instrument of Cleveland, OH
- Purpose: manometer indicating fluid
- Common name: 175 Blue fluid
- Chemical names: (1) Diazene-42: Bromoethyl banzenes; Dibromoethyl benzenes; Tribromoethyl benzenes, (2) Kerosene, (3) Chlorotrifluoroethylene polymer, and (4) Trace of Blue dye.
- Specific gravity: 1.75 @13.2 C (water = 1)

Measurement of Pressure

- The manometer operates on the principle of relating **rate of flow** to **pressure drop** across a restriction (orifice) require a pressure measurement.
- A conduit filled with a fluid (a 50 wt% solution of $FeCl_3$, its density ρ=1.55 gm/cm^3)
- Bernoulli's equation with no friction loss



$$\Delta\frac{\langle v\rangle^2}{2}+g\Delta z+\frac{\Delta P}{\rho}=0$$

$$\frac{\Delta P}{\rho}+g\Delta z=0$$

$$\Delta P=p_a-p_b=\frac{g}{g_c}R_m(\rho_A-\rho_B)$$
$$=-\rho g(z_4-z_3)$$

Experiment 5. Measurement of pressure

Pre-laboratory Assignment
Read the MSDS sheet for Blue Fluid (located in the Appendix), and be prepared to take a quiz on the handling and hazards of this chemical.

Introduction
The measurement of pressure is an important part of virtually any chemical process. Although there are a wide variety of ways to do this, we will examine two very different pressure measurement devices in this laboratory experiment. Manometers, which are studied as part of every fluid mechanics and chemical engineering fundamentals course, are often used to measure pressure differential in units of mm of Hg or mm of H_2O. Although manometers are simple to use, they do not lend themselves well to data acquisition using a computer. In this regard, a differential pressure cell (DP cell) is used to measure pressure drop across the orifice, and gives off an electrical signal [voltage (0-5 V) or current (4-20 mA)] which is proportional to the pressure reading. The DP cells are used extensively in the unit operations lab, and in this experiment, you will develop a calibration curve for the DP cell in the flow loop using a manometer.

Theory: Lecture notes

Experimental Procedure
1. A solution of $FeCl_3$ in water was prepared and used in the manometers. The same solution is reserved in a beaker for density measurement.
2. Using a pycnometer, measure the specific gravity of the solution that is now in your manometer. Take enough data points to ensure statistical significance of your data. How does your average value compare with the literature value?
3. Pour your solution from the pycnometer into the original beaker.
4. Activate the DP cell by flipping the DC power switch on the gray box on the south-side wall. Set-up the multi-meter to read mA signal from the DP cell as demonstrated by the GTA. Insert the DP cell pressure taps (vinyl tubes) into the manometer using the labels on the manometer and on the pressure taps as your guide. The multi-meter will read 4.0 mA for zero differential pressure.
5. Pressurize your manometer using the bulb pump on the manometer (similar to that used on a device in a doctors office to measure blood pressure).
6. Record electrical signal (current in mA) versus differential pressure (as read off the manometer). Since the DP cell has a range from 4 to 20 mA, make sure to take pressure readings which correspond to both the high (20 mA) and low (4 mA) readings. Make sure to repeat the data readings several times in order to construct a statistically significant linear plot.
7. Construct a calibration curve for the DP cell that shows pressure reading versus electrical signal. This electrical signal (mA) could be directly connected to a computer for on-line data acquisition of pressure.

Data analysis
(1) Express the manometer readings in terms of Pascal, psia, ft H2O.
(2) Relate the manometer readings to DP cell reading (current signal).
(3) Density measurement.
(4) Regression lines with R^2 values
(5) Estimate differential pressure in psia corresponding to a mA signal reading of 10 mA.

Report

Following points are to be included: theory of measuring differential pressure using a manometer, density measurement of FeCl3 solution, relationship between DP cell readings vs mA signals.

Table 1. An example of data collection

DP cell calibration							
mA	H, cm	L, cm	TTL	[illegible]	psia	ft H2O	

Soluiton density (FeCl3)		
Trial	Density	
1		
2		
3		
Avg ρ		

QUICK IDENTIFIER
(as used in label and list)
175 Blue Fluid

Meriam Instrument
a ScottFetzer company

MATERIAL SAFETY DATA SHEET

SECTION I PRODUCT IDENTIFICATION

COMMON NAME
175 Blue Fluid

PRODUCT FILE NUMBER
920:405-924BB-9

MANUFACTURER'S NAME
Meriam Instrument

ADDRESS
10920 Madison Ave.

CITY, STATE, ZIP
Cleveland, Ohio 44102

PRODUCT MODEL NUMBER
924BB

PRODUCT USE
Indicating Fluid

EMERGENCY PHONE NUMBERS
1-800-424-9300 (US), 1-703-527-3887 (International)

ENGINEERING CONTROL DATA
MSDS - A35800-1, Rev. J, EO 5224
Drawing – A35321

DATE PREPARED
3-1-02

SECTION II HAZARDOUS INGREDIENTS

1.Chemical Name: Diazene-42
OSHA/PEL: NA
ACGIH/TVL: NA
% : 100
Bromoethylbenzenes **CAS No:** 1585-07-5
Dibromoethylbenzenes **CAS No:** 30812-87-4
Tribromoethylbenzenes **CAS No:** 31195-17-2

2.Chemical Name: Kerosene
CAS No: 8008-20-6
OSHA/PEL: NA
ACGIH/TVL: 50mg/M^3
% : <1

3.Chemical Name: Chlorotrifluoroethylene polymer
CAS No: 9002-83-9
OSHA/PEL: NE
ACGIH/TVL: NE
% : <1

4.Chemical Name: Blue Dye
CAS No: 17354-14-2
OSHA/PEL: NE
ACGIH/TVL: NE
% : Trace

SECTION III PHYSICAL & CHEMICAL DATA

BOILING POINT
400-500°F (250-300°C)

VAPOR DENSITY (AIR=1)
9.4

EVAPORATION RATE
NE

APPEARANCE & ODOR
Blue color, Moth ball odor

SPECIFIC GRAVITY (H_2O=1)
1.75 @ 13.2°C

SOLUBILITY IN WATER
Negligible

MELTING POINT
NE

VAPOR PRESSURE (20°C)
NA

REACTIVITY IN WATER
NA

pH
NA

SECTION IV FIRE & EXPLOSION DATA

FLASH POINT	METHOD USED	FLAMMABLE LIMITS (in Air % by Vol.)	LEL	UEL
>200°F			NA	NA

AUTO-IGNITION TEMPERATURE
NA

EXTINGUISHER MEDIA
Water, CO_2, Chemical Foam

SPECIAL FIRE FIGHTING PROCEDURES
Evacuate area of all unnecessary personnel. Use NIOSH/MSHA approved self-contained breathing apparatus and other protective equipment.

UNUSUAL FIRE AND EXPLOSION HAZARDS
Emits toxic fumes under fire conditions.

SECTION V REACTIVITY DATA

STABILITY
Stable

CONDITION TO AVOID
Avoid contact with finely divided reducing such as powdered aluminum

INCOMPATIBILITY (Materials to Avoid)
Same as above

HAZARDOUS DECOMPOSITION PRODUCTS
Carbon oxides, Hydrogen Bromide

HAZARDOUS POLYMERIZATION
Will not occur

CONDITIONS TO AVOID
NA

SECTION VI HEALTH HAZARDS

ACUTE

EYES
May cause mild irritation, redness, and tearing.

SKIN CONTACT

May cause slight irritation. May cause severe irritation with repeat or prolonged contact.

INGESTION

NA

INHALATION

May cause irritation of nasal and respiratory passages.

CHRONIC EFFECTS OF EXPOSURE

May cause Liver and Kidney damage. To the best of our knowledge all toxicological properties have not been thoroughly investigated.

CHEMICAL LISTED AS CARCINOGEN OR POTENTIAL CARCINOGEN

National Toxicology Program	I.A.R.C. Monographs	OSHA
NA	NA	NA

SECTION VII EMERGENCY & FIRST AID PROCEDURE

EYES

Immediately flush eyes with plenty of water for at least 15 minutes while holding eyelids open. Get medical attention.

SKIN CONTACT

Remove contaminated clothing and wash with soap and water. If irritation occurs, get medical attention.

INHALATION

Remove from exposure. Seek medical attention.

INGESTION

Induce vomiting. Seek medical attention immediately.

SECTION VIII SPILL OR LEAK PROCEDURES

RESPONSE TO SMALL SPILLS

Absorb with absorbent material. Dispose of properly.

WASTE DISPOSAL

Place in an appropriate disposal facility in compliance with Federal, State, and Local regulations.

SECTION IX SPECIAL PROTECTION INFORMATION

RESPIRATORY PROTECTION

Not typically required. If exposure exceeds permissible exposure limits wear a self-contained breathing apparatus in compliance with NIOSH/MSHA specifications. Comply with 29CFR 1910.134

VENTILATION

General (mechanical) room ventilation is generally satisfactory. Special, local ventilation may be needed at points where vapors can be expected to exceed exposure limits.

PROTECTIVE GLOVES

For the best protection wear compatible chemical resistant gloves. Wear additional protective garments were necessary.

EYE PROTECTION

Wear chemical goggles if there is likelihood of contact with eyes.

ADDITIONAL PROTECTIVE CLOTHING OR EQUIPMENT

Boots, aprons, or chemical suits should be used when necessary to prevent skin contact. Eye wash fountains and safety showers should be available for emergency use.

SECTION X SPECIAL PRECAUTIONS

-THIS PRODUCT IS FOR INDUSTRIAL AND LABORATORY USE ONLY
-Do not store in open, unlabeled or mislabeled containers.
-Store in cool, dry place with adequate ventilation.
-Keep away from flames and high temperatures.
-For personal hygiene protection, we recommend that employees wash thoroughly after handling product. Always wash up before eating, smoking, and using toilet facilities.
-Keep out of reach of children.

-HMIS rating HEALTH - 2 FLAMMABILITY - 1 REACTIVITY - 1

DISCLAIMER OF LIABILITY

The information contained herein is, to the best of our knowledge and belief, accurate. However, since the conditions of handling and use are beyond our control, we make no guarantee of the results, and assume no liability for damages incurred by use of this material. All chemicals may present unknown health hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards which exist. Final determination of suitability of the chemical is the sole responsibility of the user. User of any chemical should satisfy themselves that the conditions and methods of use assure that the chemical is used safely. NO REPRESENTATIONS OR WARRANTIES, EITHER EXPRESS OR IMPLIED, OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR ANY OTHER NATURE ARE MADE HEREUNDER WITH RESPECT TO THE INFORMATION CONTAINED HEREIN OR THE CHEMICAL TO WHICH THE INFORMATION REFERS. It is the responsibility of the user to comply with all applicable federal, state, local laws and regulations.

Transport Laboratory

CM3215
Lecture 6

Fluid Flow

(N_{Re})

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Fundamentals of Fluid Mechanics

- Characterization of fluid flow
  - When fluids moves through a closed channel of any cross section, either of two different types of flow may occur according to the conditions.
  - Viscous flow or turbulent flow
  - Experiment first performed by **Osborne Reynolds** (1883)
  - For straight circular pipe:
    when $N_{Re} < 2100$, flow is always viscous
    when $N_{Re} > 4000$, flow is always turbulent
  - N_{Re}: Reynolds number

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

Where D: Inside diameter; u: avg. velocity; ρ: density; and μ: viscosity

The Reynolds number is a dimensionless group. Liquid methyl ethyl ketone (MEK) flows through a pipe with an inner diameter of 2.067 inches at an average velocity of 0.48 ft/s. At the fluid temperature of 20°C the density of liquid MEK is 0.805 g/cm3 and the viscosity is 0.43 centi-poise [1 cP=1.00E-3 kg/ms]. Determine whether the flow is laminar or turbulent. (Felder & Rousseau, Problem 2.23)

$$N_{Re} = \frac{Du\rho}{\mu} = \frac{0.48 ft}{s}\,\frac{1m}{3.2808 ft}\,\frac{2.067 in}{0.43E-3 kg/ms}\,\frac{1m}{39.37 in}\,\frac{0.805 g}{cm^3}\,\frac{1kg}{1000 g}\,\frac{10^6 cm^3}{1 m^3}$$
$$= 14,380$$

The flow is **turbulent**.

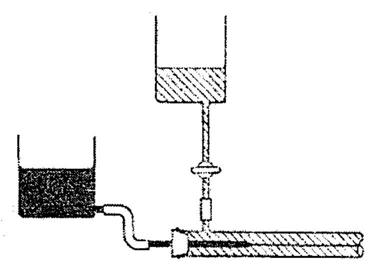


FIG. 2-4. Reynolds' experiment.

Badger and Banchero, *Introduction to Chemical Engineering*, McGraw-Hill, 1955

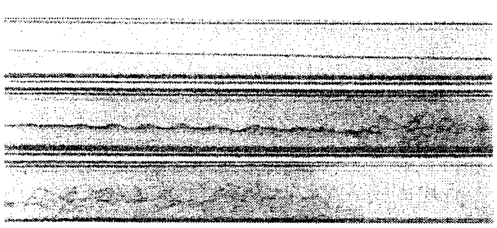


Figure 1.4.1-1 Injection of dye in pipe flow[12] laminar (top) to turbulent (bottom)

- Kessler and Greenkorn, *Momentum, Heat, and Mass Transfer Fundamentals*, Marcel Dekker, 1999

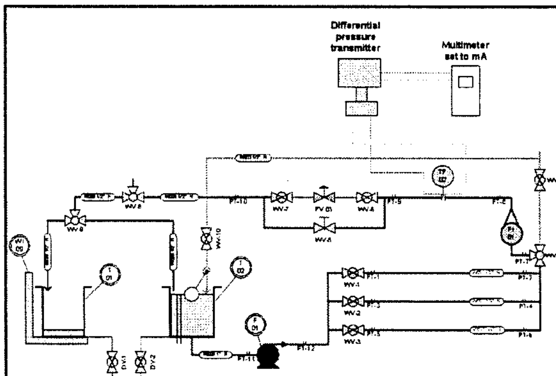


Figure 1. P&ID for Transport Lab Lab 6. Fluid Mechanics

Perry's Chem Eng Handbook 4th Ed. (6th Ed., p. 6-64)

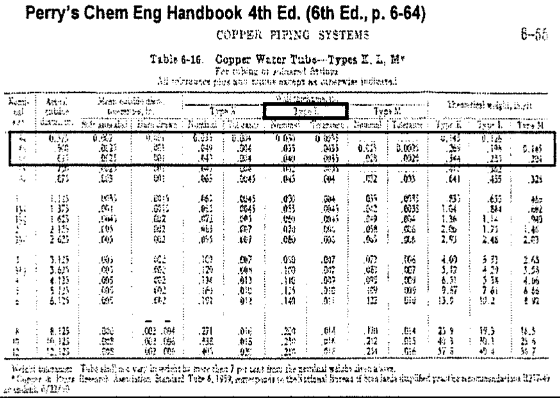

COPPER PIPING SYSTEMS 6-55

Table 6-16. Copper Water Tubes—Types K, L, M*

For tubing or soldered fittings

All tolerances plus and minus except as otherwise indicated

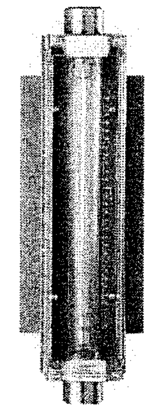
Nominal size	Actual outside diam., in.	Mean outside diam. tolerance, in.: Soft annealed	Hard drawn	Wall thickness, in.: Type K Nominal	Type K Tolerance	Type L Nominal	Type L Tolerance	Type M Nominal	Type M Tolerance	Theoretical weight, lb/ft: Type K	Type L	Type M
1/4	0.375	0.002	0.001	0.035	0.004	0.030	0.0035	......	......	0.145	0.126	
3/8	.500	.0025	.001	.049	.004	.035	.0035	0.025	0.0025	.269	.198	0.145
1/2	.625	.0025	.001	.049	.004	.040	.0035	.028	.0025	.344	.285	.204
5/8	.750	.0025	.001	.049	.004	.042	.0035	......	......	[illegible]	.362	
3/4	.875	.003	.001	.065	.0045	.045	.004	.032	.003	.641	.455	.328
1	1.125	.0035	.0015	.065	.0045	.050	.004	.035	.0035	.839	.655	.465
1 1/4	1.375	.004	.0015	.065	.0045	.055	.0045	.042	.0035	1.04	.884	.682
1 1/2	1.625	.0045	.002	.072	.005	.060	.0045	.049	.004	1.36	1.14	.940
2	2.125	.005	.002	.083	.007	.070	.006	.058	.006	2.06	1.75	1.46
2 1/2	2.625	.005	.002	.095	.007	.080	.006	.065	.006	2.93	2.48	2.03
3	3.125	.005	.002	.109	.007	.090	.007	.072	.006	4.00	3.33	2.68
3 1/2	3.625	.005	.002	.120	.008	.100	.007	.083	.007	5.12	4.29	3.58
4	4.125	.005	.002	.134	.010	.110	.009	.095	.009	6.51	5.38	4.66
5	5.125	.005	.002	.160	.010	.125	.010	.109	.009	9.67	7.61	6.66
6	6.125	.005	.002	.192	.012	.140	.011	.122	.010	13.9	10.2	8.92
8	8.125	.006	+.002 −.004	.271	.016	.200	.014	.170	.014	25.9	19.3	16.5
10	10.125	.008	+.002 −.006	.338	.015	.250	.016	.212	.015	40.3	30.1	25.6
12	12.125	.008	+.002 −.006	.405	.020	.280	.018	.254	.016	57.8	40.4	35.7

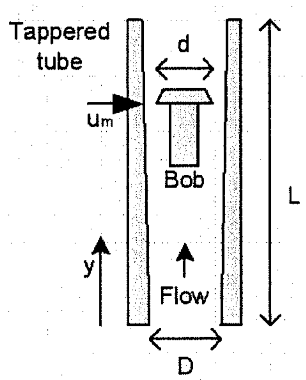
Weight tolerances: Tube shall not vary in weight by more than [illegible] per cent from the nominal weights given above.

