BIRZEIT UNIVERSITY

FACULTY OF ENGINEERING AND TECHNOLOGY

MECHANICAL ENGINEERING DEPARTMENT
AND MECHTRONICS PROGRAM

ENMC 411

Thermal Fluid Application Laboratory

Laboratory Manual

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LAB MANUAL CONTENT

Lab Safety Instructions and Rules
Mechanical and Mechatronics Engineering Department

General Behavior

- Never work in the laboratory alone, always have another qualified person in the area do not use any equipment unless you are trained and approved as a user by your instructor or staff. Ask questions if you are unsure of how to operate something.
- Perform only those experiments authorized by the instructor. Never do anything in the laboratory that is not called for in the laboratory procedures or by your instructor. Carefully follow all instructions, both written and oral. Unauthorized experiments are prohibited.
- Don't eat, drink, or smoke, in the laboratory
- Please don't yell, scream, or make any sudden loud noises that could startle others who are concentrating on their work.
- When you are done with your experiment or project, all components must be dismantled and returned to proper locations.
- When operating high noise machines put on ear protection, those are available in the lab and will be given by the instructor.
- Shoes must completely cover the foot. No sandals are allowed.
- Dress properly during all laboratory activities. Long hair, dangling jewelry, and loose or baggy clothing are a hazard in the laboratory. Long hair must be tied back and dangling jewelry and loose or baggy clothing must be secured.
- Keep aisles clear and maintain unobstructed access to all exits, fire extinguishers, electrical panels, and eyewashes.

First Aid & fire

- First aid equipment is available in the lab, ask your instructor about the nearest kit.
- Fire extinguisher are available in the lab, ask your instructor about the nearest one to your lab.

Poisons

- Certain liquids used in our apparatus, for example refrigerants, manometer fluids, and mercury, are poisonous or can give off poisonous vapors.
- Avoid contact with such liquids, clean up any that is spilled and perform operations such as the filling of manometer in well ventilated conditions.

Electricity

- Do not handle electrical equipment while wearing damp clothing (particularly wet shoes) or while skin surfaces are damp.
- Never bend or kink the power cord on an instrument, as this can crack the insulation, thereby introducing the danger of electrical shocks or burns.
- Know where the stop button, main switch or other device for stopping the apparatus is located

Machines and moving parts

- In order to avoid the possibility of injuries, it is important that the students be aware of their surroundings and pay attention to all instructions.
- Deal with caution with rotating machines, fans pumps compressors, motors etc. don’t touch any of the rotating parts; shafts, or blades.
- Read and understand operation instructions before turning on the machines, do not turn machine till you instructed by the instructor or the technician.

High pressure cylinders

- Deal with caution with high pressure cylinders and systems.
- Turn such cylinders off after finishing the experiment.
- Close LPG cylinders safely after completing your experiment**.**

Hot surfaces and burns

- Do not touch hot surfaces; hot plates boilers, heating elements machines etc.

High flow streams

- When using compressed air, use only approved nozzles and never direct the air towards any person.
- Exercise care when working with or near hydraulically- or pneumatically-driven equipment.

PREPARATION OF LABORATORY REPORTS

I. FORMAL REPORT

The report should be typewritten including graphs and figures by a computer. Use double spacing with 12 fonts. Spell checks your report.

The following sections are to be included in this order:

1. TITLE PAGE

- Course and section Number
- Number and title of the experiment
- Student's name
- Names of group members
- Date the experiment was performed
- Date the report is submitted.

2. ABSTRACT

This is a stand-alone summary of the report. It should include objective, what was done, results and conclusions. It should be clear, informative, concise and short. It should not make any references to the body of the report or to the appendices. An abstract should not exceed one page.

3. OBJECTIVE

The objective of the experiment should be stated on a separate heading OBJECTIVE. State the objective clearly, and make it relevant to the carried experiment

4. THEORY

In this section state and explain any equations or theoretical principles and assumptions that were used in the experiment and the analysis. Define all parameters used. To find this information refer to textbooks, notes etc. Write equations using equation writer in the word processor.

5. EXPERIMENTAL

Give a detailed description of how you accomplished the experiment. This should include equipment used in the experiment as well as how it was used. The description should have sufficient detail so that another experimenter could duplicate your efforts. Name all measured quantities and how they are measured. Use sketches, diagrams, or photos to describe the experimental set-up. Label the main components.

6. CALCULATIONS

Demonstrate how you performed the calculation made in the experiment. Include a detailed sample calculation including used formulas and constants. Show the generic calculations to support all your work. Provide any computer or calculator program listings, along with sample input and output.

7. RESULTS

Summarize your results in an introductory sentence. Relate your results to your objective. Present the results in the easiest way for your reader to understand and how the experiment's hand out requires: Graphs, tables, figures, etc. Spreadsheets are often a good approach. See section on preparation of graphs. All tables and figures must be referenced in the text; use a numbering system for identification of each one and each should have a distinguishable title.

8. DISCUSSION OF RESULTS

Explain the results of the experiment; comment on the shapes of the curves; compare results with expected results; give probable reasons for discrepancies from the theory; answer any questions outlined in the instructions and solve any problems that may have been presented. Tell why things happened, not only that they did happen. Comparisons should include numerical values and corresponding error percentages where relevant. Do not present calculations and formulas in this section. Your calculations should be detailed in the Appendices under SAMPLE CALCULATIONS. Formulas should be discussed in the THEORY section.

9. CONCLUSIONS

State your discoveries, judgments and opinions from the results of this experiment. Summarize your primary results in comparison with theory in two or three sentences. These should answer the objective of the experiment. Make recommendation for further study. Suggest ways to improve the experiment.
Consider that in the real world. Information like that in the RESULTS and CONCLUSIONS will be all that upper management will want to receive.

10. APPENDICES

10.1 DATA TABLES

Data tables are for the convenience of the extremely interested reader. These tables may contain any additional comparisons or calculations that you have prepared and were not included in the RESULTS section which may contain only summaries of your work. Data Tables are the place to show everything that you did.

10.2 RAW DATA SHEETS

Data sheets must be completed in ink and signed by the instructor at the completion of the laboratory period.

In the case of an error, line through the mistake, initial the mistake, and continue. Record the name of the recorder and the group members on the raw data sheets.

11. REFERENCES

List any book or publication that you have referenced in your report. Provide titles, authors, publisher, date of publication, page number, Website addresses etc.
Book reference: Author last name, Author first name. Book's title. Publisher and city of publication, year of publication.
Journal reference: Author last name, Author first name. Paper title, Name of journal, volume, pages, year.
Internet reference: Site location (http://www.) and retrieved date.

II. PREPARATION OF GRAPHS

COORDINATE AXES
Draw the axes of coordinates on the cross- sectioned part of the sheet, far enough in from the margin to leave room for inserting the scales and their identifications between the edges of the cross- sectioning and the axes.

SCALES

Start all linear scales at (0, 0) unless such a procedure would obscure the presentation of data. Of course, this is not possible when using log scales. The units on the major divisions of log scales should be powers of 10. Choose scales of 1, 2, 4, or 5 units per centimeter, or any decimal multiples, such as 0.1, .002 and 400. Proper choice of scales is important.
Guiding principles are:

1. Utilize a good portion of the graph sheet area; do not squeeze curves into one corner.
2. Do not unduly extend the scales. Have the scales readable to the precision of the instruments from which data was taken. Further extension of the scales only scatters the data points, emphasizing the experimental error.
3. Keep in mind the purpose of the graph. Avoid using scales that hide the real meaning or fail to show the intended relationships.
4. Letter in the scale numerals along the axes, putting the abscissa scale beneath the horizontal axis at appropriate intervals. Set all numerals on either axis in a vertical position as viewed from the bottom page.
5. Put major and minor ticks in the axis, use as much as needed to make graph clear and understandable.

SCALE LEGEND

Place legend beneath the abscissa scale so as to be read from the bottom of the page. Place name of the ordinate legend to the left of the ordinate scale so as to be read from the right hand of the page. If more than one ordinate scale is used, place each ordinate legend immediately adjacent to the corresponding scale. Use descriptive titles followed by dimensional units, e.g., Temperature (ºC).

DATA POINTS

Indicate data points by small circles or appropriate geometric symbols, except in the case of correction curves for instruments where the plotted points are not emphasized.

CURVES

With EXCEL Software, draw smooth curves whose positions are governed by the plotted points. The curves should not necessarily pass through every point; you may use trend curves from the EXCEL. Only in the case of perfectly smooth data will all the points lie on the curve. Draw curves with ink or with computer printer and software such as EXCEL.

On the graphs show both the experimental data point and the trend curves or data fitting curves.

When more than one curve is drawn on the same set axes, carefully identify each curve, preferable with a legend lettered immediately adjacent to the curve, or number the curves and provide a table of titles. Data points for the different curves should use different geometric symbols.

INDEPENDENT VERSUS DEPENDENT VARIABLES

Plot the independent variable horizontally along bottom of the graph. Plot the dependent variable vertically. The dependent variable is usually mentioned first, e.g., "PRESSURE VERSUS TEMPERATURE" where pressure is the ordinate. Label axis as normally they appear in literature or books, does not exchange the axis.

III. PEPARATION OF TABLES

Give a number and a title for each table, place them above the table. Give names including units for all columns or rows in the table. Use table forms with white background.

IV. TECHNICAL REPORT

In the technical report include only the following items:

Title page
Abstract
Objectives
Calculations
Results
Discussion of results

Guidelines for Fluid Mechanics Lab Reports

A laboratory report has three main functions:

1. To provide a record of the experiments and raw data included in the report,
2. To provide sufficient information to reproduce or extend the data, and
3. To analyze the data, present conclusions and make recommendations based on the experimental work.