* Copper & Brass Research Association Standard Tube 6, 1959, corresponds to the National Bureau of Standards simplified practice recommendations [illegible]

Rotameter

- Rotameter is a commonly used flow measurement device. It has **bob (or float)** in a **tapered tube**. The bob will rise to a point in the tube that the drag forces are just balanced by the weight and buoyancy forces. The position of the bob in the tube is then taken as an indication of the flow rate.





- D = 13/16"
- d =
- a = (Constant for the tube taper)
- L = 14"

- **The force balance on the bob**

➲ Drag forces + Buoyancy force = Gravity force

$$F_d + \rho_f V_b \frac{g}{g_c} = \rho_b V_b \frac{g}{g_c}$$

$$F_d = C_d A_b \frac{\rho_f (u_m)^2}{2 g_c}$$

where ρ_f = fluid density; ρ_b = bob density; V_b = the volume of the bob, g = the acceleration of the gravity; F_d = drag force; C_d = drag coefficient; A_b = frontal area of the bob; u_m = mean flow velocity in the annular space between the bob and the tube.

- Combining two equations and solving for u_m

$$u_m = \sqrt{\frac{1}{C_d} \frac{2gV_b}{A_b} \left(\frac{\rho_b}{\rho_f} - 1 \right)}$$

$$Q = A u_m = A \sqrt{\frac{1}{C_d} \frac{2gV_b}{A_b} \left(\frac{\rho_b}{\rho_f} - 1 \right)}$$

where

$$A = \frac{\pi}{4} \left[(D + ay)^2 - d^2 \right]$$

- A = annular area; D = diameter of the tube at inlet; d = maximum bob diameter; y = the vertical distance from the entrance; a = constant indicating the tube taper

- Drag coefficient, C_d, is dependent on the Reynolds number and hence on the fluid viscosity; special bobs that have an essentially constant drag can be made and essentially independent of viscosity.
- For many practical meters the quadratic area relation becomes nearly linear. Assuming a linear relation, the mass rate can be:

$$\dot{m} = C_1 y \sqrt{(\rho_b - \rho_f) \rho_f}$$

where C_1 is an appropriate meter constant.

- Consider the flow of an incompressible fluid about a solid sphere. The total force F of the fluid on the sphere is given:
- F = buoyant force + form drag + friction drag
- F_{drag} = form drag + friction drag

$$F = \frac{4}{3}\pi R^3 \rho g + 2\pi\mu R u_m + 4\pi\mu R u_m$$

$$F = \frac{4}{3}\pi R^3 \rho g + 6\pi\mu R u_m$$

$$\rho_b V_b g = V_b \rho_f g + C_d A_b [\frac{1}{2}\rho_f u_m^2]$$

$$u_m = \sqrt{\frac{1}{C_d}\frac{2gV_b}{A_b}\left(\frac{\rho_b}{\rho_f} - 1\right)}$$

Exp 6

	Rotameter		Orifice	Water							
Size	%	%	mA	Weight	Time, s	gpm	Velcoty	Temp, C	Density	Viscosity	NRe
1/2"	20										
	30										
	40										
	50										
	60										
	70										
3/8"	20										
	30										
	40										
	50										
	60										
	70										
1/4"	20										
	30										
	40										
	50										

Perry's Chem Eng Handbook 4th Ed. (6th Ed., p. 6-64)

Table 6-16. Copper Water Tube—Types K, L, M*

For tubing or soldered fittings

All tolerances plus and minus except as otherwise indicated

Nominal size	Actual outside diam., in.	Mean outside diam. tolerances, in.		Wall thickness, in.						Theoretical weight, lb./ft		
				Type K		Type L		Type M				
		Soft annealed	Hard drawn	Nominal	Tolerance	Nominal	Tolerance	Nominal	Tolerance	Type K	Type L	Type M
1/4	0.375	0.002	0.001	0.035	0.004	0.030	0.0035	.....	......	0.145	0.126	
3/8	.500	.0025	.001	.049	.004	.035	.0035	0.025	0.0025	.269	.198	0.145
1/2	.625	.0025	.001	.049	.004	.040	.0035	.028	.0025	.344	.285	.204
5/8	.750	.0025	.001	.049	.004	.042	.0035	.....	......	.418	.362	
3/4	.875	.003	.001	.065	.0045	.045	.004	.032	.003	.641	.455	.328
1	1.125	.0035	.0015	.065	.0045	.050	.004	.035	.0035	.839	.655	.465
1 1/4	1.375	.004	.0015	.065	.0045	.055	.0045	.042	.0035	1.04	.884	.682
1 1/2	1.625	.0045	.002	.072	.005	.060	.0045	.049	.004	1.36	1.14	.940
2	2.125	.005	.002	.083	.007	.070	.006	.058	.006	2.06	1.75	1.46
2 1/2	2.625	.005	.002	.095	.007	.080	.006	.065	.006	2.93	2.48	2.03
3	3.125	.005	.002	.109	.007	.090	.007	.072	.006	4.00	3.33	2.68
3 1/2	3.625	.005	.002	.120	.008	.100	.007	.083	.007	5.12	4.29	3.58
4	4.125	.005	.002	.134	.010	.110	.009	.095	.009	6.51	5.38	4.66
5	5.125	.005	.002	.160	.010	.125	.010	.109	.009	9.67	7.61	6.66
6	6.125	.005	.002	.192	.012	.140	.011	.122	.010	13.9	10.2	8.92
			+ −									
8	8.125	.006	.002 .004	.271	.016	.200	.014	.170	.014	25.9	19.3	16.5
10	10.125	.008	.002 .006	.338	.018	.250	.016	.212	.015	40.3	30.1	25.6
12	12.125	.008	.002 .006	.405	.020	.280	.018	.254	.016	57.8	40.4	36.7

Weight tolerance: Tube shall not vary in weight by more than 7 per cent from the nominal weight given above.

* Copper & Brass Research Association Standard Tube 6, 1959, corresponds to theNational Bureau of Standards simplified practice recommendations R217-49 amendent, 6/22/50.

Experiment 6. Fluid mechanics

Pre-laboratory Assignment

The Reynolds number is a dimensionless group and provides a good measure of hydrodynamic behavior of the fluid. Familiarize yourself with Reynolds number.

Introduction

Characterization of the type of flow occurring in piping systems is critical in designing heat and mass transfer equipment. The critical parameter used to characterize fluid flow is the Reynolds number.

In this experiment, you will measure the Reynolds number for straight circular pipes.

Theory: Lecture notes

Experimental Procedure

Inspect the P&ID from the Experiment 1 to see the flow loop involved with this experiment (Flow chart in Lecture notes). First we need to calibrate the rotameter (FI-01).

Rotameter calibration

(1) Make sure that Supply Tank (T-02) is empty and clean. Close the drain valve (DV-2).
(2) Open water valve (WV-10) and fill T-02 with water. Once the tank is filled, water control float valve will shut off water. It keeps water level constant at a set point, when water is drained from the tank.
(3) Open valve WV-1 and close WV-2 and WV-3. Turn tree-way valve WV-4 knob to direct the water flow through rotameter FI-01. Make sure that valve WV-6 and WV-7 are closed. Also close needle valve WV-5. Adjust three-way valve WV-8 to direct water to tanks (not to the heat exchanger E-01). Turn three-way valve WV-9 knob to direct water to T-02.
(4) Turn on pump P-01.
(5) Get an Omega DMM Thermometer with a thermocouple and be ready to measure the temperature of water in T-02.
(6) Open needle valve WV-5 gradually counter clock-wise, observing closely the rotameter reading. Adjust WV-5 to have a steady flow at 20 % rotameter reading.
(7) To turn on Ohaus electronic scale (Model CD-33: WI-09), pug the AC/DC power converter (120 VAC→9 V DC 500 mA) into the AC outlet. Ohaus scale is on and will show on screen: "Weight 4.160 kg (for example)." Press "Tare" key. It will show: "0.000 kg."
(8) Take an electronic stopwatch (ask GTA) and play with it to learn how to start, stop, and reset.
(9) Install a multi-meter to measure mA signals from the orifice meter.
(10) The moment you direct the flow from T-02 to T-01 by turning three-way valve WV-9, time it with the electronic stopwatch for approximately one minute and redirect the flow back to T-02 and stop timing.
(11) Record the weight of water collected in T-01 from WI-09 and the exact time required. This is known as the "pail and scale" method. Also record mA signal (Step 9) and water temperature (Step 6).
(12) Perform this operation at least three times for statistical analysis.
(13) Repeat Step 5 through Step 10 for different rotameter readings in steps of 10, until you have documented data for 70 %.
(14) Repeat Step 3 through Step 12 for different pipe sizes in place of ½": 3/8" and ¼".
(15) When finished, drain T-01 using DV-01. Turn off WV-10 and drain T-02 with DV-02. Turn off all the electronic devices and properly store in place.

Reynolds number computation

Compute the Reynolds number with the data collected above. Use Table 1 as a guide.

Table 1. Flow characterization (N_{Re})

Exp 6

	Rotameter		Orifice	Water							
Size	%	%	mA	Weight	Time, s	gpm	Velcoty	Temp, C	Density	Viscosity	NRe
1/2"	20										
	30										
	40										
	50										
	60										
	70										
3/8"	20										
	30										
	40										
	50										
	60										
	70										
1/4"	20										
	30										
	40										
	50										

Shut Down Procedure

(1) Turn off pump P-01
(2) Close main water valve WV-10
(3) Drain all tanks

Data Analysis

(1) Means and standard deviations
(2) Generate a plot of rotameter reading versus flow rate.
(3) For a series of different flow rates and different sized pipes, determine whether the flow is laminar, turbulent, or in the transition region. Relate the current signal to flow rate.
(4) Regression lines with R^2 values
(5) Estimate your flow rate in gpm for a rotameter reading of 45 %.

Report

Following points are to be included: rotameter calibration, the effects of pipe size, mass flow rate, and volumetric flow rate on fluid flow characteristics as expressed in N_{Re}.

Revised: August 14, 2003

Transport Laboratory

CM3215
Lecture 7

Friction Losses

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Friction losses in a piping system

- If the fluid is incompressible fluid, the mechanical-energy-balance equation becomes:

$$\Delta\left[\frac{1}{2\alpha}\left(v_{avg}\right)^2\right]+\Delta\left(\frac{P}{\rho}\right)+g\Delta z+\sum F+W_s=0$$

1 2 3 4 5

where

□numbers assigned to each term

1. Velocity head
2. Pressure head
3. Potential head
4. Friction head
5. Shaft work

☺ What we did last week

Reynolds number

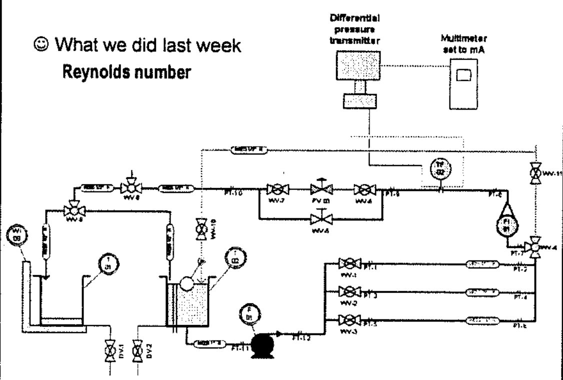

Figure 1. P&ID for Transport Lab
Lab 6. Fluid Mechanics

ΣF: friction losses

For ***one size*** pipe is

$$\sum F=\left(4f\frac{L}{D}+\sum K\right)\left[\frac{1}{2}\frac{(v_{avg})^2}{g_c}\right]$$

For ***several sizes*** of pipe is

$$\sum F=\sum_j\left[\left(4f\frac{L_j}{D_j}+\sum K_j\right)\left(\frac{1}{2}\frac{(v_{avg})_j^{\,2}}{g_c}\right)\right]$$

where

4fL/D: Friction losses (number of velocity heads) *for straight pipe*

ΣK: Friction losses (number of velocity head) *for fitting, valve, expansion/contraction.*

☺ What we will do this week.

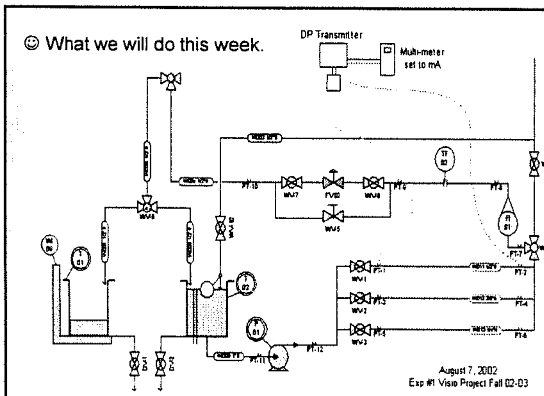

Figure 1. Friction losses in smooth straight pipes

- Applying to the **horizontal straight** pipes:

$$\Delta\left[\frac{1}{2\alpha}\left(v_{avg}\right)^2\right]+\Delta\left(\frac{P}{\rho}\right)+g\Delta z+\sum F+W_s=0$$

$$\sum F=\left(4f\frac{L}{D}+\sum K\right)\left[\frac{1}{2}\frac{(v_{avg})^2}{g_c}\right]$$

$$\Delta\left(\frac{P}{\rho}\right)+4f\frac{L}{D}\left[\frac{1}{2}\frac{(v_{avg})^2}{g_c}\right]=0$$

- Or this can be used for estimating f

$$f=\frac{\sum F}{\frac{4L}{D}\left[\frac{1}{2}\frac{(v_{avg})^2}{g_c}\right]}$$

☒A pipeline laid cross country carries oil at the rate of 795 m^3/d. The pressure of the oil (soybean) is 1793 kPa gage leaving pumping station 1. The pressure is 862 kPa at the inlet to the next pumping station 2. The second station is 17.4 m higher than the first station. Calculate the lost work (ΣF friction loss) in J/kg mass oil. The oil density is 769 kg/m^3.

- Remember that this equation is on a unit mass basis.

☐The governing equation is:

$$\frac{v_1}{2\alpha}+gz_1+\frac{P_1}{\rho}-W_s=\frac{v_2}{2\alpha}+gz_2+\frac{P_2}{\rho}+\sum F$$

☒If the pipe is 1 km long of 8" schedule 40 pipe, what is the Fanning friction factor? The viscosity of the Soybean oil is 40 cP at the operating temperature and the frictional losses (ΣF) is 10.581 J/kg. The average velocity of the fluid is 0.31223 m/s.

$$f=\frac{\sum F}{\frac{4L}{D}\left[\frac{1}{2}\frac{(v_{avg})^2}{g_c}\right]}$$

$$=\frac{10.581}{\frac{4\times 1000m}{0.2027m}\left[\frac{1}{2}\frac{(0.31223)^2}{1}\right]}$$

$$=0.011$$

$$\frac{v_1^2}{2\alpha}=\frac{v_2^2}{2\alpha}$$

$$W_s=0$$

$$\cancel{\frac{v_1^2}{2\alpha}}+0+\frac{1793\times 1000}{769}-0$$

$$=\cancel{\frac{v_2^2}{2\alpha}}+17.4\times 9.806+\frac{862\times 1000}{769}+\sum F$$

$$\sum F=1040(J/kg)$$

- Compute the Reynolds number from the data.

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

$$=\frac{0.2027m(0.31223m/s)919kg/m^3}{40cP\left(\frac{0.001kg/ms}{cP}\right)}$$

$$=1454$$

- Calculate the Fanning friction factor.

$$f=\frac{16}{N_{Re}}=\frac{16}{1454}=0.011$$

- Unit check

$$F_f=\frac{P_1-P_2}{\rho}$$

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

$$\frac{P_1-P_2}{\rho}=\frac{\Delta P}{\rho}=\sum F=4f\frac{\Delta L}{D}\left(\frac{v^2}{2}\right)$$

$$\left[\frac{N}{m^2}\frac{m^3}{kg}\right]=\left[\frac{Nm}{kg}\right]=\left[\frac{J}{kg}\right]$$

$$=\left[\frac{m^2}{s^2}\right]=\left[\frac{m^2}{s^2}\frac{kg}{kg}\right]=\left[\frac{mkg}{s^2}\frac{m}{kg}\right]=\left[\frac{Nm}{kg}\right]$$

Experiment 7. Frictional Losses in a Piping System

Pre-laboratory Assignment

Read through the section on friction losses in laminar and turbulent flow in your transport book. (Section 2.10A-E, Geankoplis)

Introduction

Flow through piping systems is always accompanied by a resulting pressure drop due to friction losses. When designing chemical processing and heat transfer equipment, characterization of the fluid friction losses is critical to specifying the correct size equipment. In order to characterize friction losses in fluid systems, the results from the previous two laboratory experiments (fluid flow measurements, pressure measurements) will be used.