General Comments:
The report should be typewritten including graphs and figures by a computer. Use double-spacing with 12 fonts. Use the spelling and grammar checkers. The grammar check can be annoying because often technical sentences are wordy and complex, but it will help you avoid using too many passive sentences. The quality of the writing will count in your grade.

The following format is required for the organization of the **Technial Report**:

- **Title Page**
- **Abstract**
- **Objectives**
- **Sample Calculation**
- **Results**
- **Discussion of Results**
- **Conclusion**
- **Appendices (Original data sheet, References, detailed calculations etc)**

Lab Report Structure:

Title Page or Cover Sheet:
This **Title Page** has the title of the lab, title of the experiment, course number and assigned lab section, your name, your lab partner's names, the date that the lab was performed, the date of submition and your instructor's name. Please make this on a separate page.

ABSTRACT:
The purpose of an abstract in a report or scientific paper is to help a reader decide if your paper is of interest to him/her. The abstract should be able to stand by itself, and it should be brief. Generally, it consists of three parts which answer these questions:

- What did you do? – A statement of the purpose of the experiment, a concise description of the experiment and fluid mechnics principles investigated.
- What were your results? – Highlight the most significant results of the experiment.
- What do these results tell you? – Depending on the type of experiment, this is conclusions and implications of the results or it may be lessons learned form the experiment.

An abstract should be one paragraph of 100-200 words. Write the abstract after all the other sections are completed. (You need to know everything in the report before you can write a summary of it.)

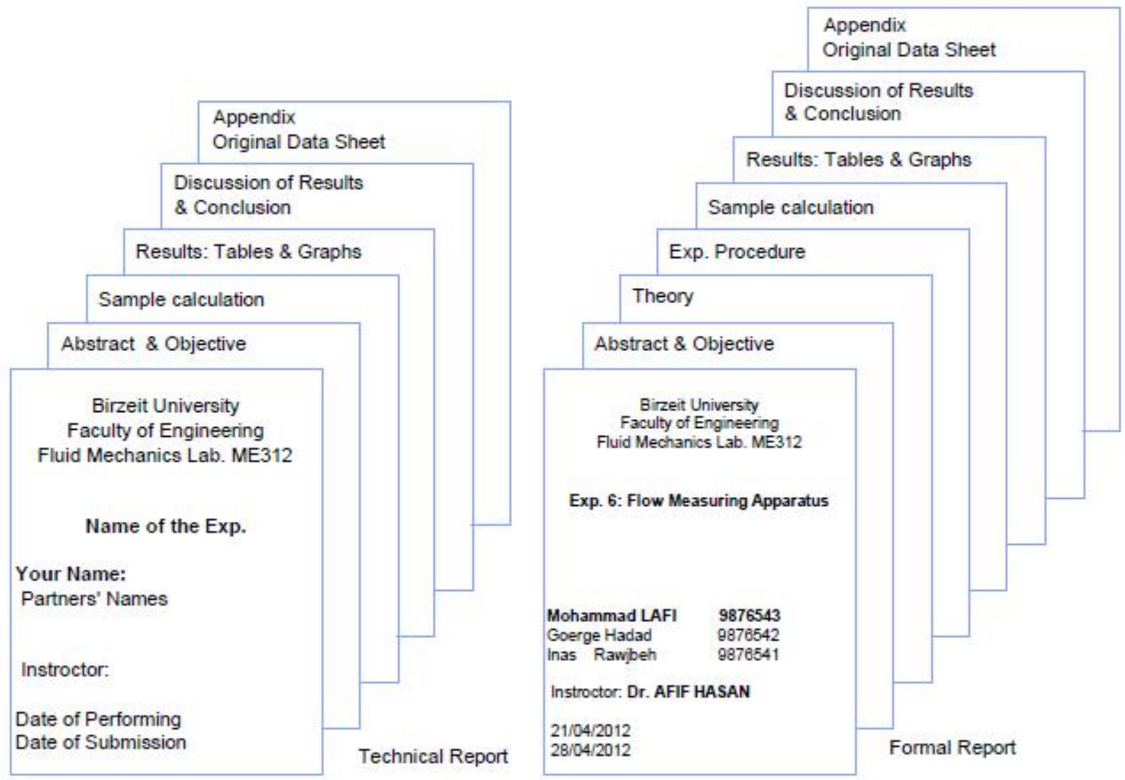

Figure 1: Format for Technical reports (left) and Formal Reports

OBJECTIVES:
Describe the specific actions you are being asked to perform in the lab, such as measure something, analyze something, test something, etc. Objectives are the activities you are being asked to do in order to complete the lab experiment. Be sure to list them as such: to measure, to analyze, to determine something.

SAMPLE CALCULATIONS:
Show calculations in a neat and orderly outline form. Include a brief description of the calculation, the equation, numbers from your data substituted into the equation and the result. Do not include the intermediate steps. Numbers in the sample calculations must agree with what you recorded in your data sheet. For calculations repeated many times, you only include one sample calculation. Answers should have the proper number of significant figures and units. (It is not necessary to show the calculation for obtaining an average, unless your instructor requests that you do so.) Use the equation editor in Microsoft Word to type the equations. Your lab instructor can give you information on using the equation editor.

RESULTS:
Include all tables and graphs that document your final results. Include all relevant information so that you can later refer to the numbers of tables and figures in the discussion section to support your conclusions.

Tables: For each experiment, the lab manual has one or more tables for recording raw data, as well as, intermediate and final data values. All numerical results should be non-dimensional or reported in SI units, such as kg for kilograms, W for Watts. Record the original data neatly in pen. This original data sheet should be approved by instructor(s) during experiment day. Place the name of the table on the above side.

Graphs: You must follow the guidelines in the lab manual for all graphs. It is preffered use computer software to make graphs. Those graphs must also conform to the guidelines in the lab manual. Remember that when plotting data with units, both the slope and intercept of a graph also have units. Place the name of the graph below the graph.

DISCUSSION OF RESULTS:
This is the most important part of the lab report; it is where you analyze the data.Begin the discussion with the experimental purpose and briefly summarize the basic idea of the experiment with emphasis on the measurements you made and transition to discussing the results. State only the key results (with uncertainty and units) quantitatively with numerical values; do not provide intermediate quantities. Your discussion should address questions such as:

- What is the relationship between your measurements and your final results?
- What trends were observable?
- What can you conclude from the graphs that you made?
- How did the independent variables affect the dependent variables? (For example, did an increase in a given measured (independent) variable result in an increase or decrease in the associated calculated (dependent) variable?

Then describe how your experimental results substantiate/agree with the theory. When comparison values are available, discuss the agreement using either uncertainty and/or percent differences. This leads into the discussion of the sources of error. In your discussion of sources of error, you should discuss all those things that affect your measurement, but which you can't do anything about given the time and equipment constraints of this laboratory. Your discussion should address questions such as:

- Are the deviations due to error/uncertainty in the experimental method, or are they due to idealizations inherent in the theory (or both)?

- If the deviations are due to experimental uncertainties, can you think of ways to decrease the amount of uncertainty?
- If the deviations are due to idealizations in the theory, what factors has the theory neglected to consider? In either case, consider whether your results display systematic or random deviations.

CONCLUSIONS:

State your discoveries, judgments and opinions from the results of this experiment. Summarize your primary results in comparison with theory in two or three sentences. These should answer the objective of the experiment. Make recommendation for further study. Suggest ways to improve the experiment.

APPENDICES:

- **Original Data Sheets:** Record the original data neatly in pen. In the case of an error, line through the mistake, and continue. Record the name of the recorder and the group members on the raw data sheets. This original data sheet should be approved by instructor(s) during experiment day.
- **References:** List any book or publication that you have referenced in your report. Provide titles, authors, publisher, date of publication, page number, Website addresses etc.
  Book reference: Author last name, Author first name. Book's title. Publisher and city of publication, year of publication.
  Journal reference: Author last name, Author first name. Paper title, Name of journal, volume, pages, year.
  Internet reference: Site location (http://www.) and retrieved date.

Example of writing a Table and plotting a Graph Result

Table 1: The mass flow, in kg, inlet, outlet and difference head, in m H_2O, theoretical $\dot{m}_{th}$ and actual (measured), $\dot{m}_{ac}$ values of mass flow rate, in kg/s for the Venturi meter.

Mass Flow	Head			mass flow rate	
	Inlet	Outlet	Head Dif		
m	H	H	ΔH	$\dot{m}_{th}$	$\dot{m}_{ac}$
kg	cm H_2O	cm H_2O	m H_2O	kg/s	kg/s
6	68	58	0.1	0.08	0.06
9	72	52	0.2	0.13	0.105
9	76	46	0.3	0.16	0.133
12	78	38	0.4	0.185	0.155
12	81	31	0.5	0.21	0.148
12	85	25	0.6	0.23	0.195
12	90	20	0.7	0.245	0.209
12	95	15	0.8	0.255	0.216
12	100	10	0.9	0.26	0.221
12	102	2	1	0.262	0.225