Theory (background): Lecture

Experimental Procedure

1. Make sure that supply tank T-02 is empty. Close the drain valve DV-2.
2. Open water valve WV-10 and fill T-02 with water. Once the tank is filled, the water control float valve will shut off the water. The water level in the tank will be held constant when the water is drained from the tank.
3. Direct the water flow through the ½" pipe by opening WV-1 and closing WV-2 and WV-3. Turn the three-way valve WV-4 to direct the water flow through the rotameter FL-01. Make sure that valves WV-6 and WV-7 are closed. Adjust three-way valve WV-8 to direct water to the tanks and not the heat exchanger. Turn three-way valve WV-9 to direct water to either T-01 or T-02.
4. Turn on pump P-01 by flipping the gray switch that is located next to the AC outlet.
5. Measure the temperature of the water using the Omega DMM Thermometer.
6. Adjust needle valve WV-5 to set rotameter reading at 20%.
7. Insert the cables from the DP cell into pressure taps PT-1 and PT-2, taking note on the high and low-pressure sides. Take note of the length of pipe between the pressure taps.
8. Set up a multi-meter to measure mA and connect the multi-meter to the DP cell.
9. Record the mA signal at the set rotameter reading. The signal can be converted to pressure with the use of the calibration curve established in Laboratory 5.
10. Change the rotameter reading with the needle valve WV-5 with increments of 10 until you have data for 70%.
11. Repeat the process from 20 to 70% rotameter reading at least three times for statistical significance.
12. Repeat steps 3-10 for the ¼" and 3/8" pipes.
13. When finished, turn off P-01 and drain T-01 using DV-1. Turn off WV-10 and drain T-02 with DV-2. Disconnect the multi meter and the DP cell cables from the pressure taps and store in proper place.

Data Analysis

1. Means and standard deviations of the readings
2. Compute the frictional losses for the three different pipe sizes at various flow rates using the equations provided in the lecture.
3. Compare your results to the measured frictional losses
4. Plot computed and measured frictional losses vs. flow rate for the three different pipes

Report

Discuss in your report the effects of mass flow rate, volumetric flow rate and pipe diameters on the frictional losses in the straight tube

Table 1. An example of friction loss computation: calculated vs. measured.

Smooth tube										Fan.	Calc	DP	Pa	**Meas**	Descripancy
	ID, m	%	Wt	s	kg/s	m3/h	gpm	m/s	Nre	f	ΣF,J/kg	mA	N/m2	ΣF,J/kg	%
1/2"	0.01486	20													
		30													
		40													
		50													
		60													
		70													
		74													
3/8"	0.01181	20													
		30													
		40													
		50													
		60													
		70													
1/4"	0.00876	20													
		30													
		40													
		50													

Meas. vs Calc

Meas. friction loss, J/kg

Measured pressure drop, Pa

Measured pressure drop in mA

Calculated friction loss, J/kg

Fanning friction factor (p. 88, Geankoplis)

Reynolds number

Velocity, m/s

Flow rate, gpm

Volume flow rate

Mass rate

Rotameter readings, %

Inside diameter of copper tubes

Nominal diameters

Transport Laboratory

CM3215
Lecture 8

Control Valve

Nam K. Kim
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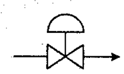
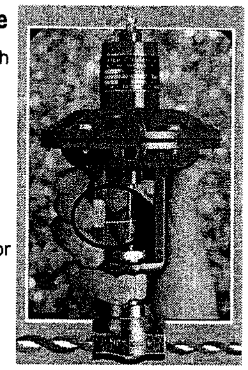
Automatic control valve

- Badger Meter Research Control Valve
- ✱ **Type 807 SS linear C trim with C_V=1.25** is being used for the **water** flow control.
- ✱ **Type 807 SS Equal percent D trim with C_V=0.8** is being used for the **steam** flow control.





☺ What we did last week.

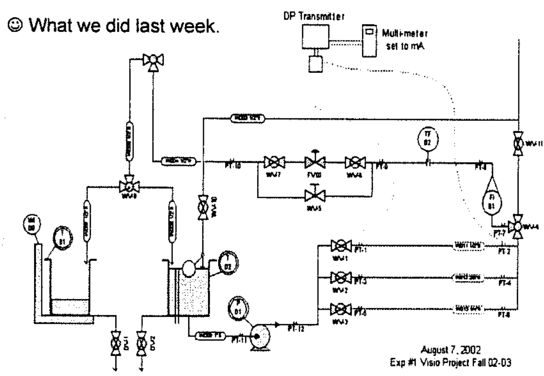
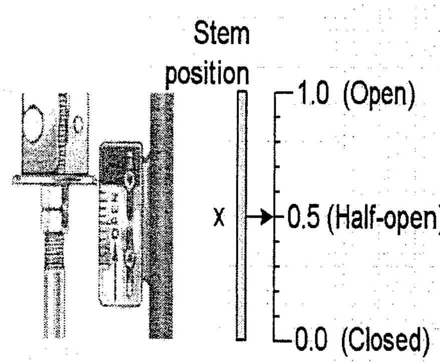


Figure 1. Friction losses in smooth straight pipes



☺ What we will do next week.

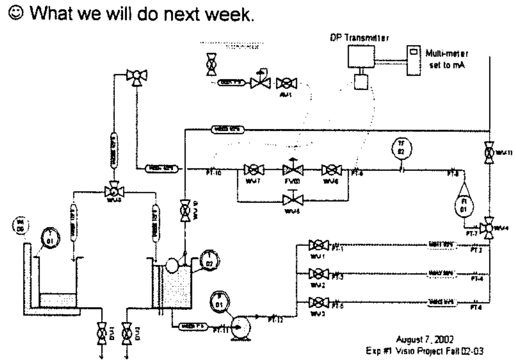
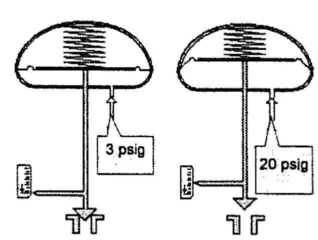


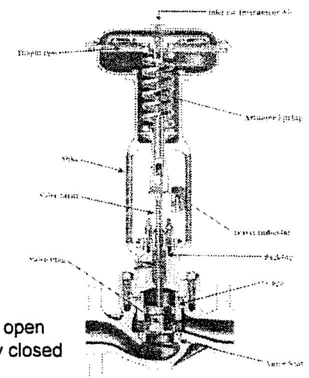
Figure 1. Control valve characterization

Pneumatic control valve

- The most common final control element is the pneumatic valve
- ⓘ Air-to-open (Instrument air)
- ⓘ Air-to-close



✱ Air-to-open



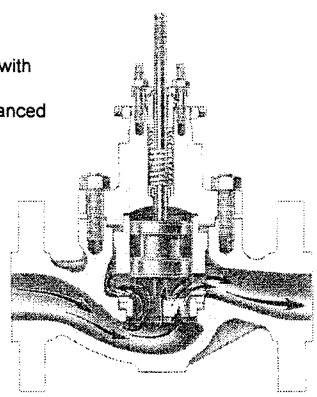
✱ Air-to-close:
3 psig --> wide open
20 psig --> fully closed

- The **flow rate**, **F**, through the control valve:

$$F = C_v f(x)\sqrt{\frac{\Delta P}{SG}}$$

- Where **F**: flow rate in gpm; $\mathbf{C_v}$: valve size coefficient; **f(x)**: valve flow characteristic curve; **ΔP**: pressure drop across the valve, psi; **SG**: specific gravity of the flowing fluid relative to water; x: valve stem position (fraction of wide open)
- The accepted method of valve sizing is the $\mathbf{C_v}$ approach.
  It is defined as the number of US gpm of 60 F water which will flow through a wide-open valve with a pressure drop of 1 psi across the valve.

- Globe valve with an unbalanced plug



- **Example**
  The water is flowing through a control valve with a linear trim. When the stem position indicates 0.5, what is the flow rate? The differential pressure across the valve is 4 psi and the valve size coefficient is 2.0.

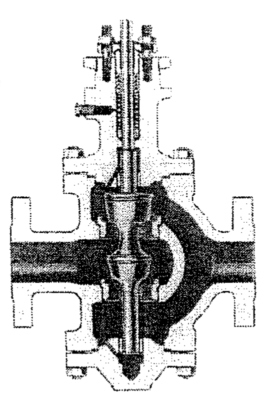
☐**Solution**

$$f(x) = \frac{F}{F_{max}} = x = 0.5$$

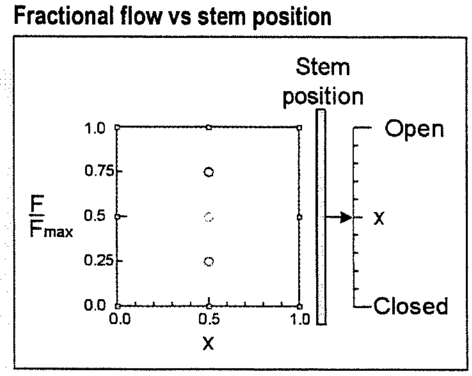
$$\Delta P = 4(psi); s.g. = 1.0; C_v = 2.0$$

$$F = C_v f(x)\sqrt{\frac{\Delta P}{s.g.}} = (2.0)(0.5)\sqrt{\frac{4.0}{1.0}} = 2.0(gpm)$$

- Globe valve with a balanced plug

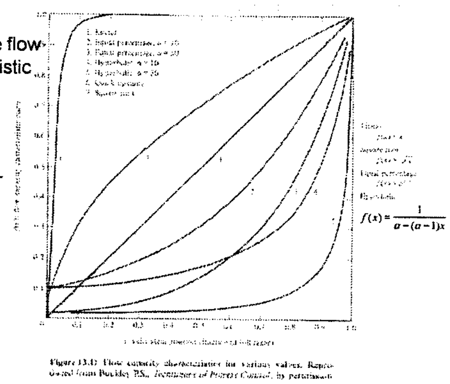


Fractional flow vs stem position



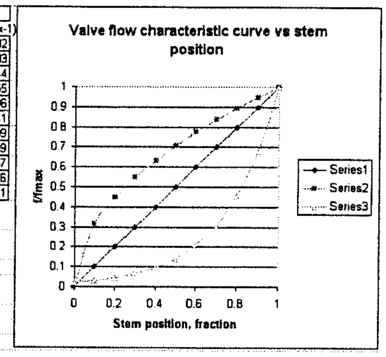
- f(x): valve flow characteristic curve.

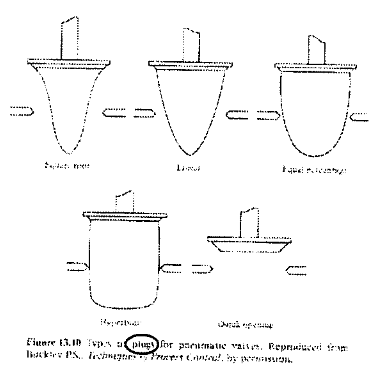
$$f(x) = \frac{F}{F_{max}}$$



- Characterization procedure: y=x^0.5 or y=50^(x-1)

x	f/fmax		
	x	x^0.5	50^(x-1)
0	0	0	0.02
0.1	0.1	0.316	0.03
0.2	0.2	0.447	0.044
0.3	0.3	0.548	0.065
0.4	0.4	0.632	0.096
0.5	0.5	0.707	0.141
0.6	0.6	0.775	0.209
0.7	0.7	0.837	0.309
0.8	0.8	0.894	0.457
0.9	0.9	0.949	0.676
1	1	1	1





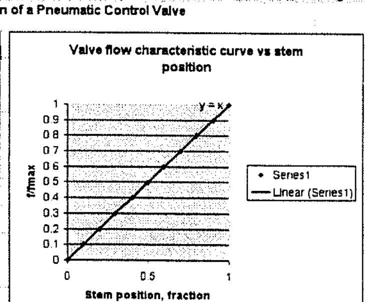
- Stephanopoulos, Chemical Process control
- Prentice Hall

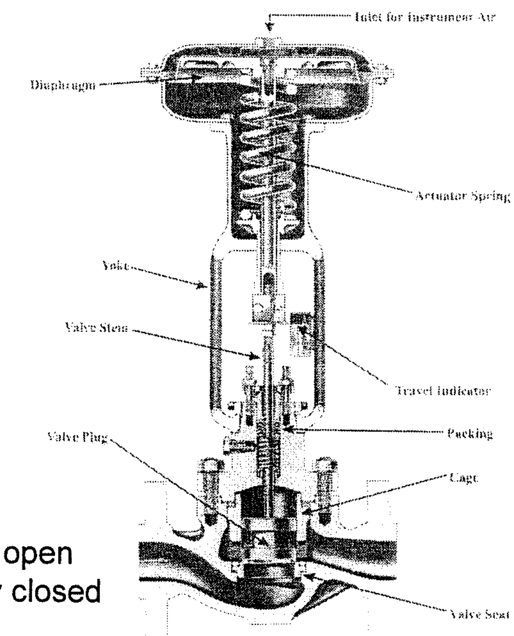
- Characterization procedure: y = x

D4 = =C4/1.5

Characterization of a Pneumatic Control Valve

x	gpm	f/fmax
1	1.5	1
0.9	1.35	0.9
0.8	1.2	0.8
0.7	1.05	0.7
0.6	0.9	0.6
0.5	0.75	0.5
0.4	0.6	0.4
0.3	0.45	0.3
0.2	0.3	0.2
0.1	0.15	0.1
0	0	0





✸ Air-to-close:
3 psig --> wide open
20 psig --> fully closed

- f(x): valve flow characteristic curve.

$$f(x) = \frac{F}{F_{\max}}$$

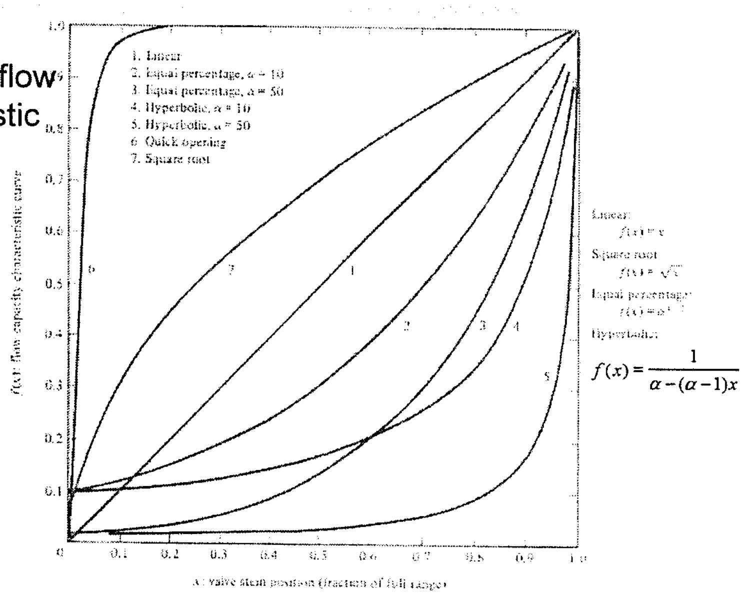


Figure 13.11 Flow capacity characteristics for various valves. Reproduced from Buckley P.S., *Techniques of Process Control*, by permission.

Experiment 8. Characterization of a Pneumatic Control Valve

Pre-laboratory Assignment
Study and review the characterization of control valves. Refer to "Control valves" (Luyben/Luyben, p 75), "Final control elements" (Stephanopoulos, p 253).

Introduction
In a vast majority of chemical engineering processes the final control element is an automatic control valve, which throttles the flow of a manipulated variable. Most control valves consist of a plug on the end of a stem that opens or closes an orifice opening as the stem is raised or lowered. The stem is attached to a diaphragm that is driven by instrument air pressure. The typical range of air pressure is 3 to 15 psig. The control valve flow characteristic is defined as the relationship between the flow through the valve and the valve position as the position is varied from 0% to 100%. There are two types of characteristics: inherent and installed flow characteristic. Inherent flow characteristic refers to the characteristic observed with constant pressure drop across the valve. Installed flow characteristic refers to the characteristic observed when the valve is in service with varying pressure drop and other changes in the system.

Background Theory: Lecture

Experimental Procedure
1. Set up flow through the ½" pipe like described in previous experiments.
2. For this experiment, the needle valve WV-5 will be closed and valves WV-6 and WV-7 will be open.
3. Use the valve pressure regulator to open the control valve FV-03 to 3 psig.
4. Note the stem position at the set pressure.
5. Use the rotameter calibration curve done in the preceding laboratory to determine the mass flow rate of water.
6. Note the water temperature.
7. Repeat steps 3-5 with different air pressures (for best results use 2 psig intervals: 3, 5, 7, 9, 11, 13 and 15).