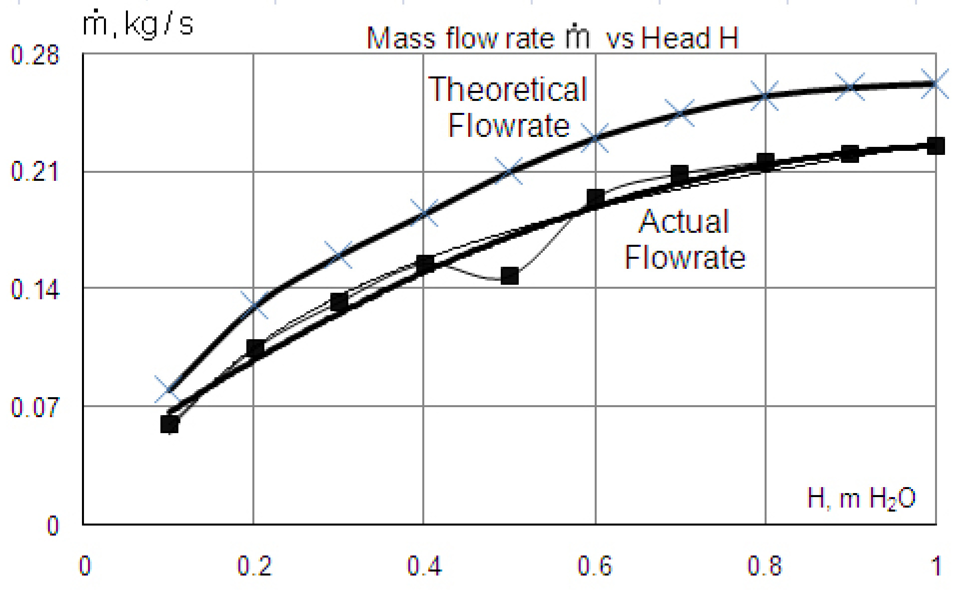

Fig. 1: The relationship between mass flow rate and head

Fluid flow measurements and devices

Methods of measurement of flow rate of liquids and gases

Flow meter is a device that measures the rate of flow or quantity of a moving fluid in an open or closed conduit. Flow measuring devices are generally classified into four groups. They are:

1. **Mechanical type flow meters**. Fixed restriction variable head type flow meters using different sensors like orifice plate, venturi tube, flow nozzle, pitot tube.
2. **Inferential type flow meters.** Variable area flow meters (Rotameters), turbine flow meter, target flow meters etc.
3. **Electrical type flow meters.** Electromagnetic flow meter, Ultrasonic flow meter, Laser doppler Anemometers etc. It works on the principle of basic electromagnetic induction. The advantages of this type of flowmeter can be summarized as:
    - It causes no obstruction to flow path.
    - It gives complete linear output in form of voltage.
    - The output is unaffected by changes in pressure, temperature and viscosity of the fluid.
    - Reverse flow can also be measured.
    - Flow velocity as low as 10^{-6}m/s can be measured.
4. **Other flow meters.** Purge flow regulators, Flow meters for Solids flow measurement, Cross-correlation flow meter, Vortex shedding flow meters, flow switches etc.

We would learn about the construction and principle of operation few types of flow meters

Hydraulic bench

Hydraulic bench is a useful apparatus in fluid mechanics. It consists of a molded plastic sump tank which supports Glass-fiber Reinforced Polyester. The hydraulics bench unit provides the basic services for the pumping and volumetric measurement of the water supply in acertain period of time. A centrifugal pump discharges water from the sump tank and delivers to a top measuring tank, then water drains and return to sump tank through flow channel and control valve. Flow control valve and by-pass valve are fitted in water line to conduct the experiment on different flow rates. Flow rate of water is measured with the help of measuring tank and stop watch. A dump valve in the base of the measuring tank is operated by a remote actuator. Lifting the actuator opens the dump valve allowing the water to return to the sump for recycling.

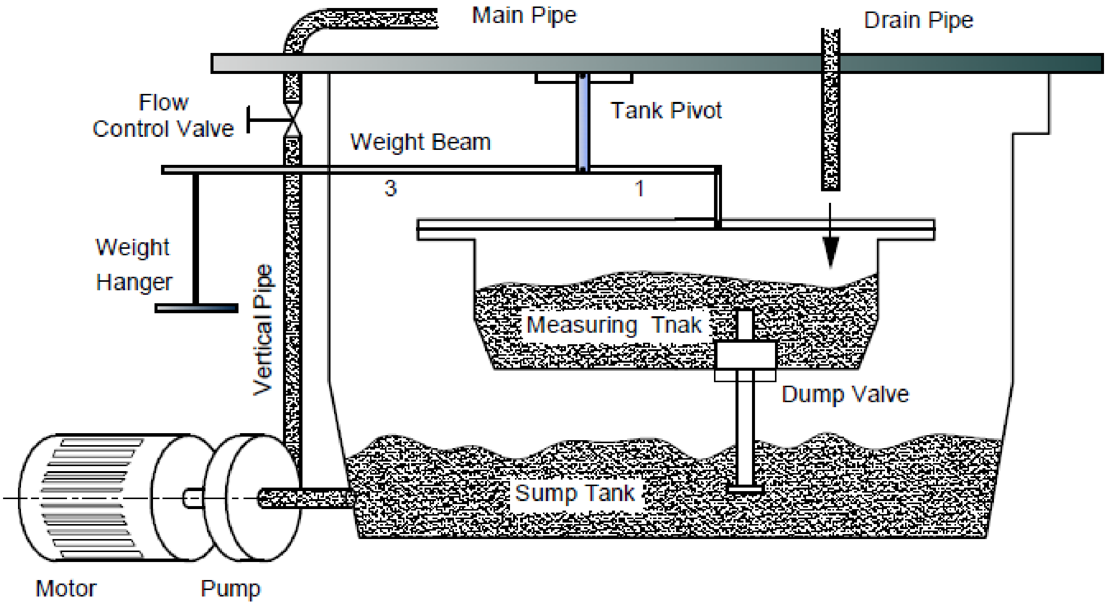

Figure 2: Hydraulic bench

Parts of Hydraulic Bench Machine:
Its parts are given below:

Centrifugal pump: It draws water from sump tank and supplies it for performing experiments.

Sump Tank: It stores water for Hydraulic bench. It is located in the bottom portion of Hydraulic bench. Water from here is transported to other parts by using a pump. It has a capacity of 160 liters.

Vertical pipe: It supplies water to the upper part of hydraulic bench from sump tank through a pump.

Control valve: It is used to regulate the flow in the pipe i.e. to increase or decrease the inflow of water in the hydraulic bench.

Connecter: With the help of this we can attach accessories with the hydraulic bench. Special purpose terminations may be connected to the pump supply by unscrewing connecter, no hand toolsare required for doing so. It is located in the channel.

Channel: It is used in number of experiments It provides passage for water for different experiments.

Drain valve: It is used for emptying sump tank.

Side channels: They are the upper sides of the channel. They are used to attach accessories on test.

Volumetric tank: It stores water coming from channel. This tank is stepped to accommodate low or high flow rates. It has a capacity of 46 l.

Stilling baffle: It decreases the turbulence of water coming from channel. It is located in the volumetric tank.

Scale & Tapping: A sight tube and scale is connected to a tapping in the base of the volumetric tank and gives an instantaneous indication of water level.

Dump valve: It is used for emptying volumetric tank. It is located in the bottom of the volumetric tank.

Actuator: Dump valve is operated by a remote actuator, lifting actuator opens the dump valve, when it is given a turn of 90' it will turn the dump valve in the open position.

Over flow: It is an opening in the upper portion of the volumetric tank. It sends the water level above 46 l to the sump tank.

Measuring cylinder: A measuring cylinder is provided for measuring of very small flow rate. The cylinder is stored in the compartment housing the pump.

Starter: It on / off the hydraulic bench.

Units of Flow

Flow measurements include measuring of flow rate of liquids. There are two basic ways of measuring flow; one on volumetric basis and the other on weight basis. Flow volume is measured in cubic meters and flow mass in kilograms. The flow rate measurement is defined as cubic meters per time or kilograms per time.

Fluids are classified into two types, namely incompressible and compressible. Fluids in liquid phase are incompressible whereas fluids in gaseous phase are compressible. Liquid occupies the same volume at different pressures where as gases occupy different volumes at different pressures. This point has to be taken care of while calibrating the flow meters.

Measuring of fluid flow rate:

The flow rate measurement requires a container to capture the entire flow, a scale to measure the volume or mass of flow of the captured fluid, and a stopwatch to measure the time it takes to capture a quantity (volume or mass) of fluid.

The method is quiet simple. If in a given time Δt in s, the conduit issues a quantity of fluid having a volume V in m^3 (..mass m in kg) into the container, and if the flow is steady, then the volume flow rate Q is calculated as volume flow, V divided by time, Δt

$$Q = \frac{V}{\Delta t} \qquad (1)$$

The volume flow rate, Q is measured as meter cubed per second. Therefore, Q is measured in $\frac{m^3}{s}$ or in m^3/s

The mass flowrate, $\dot{m}$, is calculated as mass flow, m divided by time, Δt

$$\dot{m} = \frac{m}{\Delta t} \qquad (2)$$

The mass flow rate, $\dot{m}$ is measured as kilograms per second. Therefore, $\dot{m}$ is measured in $\dot{m} = \frac{kg}{s}$ or kg/s.

The mass flow rate, $\dot{m}$ is calculated as product of density of fluid multiply by volume,

$$\dot{m} = \rho \times C \qquad (3)$$

Bernoulli's Equation:

Bernoulli's Equation for an incompressible, ρ is constant, frictionless flow is:

$$\frac{u^2}{2g} + \frac{P}{\rho g} + Z = H \qquad (4)$$

where

u is the stream velocity.
g is the acceleration due to gravity.
P is the pressure of flow.
Z is the elevation of the fuid above some datum level.
H is a constant usually called the total head.