Calculations, Plots, and Report
For each pressure interval calculate the volumetric flow rate in gpm (gallons per minute)
Generate the following plots:
1. Air pressure vs. volumetric flow rate
2. Stem position vs. volumetric flow rate
3. Stem position vs. air pressure
4. f(x) vs. stem position

Identify the trim of the valve

Table 1. An example of data collection

psig	x	Ro, %	gpm	f(x)=F/Fm
15	1			
13	0.88			
11				
9				
7				
6				
5				
3	0.15			

Revised: August 14, 2002

Transport Laboratory

CM3215
Lecture 9
Pumping System Analysis

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Pump data

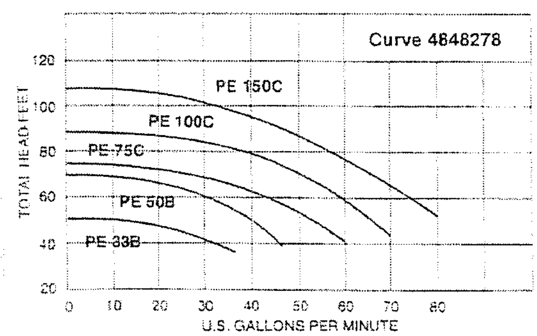
- Krum Pump Co, Kalamazoo, Michigan
- **Pump**:
  - ◆ Model: Peerless pump
  - ◆ Type: PE 50B
  - ◆ Performance curve: Curve No. 4848278
- **Motor**:
  - ◆ Baldo Electric Co., FT Smith, Arkansas
  - ◆ RPM: 3450
  - ◆ PH: 1 Class: 6
  - ◆ Nema Nom. Efficiency: 66%
  - ◆ PF: 61%

- This week's report: **Lab 7** Frictional losses in a piping system
- This week's lab: **Lab 8 Control valve trim**

Frictional losses

- ✱ Calculated frictional losses:
  - ✱ Calculate N_{Re}
  - ✱ Compute f
  - ✱ Compute frictional losses
- ✱ Find the measured frictional losses
- ✱ Compare them

Pump characteristic curve



Pumping system

☺ What we will do this week.

- Consider a pumping system with the 1/2" copper tube branch:

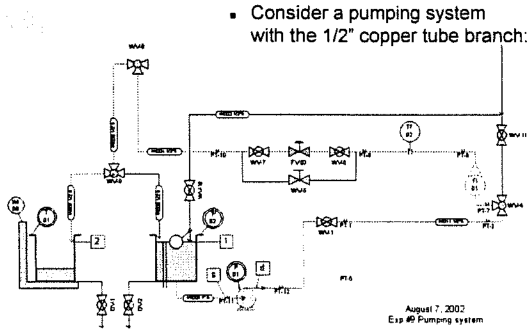
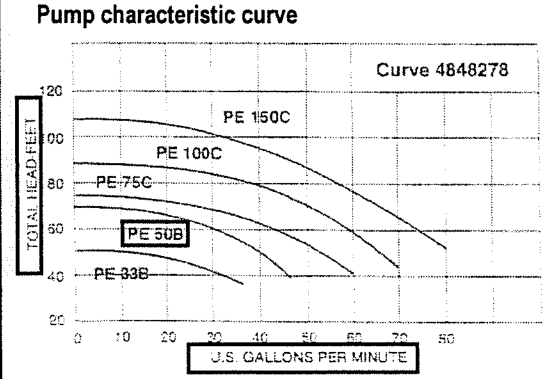


Figure 2. Transport Lab P&ID Visio Printout

Pump characteristic curve



Construct a system curve

- ⊠Start from Bernoulli Eq in terms of **head** (feet).
- ✱Apply the equation to "d-2" (See P&ID)
- ✱Likewise to "1-s" (See Slide #**)
- ✱Add these two Eqs and solve for H_d-H_s. The pump head in feet is expressed as a function of flowrate in gpm
- ✱Evaluate the sums of frictional losses for "d-2" and "1-s"
- ✜Compute the heads for flowrates of 1, 2, 3, and 4 gpm
- ✜Plot the total head (feet) vs flow rate (gpm) on the pump characteristic curve (given).
- ✧Find the operating point.

Number of valves and fittings

- **Discharge** line (1"-->1/2"ϕ). Number of
  - Contraction:
  - Elbows:
  - Tee:
  - Valves
  - etc
  - Straight tube: length
    - 1"ϕ:
    - 1/2"ϕ:
- **Suction line** (1"ϕ)
  - Elbow:
  - Tee: Union:
  - Straight tube:

Frictional losses

for Step 6

Table 5-19. Additional Frictional Loss for Turbulent Flow through Fittings and Valves

Type of Fitting or Valve	Additional Friction Loss, Equivalent No. of Velocity Heads, K
45-deg. ell, standard	0.35
45-deg. ell, long radius	0.2
90-deg. ell, standard	0.75
Long radius	0.45
Square or miter	1.3
180-deg. bend, close return	1.5
Tee, standard, along run, branch blanked off	0.4
Used as ell, entering run	1.3
Used as ell, entering branch	1.5
Branching flow	1
Coupling	0.04
Union	0.04
Gate valve, open	0.17
¾ open	0.9
½ open	4.5
¼ open	24.0
Diaphragm valve, open	2.3
¾ open	2.6
½ open	4.3
¼ open	21.0

Bernoulli Eq.

- From the pump discharge (d) to the point (2)

$$\left(\frac{v_2^2}{2\alpha_2 g}+z_2+\frac{P_2}{\rho g}\right)-\left(\frac{v_d^2}{2\alpha_d g}+z_d+\frac{P_d}{\rho g}\right)$$
$$+\frac{v_2^2}{2g}\left(4f_2\frac{L_2}{D_2}+\Sigma K_2\right)=0$$

- From the point (1) to the pump suction (s)

$$\left(\frac{v_s^2}{2\alpha_s g}+z_s+\frac{P_s}{\rho g}\right)-\left(\frac{v_1^2}{2\alpha_1 g}+z_1+\frac{P_1}{\rho g}\right)$$
$$+\frac{v_s^2}{2g}\left(4f_s\frac{L_s}{D_s}+\Sigma K_s\right)=0$$

Globe valve, bevel seat, open	6.4
½ open	9.5
Composition seat, open	6.0
½ open	8.5
Plug disk, open	9.0
¾ open	13.0
½ open	36.0
¼ open	112.0
Angle valve, open	3.0
Y or blowoff valve, open	3.0
Plug cock (Fig. 5-38) θ = 5°	0.05
10°	0.29
20°	1.56
40°	17.3
60°	206.0
Butterfly valve (Fig. 5-39) θ = 5°	0.24
10°	0.52
20°	1.54
40°	10.8
60°	118.0
Check valve, swing	2.0
Disk	10.0
Ball	70.0
Foot valve	15.0
Water meter, disk	7.0
Piston	15.0
Rotary (star-shaped disk)	10.0
Turbine-wheel	6.0

- Perry's HB 4th Ed.

Bernoulli Eq.

- From the pump discharge (d) to the point (2)

H2 $\left(\frac{v_2^2}{2\alpha_2 g}+z_2+\frac{P_2}{\rho g}\right)-\left(\frac{v_d^2}{2\alpha_d g}+z_d+\frac{P_d}{\rho g}\right)$ Hd

$$+\frac{v_2^2}{2g}\left(4f_2\frac{L_2}{D_2}+\Sigma K_2\right)=0$$

- From the point (1) to the pump suction (s)

Hs $\left(\frac{v_s^2}{2\alpha_s g}+z_s+\frac{P_s}{\rho g}\right)-\left(\frac{v_1^2}{2\alpha_1 g}+z_1+\frac{P_1}{\rho g}\right)$ H1

$$+\frac{v_s^2}{2g}\left(4f_s\frac{L_s}{D_s}+\Sigma K_s\right)=0$$

- Adding two equations

$$H_d - H_s = H_2 - H_1 + \frac{v_2^2}{2g}\left(4f_2\frac{L_2}{D_2}+\Sigma K_2\right)+\frac{v_s^2}{2g}\left(4f_s\frac{L_s}{D_s}+\Sigma K_s\right)$$

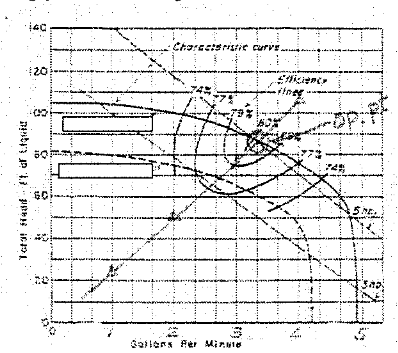
- With

$$v_1 = 0 \qquad \alpha_1 = \alpha_2 = 1 \qquad P_1 = P_2 \qquad v_{avg} = \frac{4Q}{\pi D^2}$$

$$H_d - H_s = z_2 - z_1 + \frac{8Q^2}{\pi^2 g}\left(\frac{1+4f_2\frac{L_2}{D_2}+\Sigma K_2}{D_2^4}+\frac{4f_s\frac{L_s}{D_s}+\Sigma K_s}{D_s^4}\right)$$

- This Eq relates ΔH (ft water) to Q (gpm)

Operating point of the system



NPSH (Net positive suction head)

- Apply the Bernoulli Eq to the suction line
- Choose the datum level for elevations [Let the suction inlet, z_s, be zero]
- $NPSH_R$ should be less than $NPSH_A$
- Available NPSH is given below:

$$NPSH_A = z_1 + \frac{P_1 g_c}{\rho g} - \frac{P_v g_c}{\rho g} - \frac{g_c \Sigma F}{g}$$

- Where
  - $NPSH_A$: Required
  - $NPSH_R$: Available
  - P_V: Vapor pressure (=f(T))

Frictional losses

for Step 6

Table 5-19. Additional Frictional Loss for Turbulent Flow through Fittings and Valves[k]

Type of Fitting or Valve	Additional Friction Loss, Equivalent No. of Velocity Heads, K[c]
45-deg. ell, standard[a,b,c,g,i]	0.35
45-deg. ell, long radius[b]	0.2
90-deg. ell, standard[a,b,d,g,i,m]	0.75
Long radius[a,b,c,g]	0.45
Square or miter[m]	1.3
180-deg. bend, close return[a,b,g]	1.5
Tee, standard, along run, branch blanked off[g]	0.4
Used as ell, entering run[d,g]	1.3
Used as ell, entering branch[b,d,g]	1.5
Branching flow[f,h,j]	1[e]
Coupling[b,g]	0.04
Union[g]	0.04
Gate valve,[a,g,i] open	0.17
¾ open[p]	0.9
½ open[p]	4.5
¼ open[p]	24.0
Diaphragm valve,[n] open	2.3
¾ open[p]	2.6
½ open[p]	4.3
¼ open[p]	21.0
Globe valve,[g,i] bevel seat, open	6.4
½ open[p]	9.5
Composition seat, open	6.0
½ open[p]	8.5
Plug disk, open	9.0
¾ open[p]	13.0
½ open[p]	36.0
¼ open[p]	112.0
Angle valve,[a,g] open	3.0
Y or blowoff valve,[g,i] open	3.0
Plug cock (Fig. 5-38)[c] θ = 5°	0.05
10°	0.29
20°	1.56
40°	17.3
60°	206.0
Butterfly valve[c] (Fig. 5-39) θ = 5°	0.24
10°	0.52
20°	1.54
40°	10.8
60°	118.0
Check valve,[a,g,i] swing	2.0[q]
Disk	10.0[q]
Ball	70.0[q]
Foot valve[g]	15.0
Water meter,[m] disk	7.0[r]
Piston	15.0[r]
Rotary (star-shaped disk)	10.0[r]
Turbine-wheel	6.0[r]

- Perry's HB 4th Ed.

Bernoulli Eq.

- From the pump discharge (d) to the point (2)

$$\underbrace{\left(\frac{v_2^2}{2\alpha_2 g}+z_2+\frac{P_2}{\rho g}\right)}_{H2}-\underbrace{\left(\frac{v_d^2}{2\alpha_d g}+z_d+\frac{P_d}{\rho g}\right)}_{Hd}+\frac{v_2^2}{2g}\left(4f_2\frac{L_2}{D_2}+\sum K_2\right)=0$$

- From the point (1) to the pump suction (s)

$$\underbrace{\left(\frac{v_s^2}{2\alpha_s g}+z_s+\frac{P_s}{\rho g}\right)}_{Hs}-\underbrace{\left(\frac{v_1^2}{2\alpha_1 g}+z_1+\frac{P_1}{\rho g}\right)}_{H1}+\frac{v_s^2}{2g}\left(4f_s\frac{L_s}{D_s}+\sum K_s\right)=0$$

- Adding two equations

$$H_d-H_s=H_2-H_1+\frac{v_2^2}{2g}\left(4f_2\frac{L_2}{D_2}+\sum K_2\right)+\frac{v_s^2}{2g}\left(4f_s\frac{L_s}{D_s}+\sum K_s\right)$$

- With

$$v_1=0 \qquad \alpha_1=\alpha_2=1 \qquad P_1=P_2 \qquad v_{avg}=\frac{4Q}{\pi D^2}$$

$$H_d-H_s=z_2-z_1+\frac{8Q^2}{\pi^2 g}\left(\frac{1+4f_2\frac{L_2}{D_2}+\sum K_2}{D_2^4}+\frac{4f_s\frac{L_s}{D_s}+\sum K_s}{D_s^4}\right)$$

- This Eq relates ΔH (ft water) to Q (gpm)

Experiment 9. Pumping System Analysis

Pre-laboratory Assignment
Read through the section on *Friction losses in expansion, contraction, and pipe fittings* in your transport book. (Section 2.10F-I Geankoplis)

Introduction
A pump is used in a flow system to increase the mechanical energy of the flowing fluid, the increase being used to maintain flow, provide the kinetic energy, offset friction losses, and increase the potential energy. A pump is installed between two points: Point 1 and Point 2. Since the Bernoulli equation is a balance of mechanical energy only, account must be taken of friction occurring within the pump. Whenever the velocity of a fluid is changed, either in direction or magnitude, by a change in the direction or size of the conduit, friction is generated in addition to the skin friction from flow through the straight pipe. Such friction includes form friction resulting from vortices that develop when the normal streamlines are disturbed and when boundary layer separation occurs.

Theory: Lecture

Experimental Procedure
There is no need to run water through the process. You will only be taking length measurements of the system.

1. Consider a complete flow system with the ½" pipe. The starting point of this experiment is the suction port, which is at the bottom of tank T-02. The ending point is the discharge port, which is where the water from the system comes out into either tank T-01 or T-02.
2. Inspect carefully the system and make a table of:
   a. Total length of straight pipe (length to the nearest ¼ inch.)
   b. Total number of valves: ball, three-way, needle, etc.
   c. Total number of elbows, tees, expansions, etc.
   d. Total number of miscellaneous: rotameter, orifice, etc.
3. Make sure that everything in the system is accounted for within your table. This will ensure proper results.

Hints on making precise measurements:

- When measuring the length of straight pipe that is connected to an elbow or tee, the measurement should start from where the straight pipe begins that is reset into the elbow or tee itself. By visual inspection, you will be able to see where to begin your measurement. Refer to Figures 1 and 2 for an example. The bold black arrows indicate the starting point.

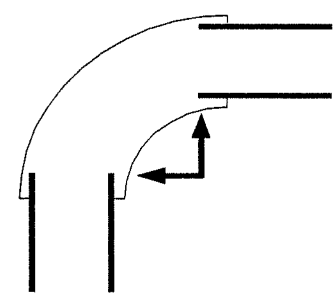


Figure 1: Elbow connected to straight tubing

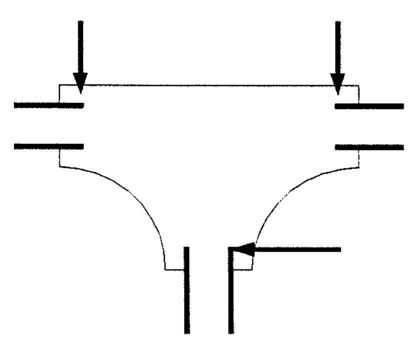


Figure 2. Tee connected to straight tubing

- When measuring the length of straight pipe that is connected to an expansion, contraction or valve, the measurement should begin after the weld joint which fastens the pieces together. Refer to Figure 3 for clarification. The bold black arrow indicates the starting point.

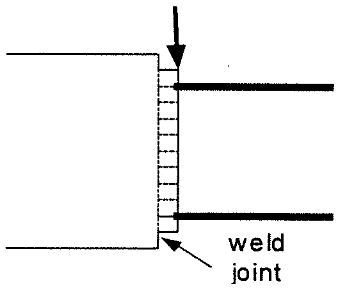


Figure 3: Expansion fitting connected to straight tubing

Calculations, Plots, & Report

1. Compute the total number of velocity heads from the gathered information.
2. Develop the system curve on the pump characteristic curve, which is provided in your lecture notes.
3. Discuss the required pump discharge head as a function of pumping rate. In other words, find the operating point.

Table 1. An example of data collection

Discharge line					Suction line		
	No.	k	Source	Total	No.	k	Total
Expansion							
Contract							
Elbow							
Tee a							
Tee b							
Union							
Ball valve							
Cont valve							
Rotameter							
elbow							
Orifice							
3 W valve							

Revised: August 14, 2002

Transport Laboratory

CM3215 Lecture 10

Heat Transfer Coefficient for the HE

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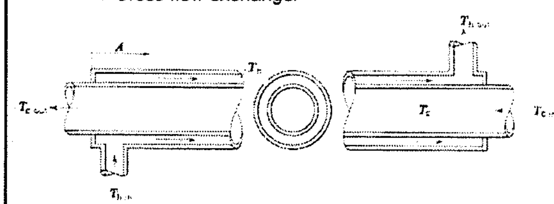
Heat exchangers

- A device that facilitates the transfer of heat between two fluids.
- Double pipe heat exchanger
- Shell-and-tube exchanger
- Cross-flow exchanger



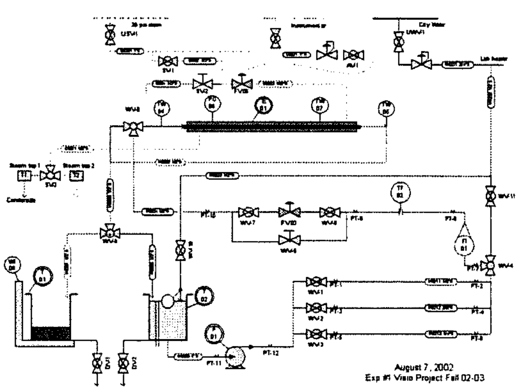
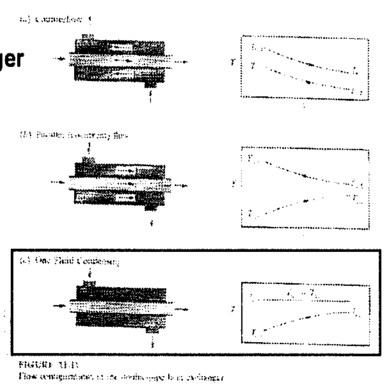


Figure 2. Transport Lab P&ID Visio Printout

Double-pipe heat exchanger



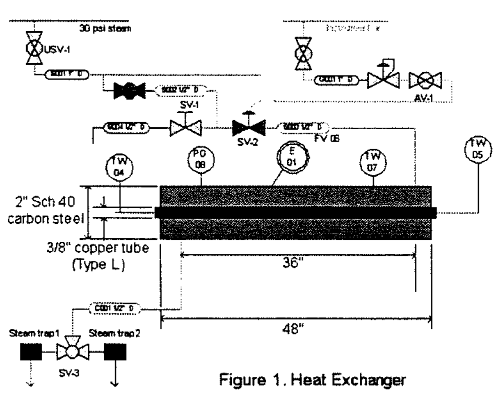
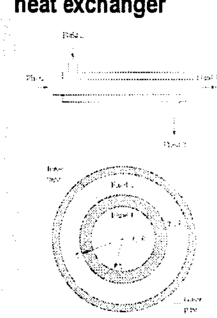


Figure 1. Heat Exchanger

Double-pipe heat exchanger



- Basic design equation

$$Q = UA\Delta T_{LM}$$

where

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)}$$

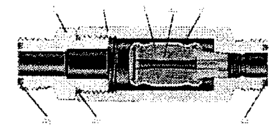
Q: heat transfer rate; U: overall heat transfer coefficient; ΔT_{LM}: log mean temperature difference

- The amount of heat added or removed:

$$Q = wC_p\Delta T$$

Lab experiment

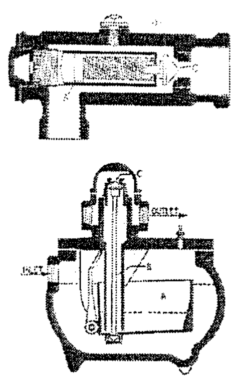
- What we need to know: Q, A, and ΔT_{lm}
  - Q: w, C_p, and ΔT of water
  - Q: steam condensate rate
  - A: HE length: Shell size: Tube size:
  - ΔT_{lm}: steam temperature and water temperature of input and output streams
- Operate the heat exchanger at:
- 20% rotameter
  - 1. With 15 psig pneumatic signal to the steam control valve
  - 2. With 9 psig pneumatic signal



Materials of Construction

Component	Material/ASME Specification
Body	316 stainless steel/ASME SA-479
Adapter	
Modulator assembly	expansion medium: hydrocarbon wax; bonded modulator: fluorocarbon FKM: brass 360/ASME B-16; outer casing: brass 260/ ASME B-36
O-rings	VCO® face seal fitting: 70 durometer fluorocarbon FKM; body to adapter: 90 durometer fluorocarbon FKM

- **Figure 5. Steam traps**
  - **Expansion** type
    A: cartridge,
    B: corrugated tube,
    C: valve
  - **Variable orifice** type
  - **Bucket** type
    A: bucket,
    B: valve rod,
    C: discharge valve
  - **Inverted bucket** type

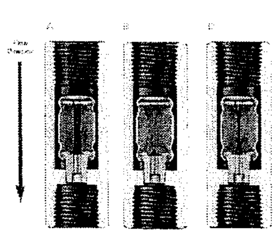


Condensate Capacity

- Start-up removal: 1000 lb/h (454 kg/h) maximum.
- Full 200 lb/hr condensate removal rate at body operating temperature of:
  - 220°F (104°C) for -M1 ordering number
  - → 180°F (82°C) for -M2 ordering number.
- Condensate removal rate decreases with increase in body temperature.

Swagelok

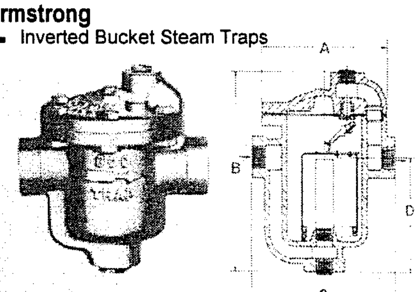
- Automatic **variable orifice type:** Temperature sensitive hydrocarbon wax responds to the temperature of condensate and steam to open and close the trap.



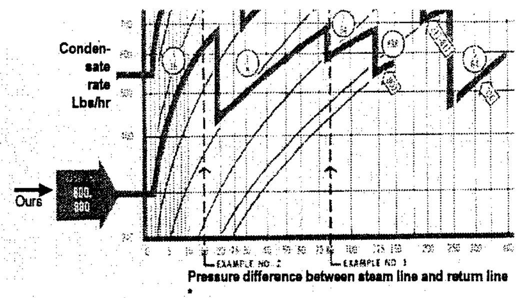
- Figure 6. Automatic variable orifice steam trap: A: Initial opening (wide open); B: closes with live steam; C: open to allow the condensate to flow.

Armstrong

- Inverted Bucket Steam Traps

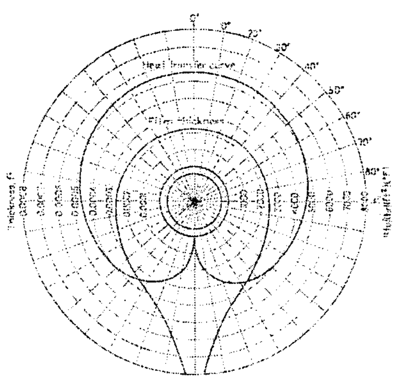


- Figure 7. Bertsch Co. 108 Catalog, Grand Rapids, MI, p. 204 A: 3-3/4"; B: 5"; C: 5"; D: 2-3/4"



- Figure 8. Steam trap capacity. Bertsch Co. 108 Catalog, Grand Rapids, MI, p. 205

- Figure . Plot of the HTC and film thickness of water on a horizontal tube. [Kern Proc Heat Tr p. 264]



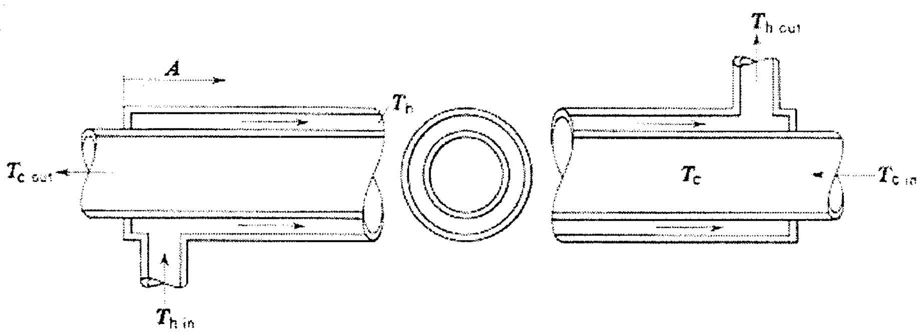
Typical overall heat transfer coefficients (HTC)

Heat-Exchanger Duty	U ($W/m^2 \cdot K$)
Water-to-water	800–2000
Water-to-oil	100–350
Water-to-fuel	200–1000
Water-to-heat-transfer liquids	650–1500
Steam condenser	1000–6000
Refrigerant condenser	300–1000
Water-to-gas	40–75
Steam-to-gas	20–300
Gas-to-gas	10–40

- Hagen, Heat Transfer with Applications, Prentice Hall, p. 392.

Heat exchangers

- A device that facilitates the transfer of heat between two fluids.
- ✶ Double pipe heat exchanger
- ✷ Shell-and-tube exchanger
- ✸ Cross-flow exchanger



Double-pipe heat exchanger

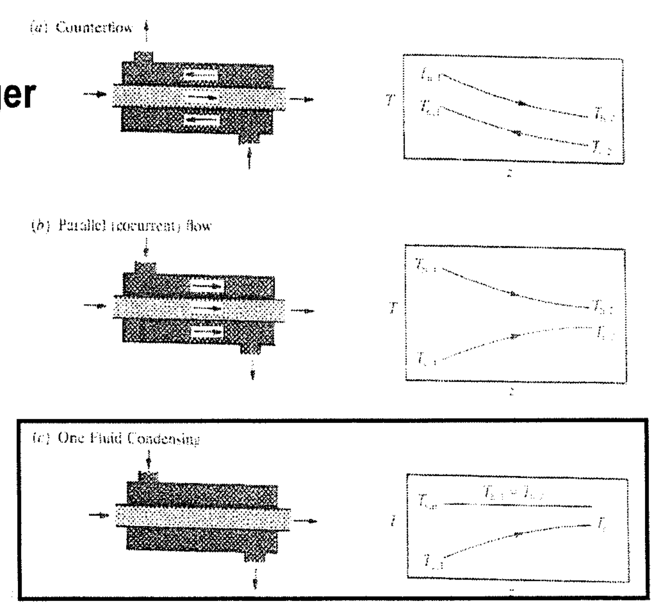
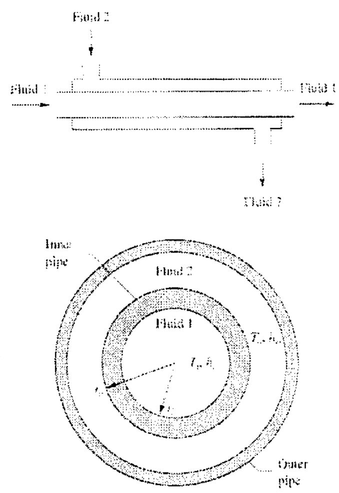


FIGURE 11.11
Flow configurations in the double-pipe heat exchanger.

Double-pipe heat exchanger



- Basic design equation

$$Q = UA\Delta T_{LM}$$

where

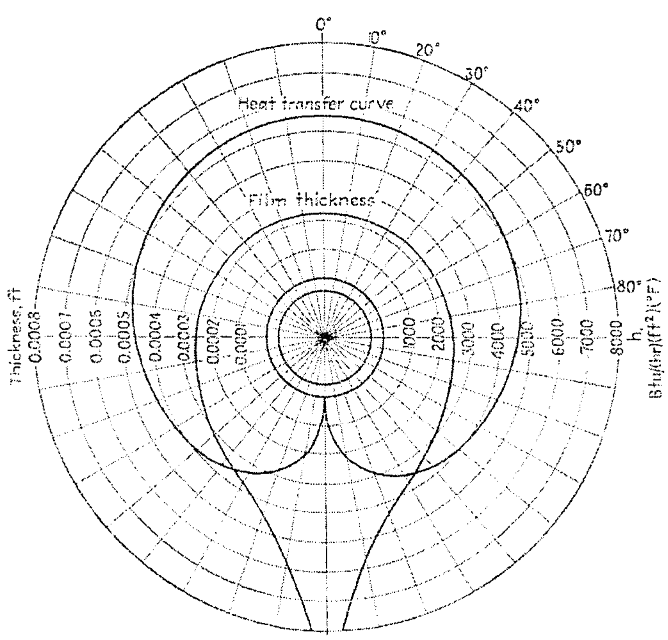
$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)}$$

Q: heat transfer rate; U: overall heat transfer coefficient; ΔT_{LM}: log mean temperature difference

- The amount of heat added or removed:

$$Q = wC_p\Delta T$$

- Figure . Plot of the HTC and film thickness of water on a horizontal tube. [Kern Proc Heat Tr p. 264]



Experiment 10. Heat Transfer Coefficient for Heat Exchanger

Pre-laboratory Assignment
Review the following concepts
1. Heat transfer by conduction, convection and radiation
2. Double pipe heat exchanger
3. Overall heat transfer coefficient and Logarithmic Mean Temperature Difference (LMTD)
4. Steam traps

Introduction
Heat transfer is on of the most common unit operations in chemical process industries. Most unit operation and processes like distillation, evaporation and reactions involve heat transfer. Typically a process plant consumes tons of fuel (including steam). Owing to the raising fuel costs and environmental considerations, it is important to utilize available heat in a very efficient manner. Also, temperature control is essential in exothermic reactions, to prevent run away conditions. Hence, heat transfer calculations involved become crucial. In this lab, you will be studying a simple device called a heat exchanger, which is commonly used for heat transfer.

Theory: Lecture

Safety Instructions
Always wear insulated gloves when adjusting the steam valve, when touching uninsulated piping or handling condensate!

Experimental Procedure
Examine the heat exchanger set up and identify the following items:
Steam valve, steam trap, thermocouple wells (for steam, cold water inlet and hot water outlet). A brief description about these items is given in the appendix.

Setup water flow through the heat exchanger by following the steps below:

1. Set up water flow through the ½" pipe.
2. Direct water flow to the heat exchanger using WV-8.
3. Open the main steam valve SV-1.
4. Using insulated gloves, open SV-2 slowly to drain all of the line condensate into the Styrofoam bucket. Close the valve when steam begins to come out. Dispose of the condensate only in the floor drain.
5. Open main air valve AV-1. Set the instrument air pressure to 15 psi by using the pressure regulator. Make sure that the control valve (FV-06) is wide open. The stem positioner should point to 1.0 (wide open)
6. Set up temperature readings by placing thermocouple wires into the thermo wells TW-04, TW-05 and TW-07.
7. Fix the water flow rate to 20 % on FI-01 by using the needle valve WV-5.
8. Direct the water flow rate to T-01 using WV-9.
9. Make sure DV-1 is open.
10. Allow the system to go to steady state. Note the temperatures of the inlet and outlet water using the thermocouple. **CAUTION:** The outlet water temperature should not exceed 120°F (50°C).
11. Use the rotameter calibration curve to determine the mass flow rate of the water.
12. Note the steam temperature and measure the length of the heat exchanger.
13. Collect the condensate for at least 5 minutes and measure its flow rate by the pail and scale method.
14. Repeat steps 1-13 for different rotameter readings: 30, ____, ____.
15. Repeat steps 1-13 with a different value of the steam rate by adjusting the instrument air pressure to 12 psi (or 10 psi).

Shut Down Procedure

(6) Close the regulator to the steam valve
(7) Close main steam valve SV-1
(8) Allow the cold water to cool the heat exchanger for 3 minutes
(9) Turn off pump P-01
(10) Close main water valve WV-10
(11) Drain all tanks

Calculations, Plots, and Report

Calculate the average velocity, Reynolds number and overall heat transfer coefficient U for each flow rate. Plot U as a function of flow rate and Reynolds number. State your observations.

Table 1. An example of values to be reported

15 psig* 20 %**	A: Area	m2		ft2	
	ΔT: log m	C		ft2	
	Q: HT rate	KJ/s		BTU/h	
	U	KJ/m2Cs		BTU/ft2Fh	
		W/m2C			
12 psig %	A: Area	m2		ft2	
	ΔT: log m	C		ft2	
	Q: HT rate	KJ/s		BTU/h	
	U	KJ/m2Cs		BTU/ft2Fh	
		W/m2C			

* 15 psi: Instrument air pressure to steam flow control valve (FV-06)
** 20 %: Rotameter reading

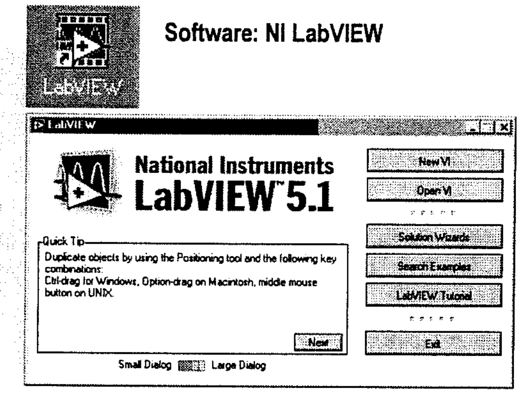
Transport Laboratory

CM3215 Lecture 11

System Identification of TC Dynamics

Nam K. Kim
Chemical Engineering
Michigan Technological University

Software: NI LabVIEW



☺What we will do this week.