Bernoulli's Equation for two positions, Section 1 as the position of upstream tap and Section-2 for downstream is:

$$\frac{u_1^2}{2g} + \frac{P_1}{\rho g} + Z_1 = \frac{u_2^2}{2g} + \frac{P_2}{\rho g} + Z_2 = H \qquad (5)$$

Each of the three terms on the left-hand side is measured in m H_2O:

- The term $\frac{u^2}{2g}$ is referred to as the **Dynamic Head** (also known as **Kinetic or Velocity Head)**, represents the kinetic energy of fluid per 1 kg.
- The term $\frac{P}{\rho g}$ is referred to as the **Pressure Head** and represents the energy per 1 kg of fluid required to raise the pressure by an amount equal to P. The term ρg is the gravity force or the weight per unit volume, the specific weight.

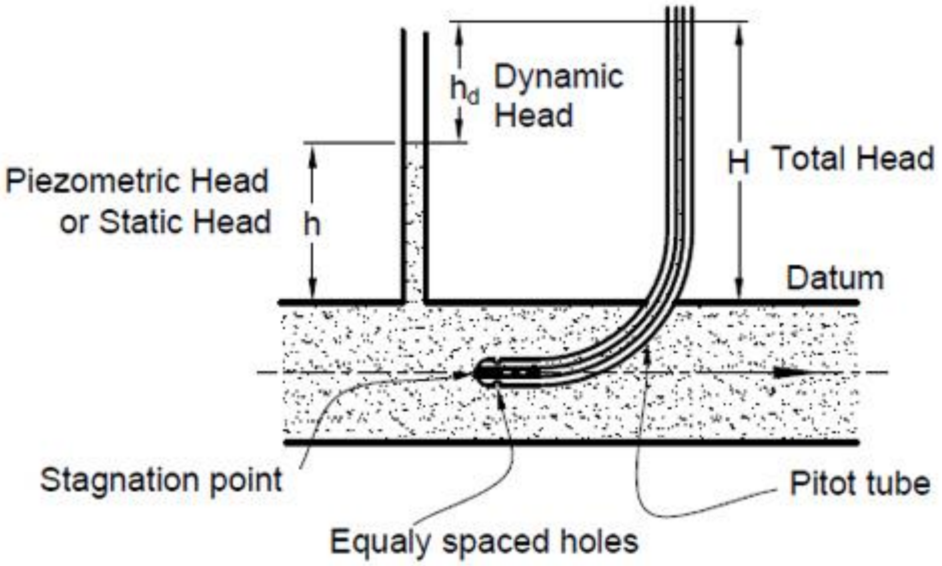

Figure 3: Total Head, Static head and Dynamic Head

- The term Z represents the elevation of the fluid above some datum level and represents the potential energy of the fluid per 1 kg measured from this datum.
- The term H is a constant usually called the **Total Head**.

It is sometimes convenient to refer to the sum of the terms ($h = \frac{P}{\rho g} + Z$) as the **piezometric head or the Static Head,** h, in which case the Bernoulli's equation may be written in the form of Total Head is equal to the Static Head plus Dynamic Head.

$$H = h + \frac{u^2}{2g} \qquad (6)$$

Continuity equation

The continuity equation for this type of flow is

$$Q = A_2V_2 = A_1V_1 \qquad (7)$$

where A is the cross section area.

Pitot Tube

The Pitot (pronounced Pee-toe) static tube system is an ingenious device used by airplanes and boats for measuring forward speed. The device is really a differential pressure gauge and was invented by Henri Pitot in 1732. As an example of a Pitot tube meter is a tire pressure gauge, **Fig. 6.**

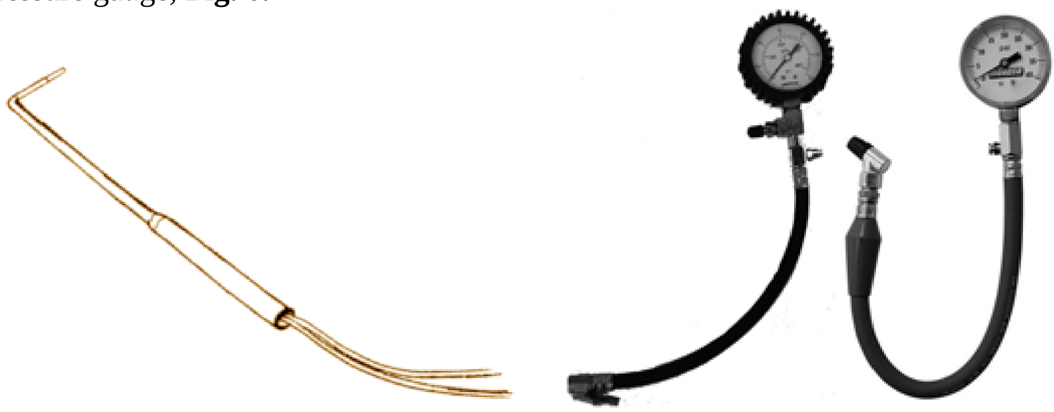

Figure 4: Typical Pitot Static tube & tire pressure gauges

The Pitot tube measures a fluid velocity by converting the kinetic energy of the flow into potential energy, which it takes place at the stagnation point, located at the Pitot tube entrance. Its basic principle can be understood from **Fig. 7**, where the velocity of fluid at the entrance point will be zero.