Thermocouples reading (dynamic)

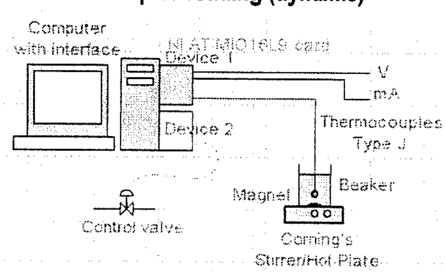
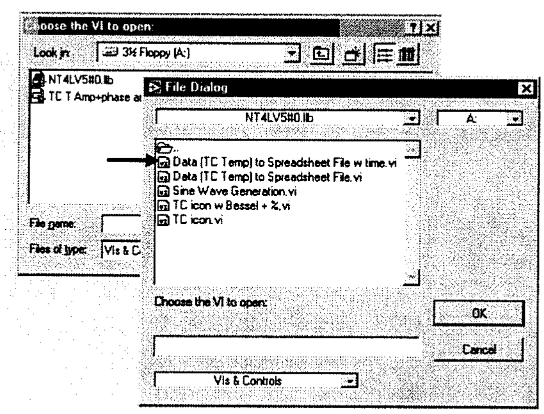
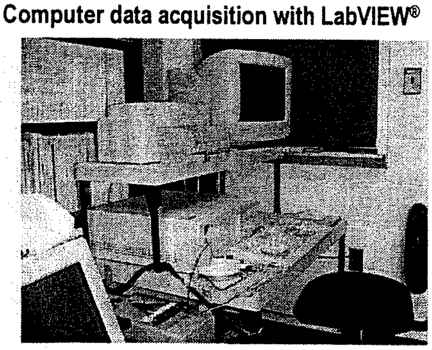
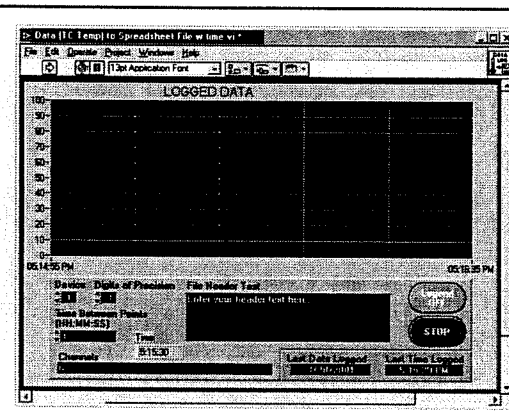


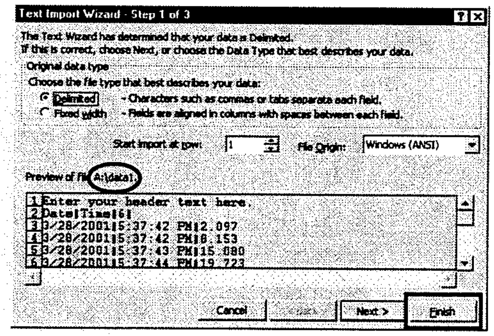
Figure 1. Data acquisition with computer interface



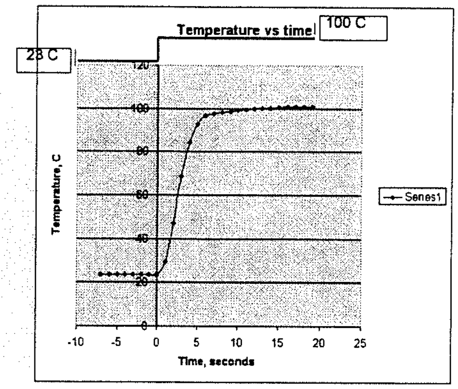
Computer data acquisition with LabVIEW®

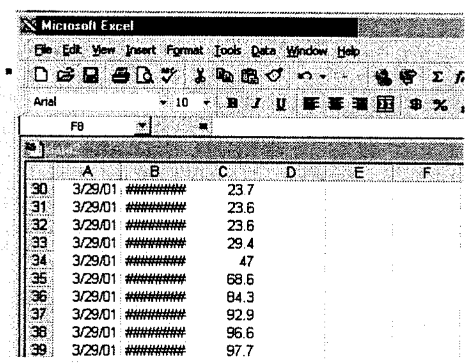






- Data retrieval to Excel spreadsheet



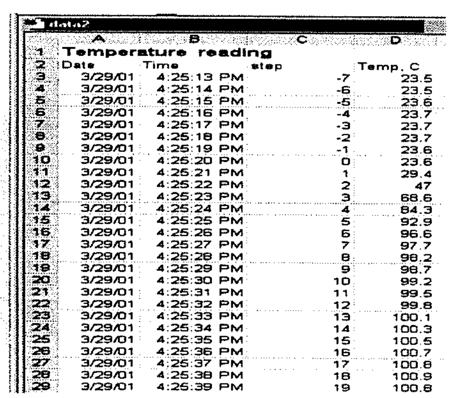


	A	B	C	D	E	F
30	3/29/01	########	23.7			
31	3/29/01	########	23.6			
32	3/29/01	########	23.6			
33	3/29/01	########	29.4			
34	3/29/01	########	47			
35	3/29/01	########	68.6			
36	3/29/01	########	84.3			
37	3/29/01	########	92.9			
38	3/29/01	########	96.6			
39	3/29/01	########	97.7			

- Adjust the column width for B

Dynamic response to the step change

- Operation
- ✱ Set the water bath temperature to 60 - 90 C.
  - ✱ Make a step change in the forcing function from room temperature to 60 - 90 C.
  - ✱ Record the TC temperature every minute.
- ✱ Derive a mathematical model to describe its dynamic behavior.
- ✱ Compare the simulated data against the experimental data.



	A	B	C	D
1	Temperature reading			
2	Date	Time	step	Temp, C
3	3/29/01	4:25:13 PM	-7	23.5
4	3/29/01	4:25:14 PM	-6	23.5
5	3/29/01	4:25:15 PM	-5	23.6
6	3/29/01	4:25:16 PM	-4	23.7
7	3/29/01	4:25:17 PM	-3	23.7
8	3/29/01	4:25:18 PM	-2	23.7
9	3/29/01	4:25:19 PM	-1	23.6
10	3/29/01	4:25:20 PM	0	23.6
11	3/29/01	4:25:21 PM	1	29.4
12	3/29/01	4:25:22 PM	2	47
13	3/29/01	4:25:23 PM	3	68.6
14	3/29/01	4:25:24 PM	4	84.3
15	3/29/01	4:25:25 PM	5	92.9
16	3/29/01	4:25:26 PM	6	96.6
17	3/29/01	4:25:27 PM	7	97.7
18	3/29/01	4:25:28 PM	8	98.2
19	3/29/01	4:25:29 PM	9	98.7
20	3/29/01	4:25:30 PM	10	99.2
21	3/29/01	4:25:31 PM	11	99.5
22	3/29/01	4:25:32 PM	12	99.8
23	3/29/01	4:25:33 PM	13	100.1
24	3/29/01	4:25:34 PM	14	100.3
25	3/29/01	4:25:35 PM	15	100.5
26	3/29/01	4:25:36 PM	16	100.7
27	3/29/01	4:25:37 PM	17	100.8
28	3/29/01	4:25:38 PM	18	100.9
29	3/29/01	4:25:39 PM	19	100.8

✱ **Data collection**

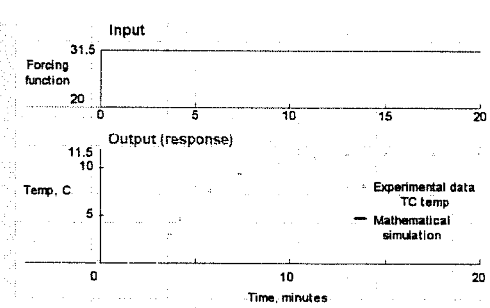


Figure 1. Dynamic response to the step change

✱ **Mathematical modeling** and **simulation.**

* Energy balance

$$A = I + G - O - C \pm Q$$

$$A = \frac{dH}{dt}$$

A: accumulation; **I**: input; **G**: generation; **O**: output; **C**: consumption; Q: heat +: heat added; -: heat removed

* Applied to the TC (thermocouples)

$$\frac{d(V\rho C_p)}{dt} = 0 + 0 - 0 - 0 + Q$$

$$Q = UA\Delta T = h_c A(T_w - T)$$

Inverse transform

$$T(t) = 77\left(1 - e^{-\frac{1}{\tau_p}t}\right)$$

Equation with dead time

$$T(t) = 77\left(1 - e^{-\frac{1}{\tau_p}(t-t_d)}\right)u(t - t_d)$$

$$\frac{V\rho C_p}{h_c A}\frac{dT}{dt} + T = T_w$$

$$\tau_p \frac{dT}{dt} + T = T_w \quad \text{where} \quad \tau_p = \frac{V\rho C_p}{h_c A}$$

* Taking Laplace Transform

$$\tau_p s\bar{T}(s) + \bar{T}(s) = \bar{T}_w(s)$$

$$\bar{T}(s)(\tau_p s + 1) = \bar{T}_w(s)$$

$$\bar{T}(s) = \frac{1}{\tau_p s + 1}\bar{T}_w(s)$$

$\frac{1}{\tau_p s + 1}$: Transfer function

$\bar{T}_w(s)$: Forcing function

---

* **Parameter estimation** from the experimental data

T_d: dead time; τ_p: Process time constant; Compute τ_p: 11.5*0.6321=7.27 --> 1 τ_p

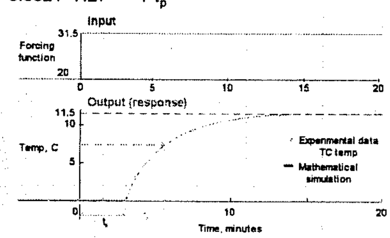


Figure 1. Dynamic response to the step change

---

* The forcing function takes a step change

$$\bar{T}(s) = \frac{1}{(\tau_p s + 1)}\frac{77}{s} = 77\left(\frac{1}{(\tau_p s + 1)}\frac{1}{s}\right)$$

$$\bar{T}(s) = 77\left(\frac{c_1}{s} + \frac{c_2}{\tau_p s + 1}\right) \quad \text{where}$$

$$c_1 = \left[\frac{1}{\tau_p s + 1}\right]_{s=0} = 1$$

$$c_2 = \left[\frac{1}{s}\right]_{s=-\frac{1}{\tau_p}} = -\tau_p$$

$$\bar{T}(s) = 77\left(1 - \frac{\tau_p}{\tau_p s + 1}\right) = 77\left(1 - \frac{1}{s + \frac{1}{\tau_p}}\right)$$

Process parameters: K_p, τ_p, t_d

* **Simulate** the response in TC temperature.
* Plot both data on the same figure.

$$\frac{V\rho C_p}{h_c A}\frac{dT}{dt} + T = T_w$$

$$\tau_p \frac{dT}{dt} + T = T_w \qquad \text{where} \qquad \tau_p = \frac{V\rho C_p}{h_c A}$$

- Taking Laplace Transform

$$\tau_p s\overline{T}(s) + \overline{T}(s) = \overline{T}_w(s)$$

$$\overline{T}(s)(\tau_p s + 1) = \overline{T}_w(s)$$

$$\overline{T}(s) = \frac{1}{\tau_p s + 1}\overline{T}_w(s)$$

$\frac{1}{\tau_p s + 1}$: Transfer function

$\overline{T}_w(s)$: Forcing function

- The forcing function takes a step change

$$\overline{T}(s) = \frac{1}{(\tau_p s + 1)}\frac{77}{s} = 77\left(\frac{1}{(\tau_p s + 1)}\frac{1}{s}\right)$$

$$\overline{T}(s) = 77\left(\frac{c_1}{s} + \frac{c_2}{\tau_p s + 1}\right) \qquad \textit{where}$$

$$c_1 = \left[\frac{1}{\tau_p s + 1}\right]_{s=0} = 1$$

$$c_2 = \left[\frac{1}{s}\right]_{s=-\frac{1}{\tau_p}} = -\tau_p$$

$$\overline{T}(s) = 77\left(1 - \frac{\tau_p}{\tau_p s + 1}\right) = 77\left(1 - \frac{1}{s + \frac{1}{\tau_p}}\right)$$

- Inverse transform

$$T(t) = 77\left(1 - e^{-\frac{1}{\tau_p}t}\right)$$

Equation with dead time

$$T(t) = 77\left(1 - e^{-\frac{1}{\tau_p}(t-t_d)}\right)u(t-t_d)$$

- **Parameter estimation** from the experimental data
  T_d: dead time; τ_p: Process time constant; Compute τ_p: 11.5*0.6321=7.27 --> 1 τ_p

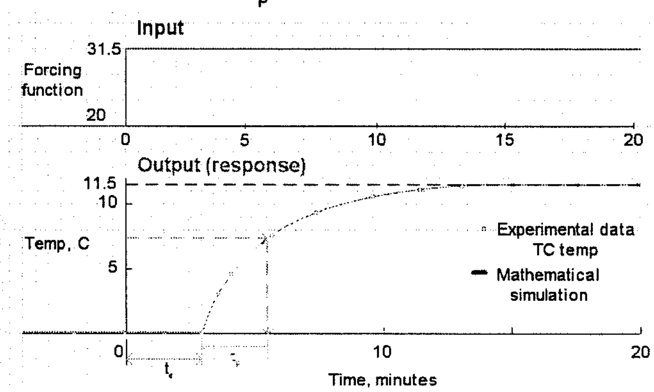


Figure 1. Dynamic response to the step change

Experiment 11. System Identification of Thermocouple Dynamics

Objective

1. Derive the mathematical model for the dynamic behavior of a thermocouple (TC) by disturbing the forcing function.
2. Collect the experimental dynamic response of the TC output temperature to the step change in the forcing function.
3. Compare the experimental results with the simulation. Plot them on the same figure.

Simulation

Derive the working equation from the mathematical model.

$$T(t) = K_p\left(1 - e^{-\frac{1}{\tau_p}t}\right)$$

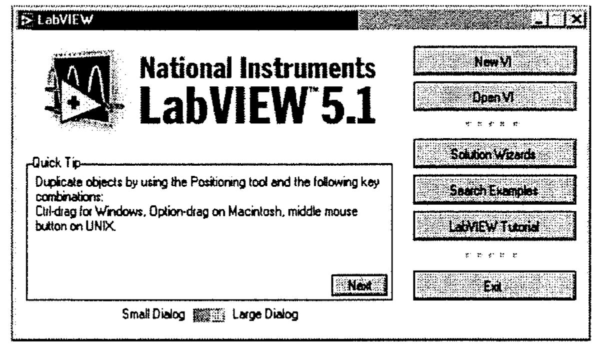
Identify the τ_p and K_p (also t_d). The process is also known as "System Identification." Plot temperature T as a function of time t.

Theory: Lecture

Experimental procedure

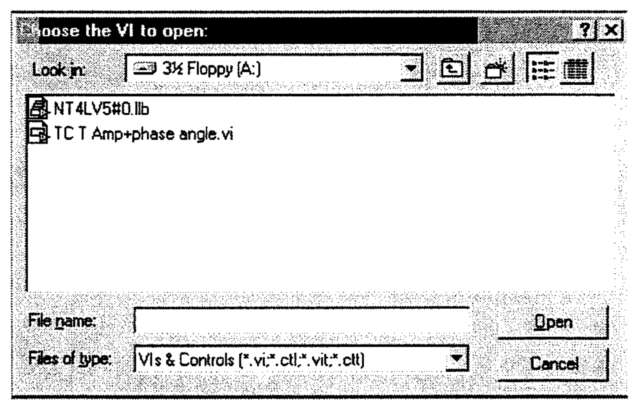
Start up

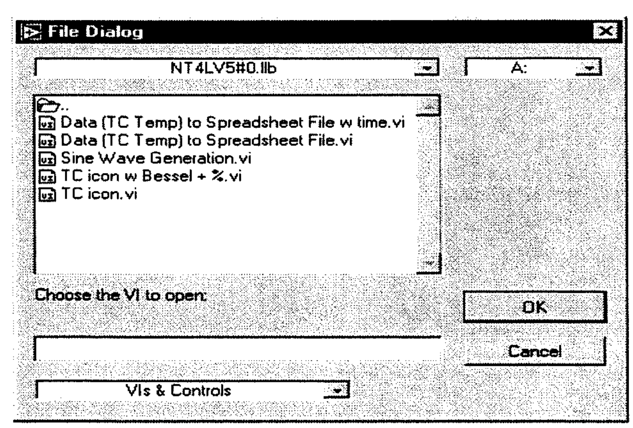
1. Fill the clean 250 ml beaker with 200 ml of distilled water. Place the beaker with a stirring magnet in it on the top center of Corning's Stirrer/Hot Plate (SHP).
2. Power up the SHP. Set the temperature to approximately 80 C, while gently stirring.
3. Boot up the computer station #6. The main switch is under the front center.
4. Password: just hit the enter key
5. Windows NT version 4.0 will appear. Select the "Shortcut to labview" icon by double-clicking on it.



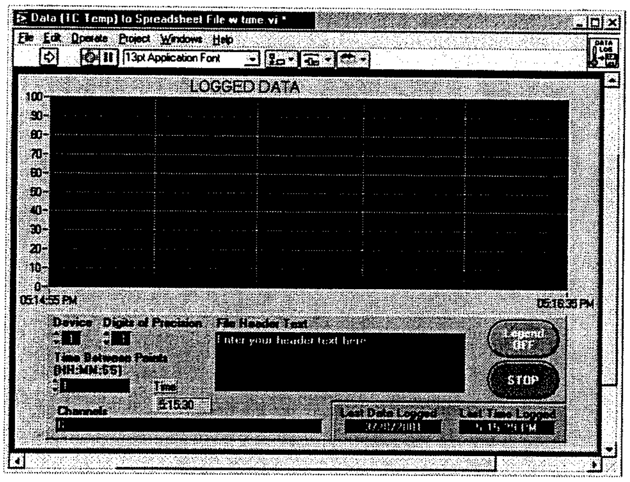
6. LabVIEW 5.1 will appear. Click on "Open VI". "Choose the VI to open" screen will appear

(12) Set the search path to the 3-1/2" Floppy [A:\]. Double-click on "NT4LV5#0" and choose "Data (TC Temp) to Spreadsheet file with time.vi"





(13) "Data (TC Temp) to Spreadsheet file w Time.vi" will appear as below.



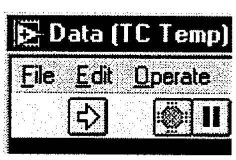
(14) Be sure that the digits of precision is set to 1. One digit beyond decimal point is sufficient.

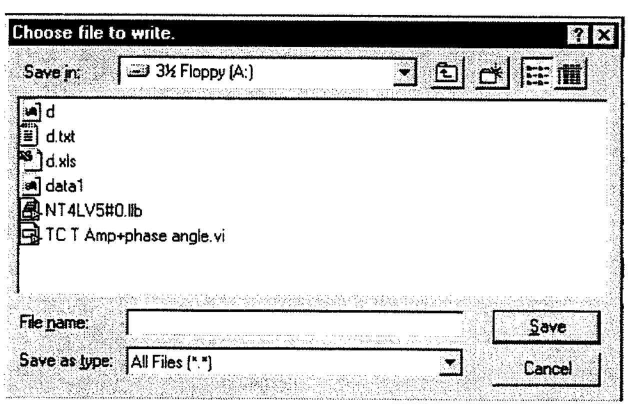
(15) Set "Time between points" to 1. This means that the sampling frequency is one point per second.

(16) Make sure that the Channel is 6. This means that the thermocouples are connected to the No. 6 channel.

(17) File header text: Type "<u>TC Reading</u>" for "Enter your header text here".

(18) To start click on the "Arrow" pointing to the right.





(19) Make sure you save your data in your disk in A:. Select a name for he file such as "data1".

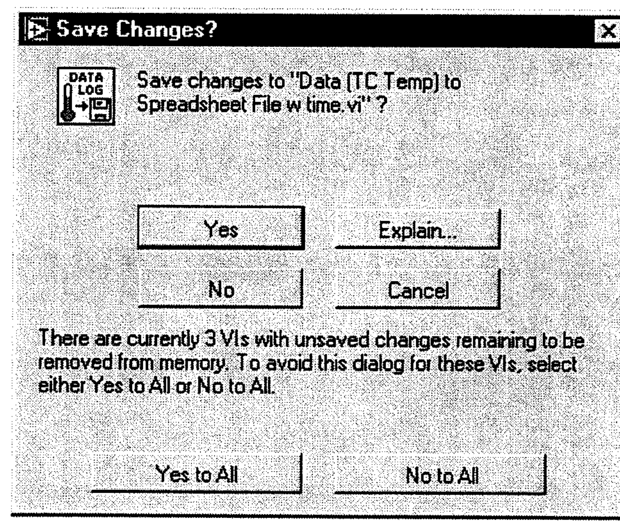
(20) Program will run saving a thermocouple temperature value every second in spreadsheet format under "data1" file name.

(21) Once steady state is observed, insert the thermocouple tip into the hot water in the beaker. Important: make sure that you read the time of insertion and make note of it.

Shutdown

(22) Go to "Start" and "Shutdown". Select "Close all programs and log on as a different user?", unless you are the last group. The last group will select "Shutdown the computer" and click "Yes".

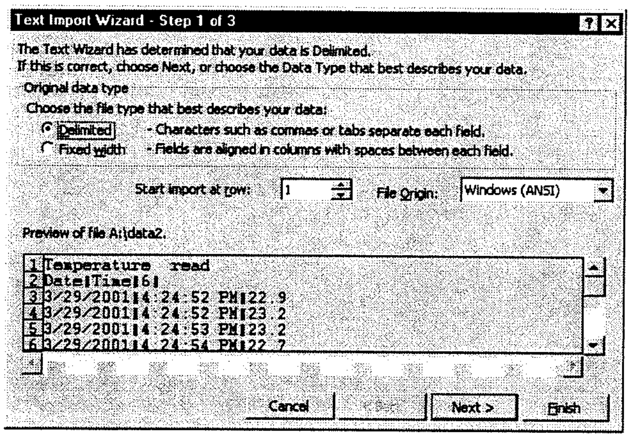
(23) If a screen appears as below during the shutdown,



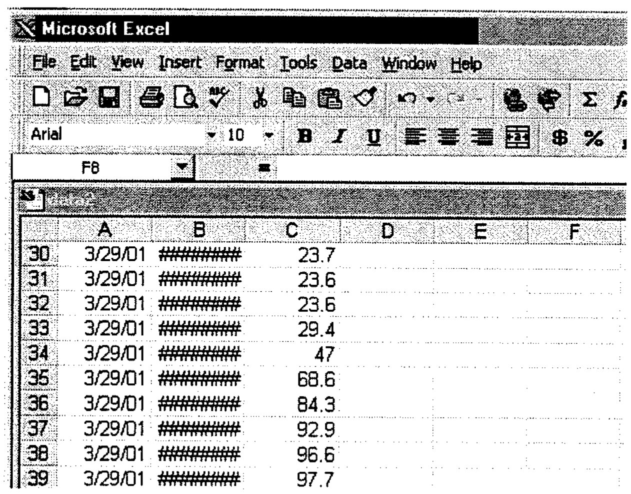
(24) Select "**No to all**".

Excel

20. Go to "File" and "Open". Choose "A:" and select "data1".

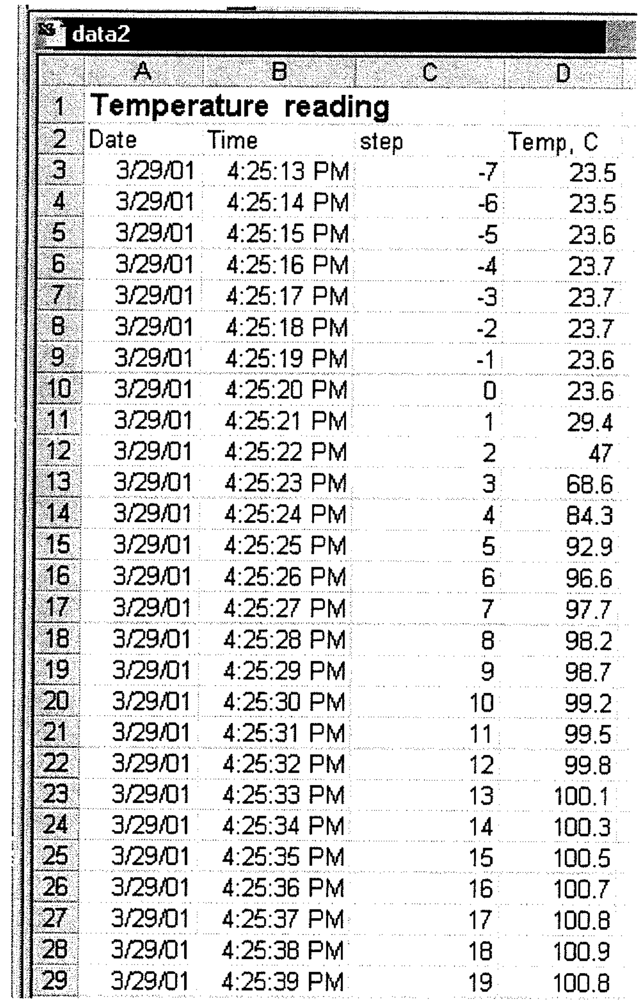


21. Click on “Finish”.



	A	B	C	D	E	F
30	3/29/01	########	23.7			
31	3/29/01	########	23.6			
32	3/29/01	########	23.6			
33	3/29/01	########	29.4			
34	3/29/01	########	47			
35	3/29/01	########	68.6			
36	3/29/01	########	84.3			
37	3/29/01	########	92.9			
38	3/29/01	########	96.6			
39	3/29/01	########	97.7			

22. Adjust the B column width to see data as shown below.



	A	B	C	D
1	**Temperature reading**			
2	Date	Time	step	Temp, C
3	3/29/01	4:25:13 PM	-7	23.5
4	3/29/01	4:25:14 PM	-6	23.5
5	3/29/01	4:25:15 PM	-5	23.6
6	3/29/01	4:25:16 PM	-4	23.7
7	3/29/01	4:25:17 PM	-3	23.7
8	3/29/01	4:25:18 PM	-2	23.7
9	3/29/01	4:25:19 PM	-1	23.6
10	3/29/01	4:25:20 PM	0	23.6
11	3/29/01	4:25:21 PM	1	29.4
12	3/29/01	4:25:22 PM	2	47
13	3/29/01	4:25:23 PM	3	68.6
14	3/29/01	4:25:24 PM	4	84.3
15	3/29/01	4:25:25 PM	5	92.9
16	3/29/01	4:25:26 PM	6	96.6
17	3/29/01	4:25:27 PM	7	97.7
18	3/29/01	4:25:28 PM	8	98.2
19	3/29/01	4:25:29 PM	9	98.7
20	3/29/01	4:25:30 PM	10	99.2
21	3/29/01	4:25:31 PM	11	99.5
22	3/29/01	4:25:32 PM	12	99.8
23	3/29/01	4:25:33 PM	13	100.1
24	3/29/01	4:25:34 PM	14	100.3
25	3/29/01	4:25:35 PM	15	100.5
26	3/29/01	4:25:36 PM	16	100.7
27	3/29/01	4:25:37 PM	17	100.8
28	3/29/01	4:25:38 PM	18	100.9
29	3/29/01	4:25:39 PM	19	100.8

Data analysis and Report

Collect the dynamic temperature data from a thermocouple by suddenly exposing it to a water bath of known temperature using a computer. Plot the data with Excel and identify three process key parameters: K_p, τ_p, and t_d.

Construct a mathematical model with three key parameters and simulate.

Plot simulated temperature along with experimental data.

Summarize what you have learned.

Revised: August 14, 2002

Transport Laboratory

CM3215 Lecture 12

Unsteady-State Heat Transfer to a Solid Ball

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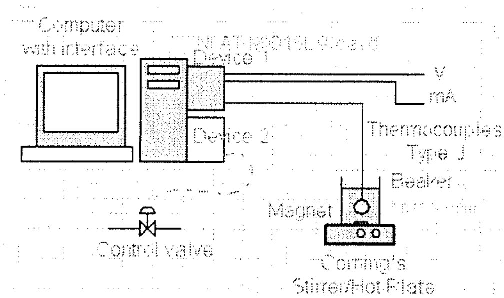


Figure 1. Dynamic temperature response at the center of Nylon ball

Lab Project

- **Lab Exp 13**. Lecture and Lab will concentrate on the computer data acquisition: theory and practice.
- Lab report for this section:
  Propose a new lab experiment
- New Lab Experiment.
  - Title:
  - Objectives
  - Experimental procedure
  - Expected outcome
    Layout: P&ID
    1 full page (font size 12) proposal plus attachments
- **Bring your own disk** to store data (floppy or Zip).

$$\rho C_p\left(\frac{\partial T}{\partial t}+v_r\frac{\partial T}{\partial r}+\frac{v_\theta}{r}\frac{\partial T}{\partial \theta}+\frac{v_\phi}{r\sin\theta}\frac{\partial T}{\partial \phi}\right)=$$
$$k\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial T}{\partial\theta}\right)+\frac{1}{r^2\sin^2\theta}\frac{\partial^2 T}{\partial\phi^2}\right]$$
$$+2\mu\left\{\left(\frac{\partial v_r}{\partial r}\right)^2+\left(\frac{1}{r}\frac{\partial v_\theta}{\partial\theta}+\frac{v_r}{r}\right)^2+\left(\frac{1}{r\sin\theta}\frac{\partial v_\phi}{\partial\phi}+\frac{v_r}{r}+\frac{v_\theta\cot\theta}{r}\right)^2\right\}$$
$$+\mu\left\{\begin{array}{l}\left[r\frac{\partial}{\partial r}\left(\frac{v_\theta}{r}\right)+\frac{1}{r}\frac{\partial v_r}{\partial\theta}\right]^2+\left[\frac{1}{r\sin\theta}\frac{\partial v_r}{\partial\phi}+r\frac{\partial}{\partial r}\left(\frac{v_\phi}{r}\right)\right]^2\\+\left[\frac{\sin\theta}{r}\frac{\partial}{\partial\theta}\left(\frac{v_\phi}{\sin\theta}\right)+\frac{1}{r\sin\theta}\frac{\partial v_r}{\partial\phi}\right]^2\end{array}\right\}$$

- BSL, Transport Phenomena, p. 319.

Heat transfer to a spherical plastic

- A solid sphere of radius **r**
  - which is initially at a uniform temperature T_i
  - for times t>0 the boundary surface at r = b absorb/dissipates heat by convection from/into a medium at temperature T_e with a heat transfer coefficient h
- Mathematical formulation of this problem

$$\frac{1}{k/\rho C_p}\left(\frac{\partial T}{\partial t}\right)=\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)$$

- Let $\theta(r,t)=\frac{T(r,t)-T_e}{T_i-T_e}$
  replacing T with θ

$$\frac{1}{\alpha}\left(\frac{\partial\theta}{\partial t}\right)=\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial\theta}{\partial r}\right)$$ in 0<=r<=b, t>0

where
$\frac{\partial\theta}{\partial r}=0$ at r=0, t>0
$k\frac{\partial\theta}{\partial r}+h\theta=0$ at r=b, t>0
$\theta=1$ for t=0, 0<=r<=b

Various balls in Lab

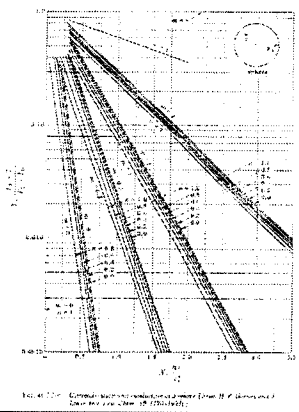
- Information
- Nylon ball (6PA) by Midland Plastics
  - Diameter: (1) 3/4" (2)1"
  - Sp. Gr. = 1.14-1.18
  - Thermal conductivity=0.334 Btu/ftFh
  - Convective HTC, h=100 Btu/ft²Fh
- Steel
- Brass

$$n = \frac{x}{x_1}$$

$$m = \frac{k}{hx_1}$$

$$X = \frac{\alpha t}{x_1^2}$$

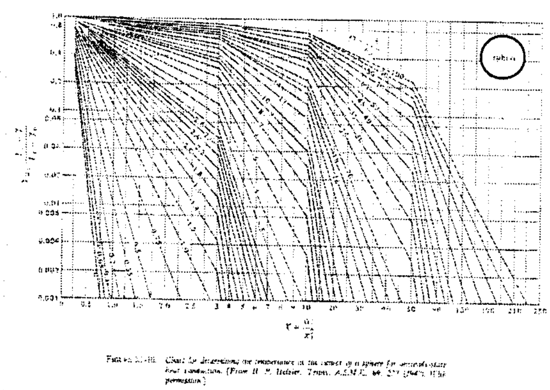
$$\alpha = \frac{k}{\rho C_p}$$



Geankoplis, Ch 5
Example 5.3-3

Example problem

- A Nylon ball (Midland Plastics) with D=1 inch diameter, k=0.334 Btu/ftFh, and α=0.0108 ft²/h is initially at a uniform temperature T_i=77 F. For times t>0, the boundary surface at x=1 inch absorbs heat by convection into the ball from the hot water at temperature T_e=151 F with a heat transfer coefficient of h=100 Btu/ft²Fh. Determine the temperature of the center of the ball at times t = 110 seconds upon immersion. Use transient temperature chart.



Example

$$\theta = \frac{T - T_e}{T_i - T_e} = \frac{140-151}{77-151} = 0.148 \doteq 0.15$$

$$b(radius, ft) = \left(\frac{3}{4}\right)\frac{1}{2}\frac{1}{12} = 0.03125$$

$$\frac{k}{hb} = \frac{0.334}{(100)0.03125} = 0.10688$$

$$\alpha = \frac{k}{\rho C_p} = \frac{0.334}{72(0.43)} = 0.0108$$

$$\frac{\alpha t}{b^2} = 0.32 = \frac{0.0108t}{(0.03125)^2}$$

$$t(h) = 0.0289$$

$$t(s) = 104$$

$$\rho C_p\left(\frac{\partial T}{\partial t}+v_r\frac{\partial T}{\partial r}+\frac{v_\theta}{r}\frac{\partial T}{\partial \theta}+\frac{v_\phi}{r\sin\theta}\frac{\partial T}{\partial \phi}\right)=$$
$$k\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial T}{\partial\theta}\right)+\frac{1}{r^2\sin^2\theta}\frac{\partial^2 T}{\partial\phi^2}\right]$$
$$+2\mu\left\{\left(\frac{\partial v_r}{\partial r}\right)^2+\left(\frac{1}{r}\frac{v_\theta}{\partial\theta}+\frac{v_r}{r}\right)^2+\left(\frac{1}{r\sin\theta}\frac{\partial v_\phi}{\partial\phi}+\frac{v_r}{r}+\frac{v_\theta\cot\theta}{r}\right)^2\right\}$$
$$+\mu\left\{\begin{array}{l}\left[r\frac{\partial}{\partial r}\left(\frac{v_\theta}{r}\right)+\frac{1}{r}\frac{\partial v_r}{\partial\theta}\right]^2+\left[\frac{1}{r\sin\theta}\frac{\partial v_r}{\partial\phi}+r\frac{\partial}{\partial r}\left(\frac{v_\phi}{r}\right)\right]^2\\+\left[\frac{\sin\theta}{r}\frac{\partial}{\partial\theta}\left(\frac{v_\phi}{\sin\theta}\right)+\frac{1}{r\sin\theta}\frac{\partial v_r}{\partial\phi}\right]^2\end{array}\right\}$$

- BSL, Transport Phenomena, p. 319.

$$\frac{1}{\frac{k}{\rho C_p}}\left(\frac{\partial T}{\partial t}\right)=\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)$$

- Let $\theta(r,t)=\dfrac{T(r,t)-T_e}{T_i-T_e}$

  replacing T with θ

$$\frac{1}{\alpha}\left(\frac{\partial\theta}{\partial t}\right)=\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial\theta}{\partial r}\right)\quad \text{in } 0\le r\le b,\ t>0$$

where

$\frac{\partial\theta}{\partial r}=0$ at r=0, t>0

$k\frac{\partial\theta}{\partial r}+h\theta=0$ at r=b, t>0

$\theta=1$ for t=0, 0<=r<=b

$$n = \frac{x}{x_1}$$

$$m = \frac{k}{hx_1}$$

$$X = \frac{\alpha t}{x_1^{\,2}}$$

$$a = \frac{k}{\rho C_p}$$

Geankoplis, Ch 5
Example 5.3-3

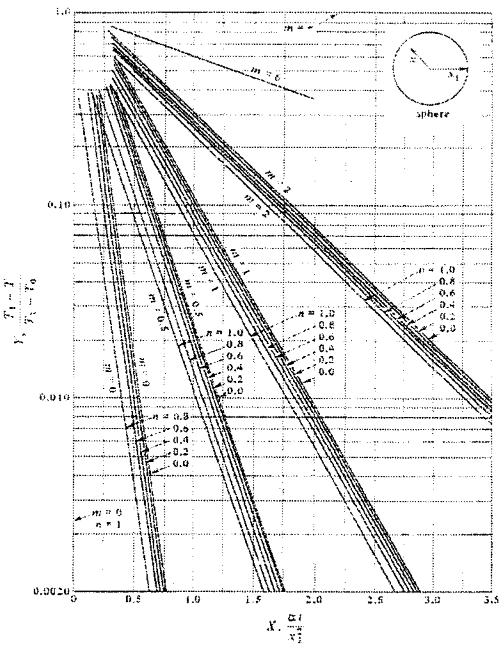


FIGURE 5.3-6. Unsteady-state heat conduction in a sphere. [From H. P. Gurney and J. Lurie, Ind. Eng. Chem., 15, 1170 (1923).]

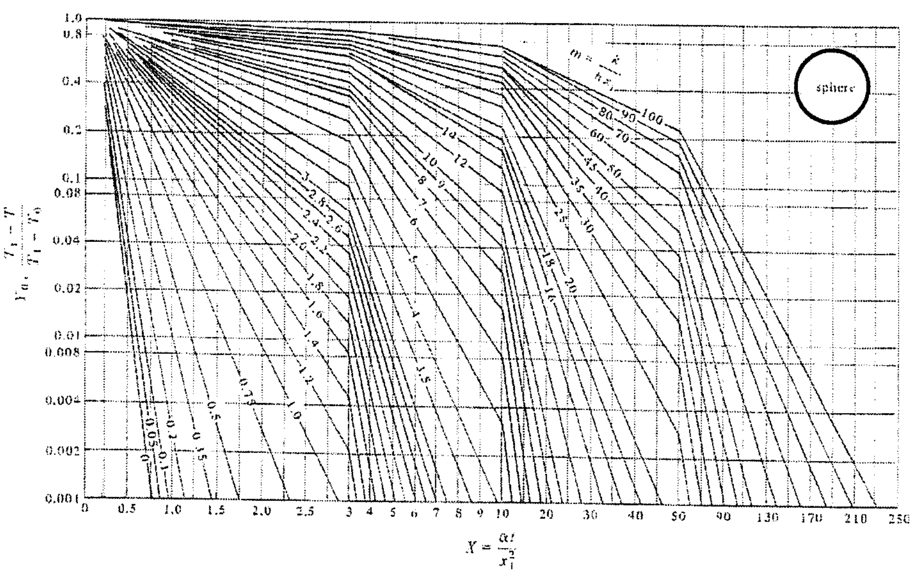


FIGURE 5.3-10. Chart for determining the temperature at the center of a sphere for unsteady-state heat conduction. [From H. P. Heisler, Trans. A.S.M.E., 69, 227 (1947). With permission.]

Experiment 12. Heat transfer of a ball in liquid

Pre-laboratory Assignment
Study Chapter 5, "Principles of Unsteady-State Heat Transfer" (Geankoplis). Know how to used Figure 5.3-10 (G).

Introduction
Figure 4.7 (handout) shows a typical transient-temperature chart for a solid sphere of radius b, which is initially at a uniform temperature T_i. For times t>0 the boundary surface at r=b absorbs heat by convection from the medium at temperature T_e with a heat transfer coefficient h. The mathematical formulation of this problem is:
Governing equation for heat transfer

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial\theta}{\partial r}\right)=\frac{1}{\alpha}\frac{\partial\theta}{\partial t}$$

$$0 \le r \le b, t > 0$$

Boundary and initial conditions

$$\frac{\partial\theta}{\partial r}=0:0\le r\le b,t>0$$

$$k\frac{\partial\theta}{\partial r}+h\theta=0:r=b,t>0$$

$$\theta=1:t=0,0\le r\le b$$

where

$$\theta(r,t)=\frac{T(r,t)-T_e}{T_i-T_e}$$

The attached figure gives the dimensionless center point temperatures for the sphere.

Further Theory: Lecture

Experimental Procedure
Have your computer ready for data acquisition with the same program.
There are three different types of balls (steel, brass, and Nylon) of two different sizes. Choose 1"-Nylon ball for your experiment.
Connect to the proper terminals on the User Termination Board. Use Channels 6/14 or Channels 7/15. Make sure that you connect the positive terminal of the thermocouples to 6 (or 7) and negative terminal to 14 (or 15).
Power up Corning's Stirrer/Hot Plate by setting stirrer to 8 and hot plate to 3. Once the temperature reaches a steady state, be ready to dip a Nylon ball into the hot water to collect a dynamic response of the center temperature.

Check your estimated time required reaching the target temperature against the experimental data.

Important: Notify the instructor to double-check before you execute the acquisition. Make sure you register the time your ball is immersed. This is t=0.
Save the data in your floppy disk. _Bring your own floppy or Zip disks to store the data._

Revised: August 14, 2002

Transport Laboratory

CM3215 Lecture 13

Data Acquisition (and Control) using Digital Computer

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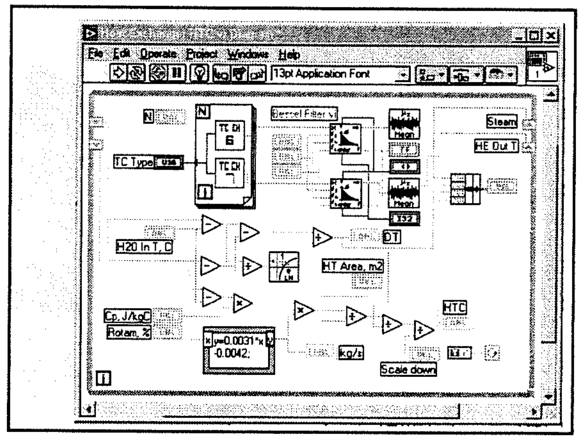
Michigan Technological University



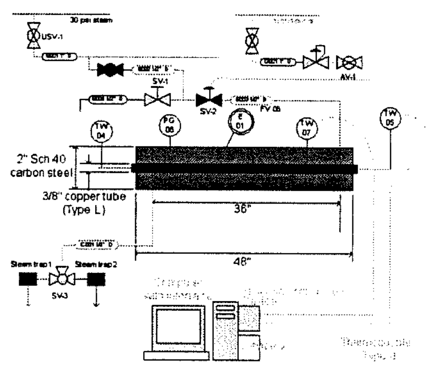
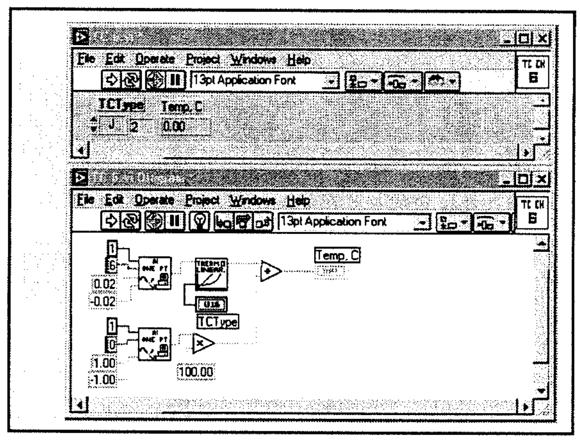
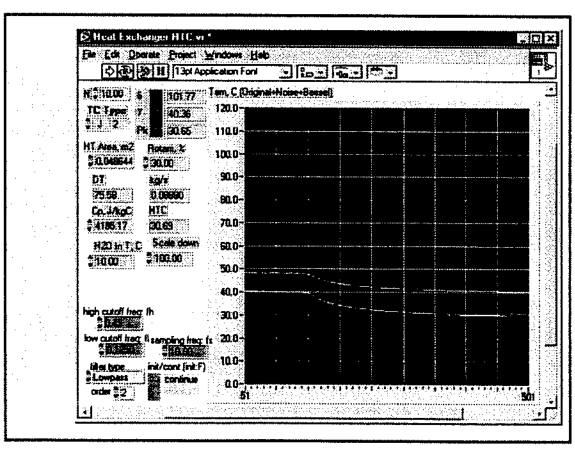
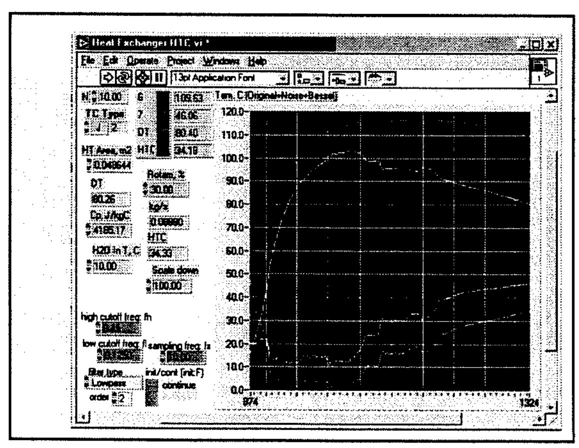
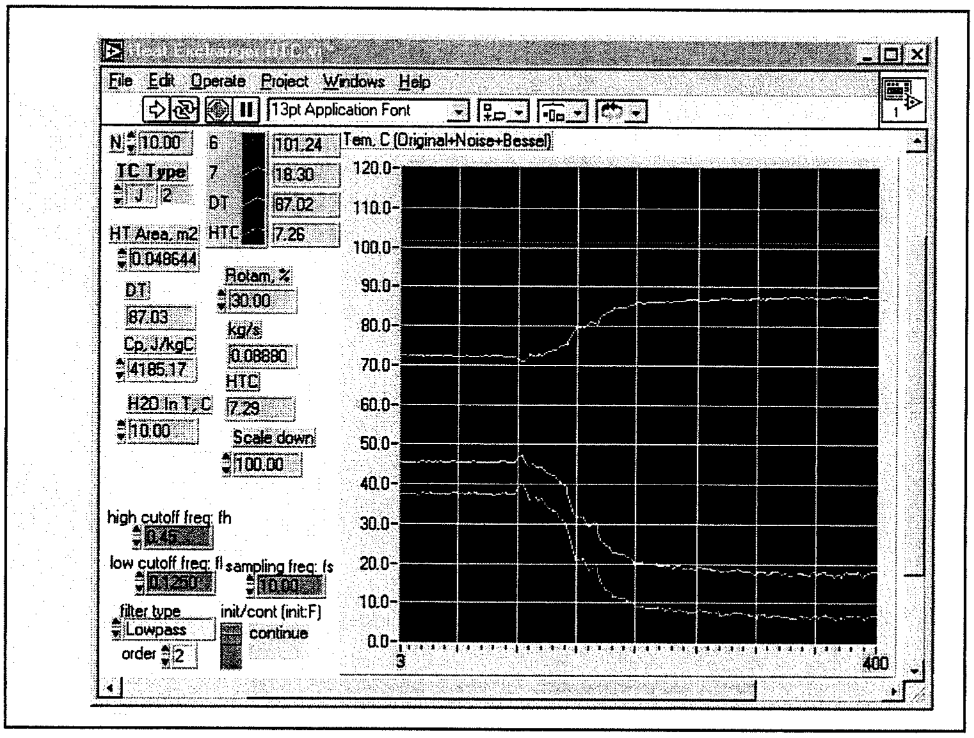


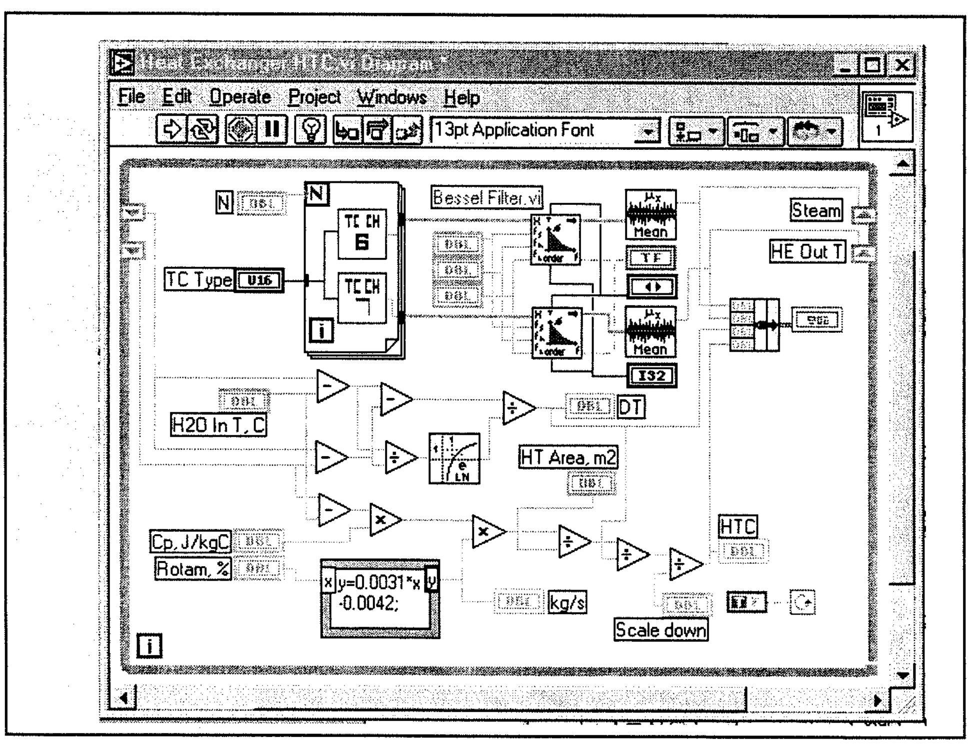
Figure 1. On-line data acquisition








File Edit Operate Project Windows Help
13pt Application Font
N 10.00
TC Type
J 2
HT Area, m2
0.048644
DT
87.03
Cp, J/kgC
4185.17
H20 In T, C
10.00
6 101.24
7 18.30
DT 87.02
HTC 7.26
Rotam, %
30.00
kg/s
0.08880
HTC
7.29
Scale down
100.00
high cutoff freq: fh
0.45
low cutoff freq: fl
0.1250
sampling freq: fs
10.00
filter type
Lowpass
order 2
init/cont (init:F)
continue
Tem. C (Original+Noise+Bessel)
120.0
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
3
400


File Edit Operate Project Windows Help
13pt Application Font
N
TC Type
U16
TC CH 6
TC CH 7
Bessel Filter.vi
Mean
TF
I32
Steam
HE Out T
H20 In T, C
DT
HT Area, m2
Cp, J/kgC
Rotam, %
y=0.0031*x -0.0042;
kg/s
Scale down
HTC

Transport Laboratory

CM3215
Lecture 14

Summary

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Proposed Lab Experiment

- **Lab Exp 13**. Lecture and Lab will concentrate on the computer data acquisition: theory and practice.
- Lab report for this section:
  Propose a new lab experiment
- Proposed Lab Experiment.
  - Title:
  - Objectives
  - Experimental procedure
  - Expected outcome
  - Layout: P&ID
  - 1 full page (font size 12) proposal plus attachments
  - (What you would like to see.)

Review

- **1. Safety.** Preparation of **P&ID** using Visio
- **2. Applied statistics I**
  - Standard normal distribution
  - Hypothesis testing
  - z test and t test
  - Correlation
  - Regression/Multiple regression
- **3. Applied statistics II**
  - Coefficient of determination
  - Chi-square
  - Test for Goodness of Fit
  - Test for Independence
  - F distribution
  - Analysis of variance

- **4. Viscosity**
  Defining equation
  Hagen-Poiseuille equation
- **5. Pressure**
  Bernoulli equation
- **6. Fluid mechanics**
  Reynolds number
- **7. Friction losses**
  Velocity head
- **8. Control valve**
  Characterization
- **9. Pumping system analysis**
  System curve

- **10. Heat transfer coefficient**
  Heat Exchanger
- **11. System identification**
  Dynamic behavior
- **12. Heat transfer to a Nylon ball**
  Unsteady state heat transfer
- **13. Computer data acquisition**
  On-line heat transfer coefficient
- **14. Review**
- **15. Final exam (1 hr in class)**
  Bring a blue notebook