Multiplying the equation 4 by ρg

$$\rho g \times H = \rho g \times \left\{ \frac{u^2}{2g} + h \right\} \qquad (8)$$

Knowing that Total Pressure $P_t = \rho gH$ and Static Pressure $P_s = \rho gh$, we have:

$$u = \sqrt{\frac{2}{\rho} \times (P_t - P_s)} \qquad (9)$$

Or directly from eqn 3 as a difference between total head and static head.

$$u = \sqrt{2g \times (H - h)} \qquad (10)$$

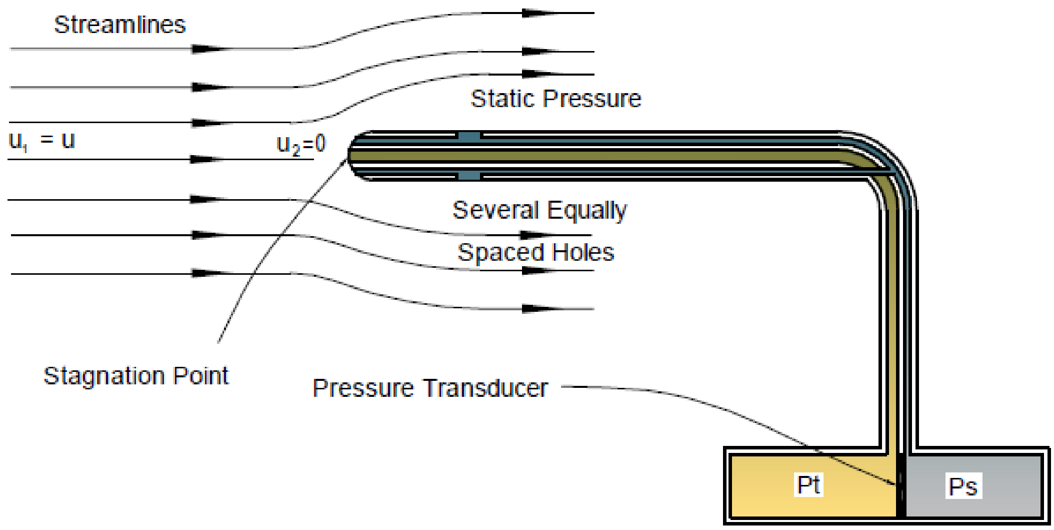

Figure 5: Cross-section of a Typical Pitot Static Tube

Manometer

A manometer measures the difference in air or liquid pressure by comparing it to an outside source, usually a sample of Earth's atmosphere. There are several types of manometers, the simplest being a piezometer tube, which is a single tube and a base that holds the liquid. More common manometers are U-shaped and have interconnected tubes. The multi-tube manometer consists of 16 manometers with a mm scale mounted on a swiveling panel, while water is supplied to the manometers centrally from a water reservoir.

Manometers are used in atmospheric surveys, weather studies, gas analyses and research of the atmospheres of other planets. They are usually made of glass or plastic, and while most are scored for measurement, some can measure changes digitally.

U Tube Manometer

It consists of a clear glass or plastic tube shaped into the form of a 'U'. The tube is partially filled with a liquid, such as water, alcohol, or mercury (no longer used). The lower the density of the liquid, the higher the sensitivity of the manometer. A liquid is placed in the tube is stable under pressure on both sides. Both ends of the tube are open,and atmospheric pressure acts equally on the liquid through each end. Therefore, the height of the liquid on each side of the U (in each limb) is equal.

The gas under pressure $P_{unknown}$ is connected to the left side of the U. Because the liquid is incompressible, it pushes the liquid down on that limb and forcing the liquid up to the other side. Hence the height of the liquid on either side of the tube is no longer equal. The difference between the height of the liquid in each limb, h, is proportional to the difference between the unknown pressure and atmospheric pressure.

In a U tube manometer, the difference between the unknown pressure and atmospheric pressure is the gauge pressure. Therefore

$$Pgauge = Punknown - Patm = \rho gh \qquad (11)$$

where,

ρ is the density of the liquid in the tube, in kg/m^3
g is the acceleration due to gravity, that is, 9.81 m/s^2
h is difference between the heights of the liquid in each limb, in m

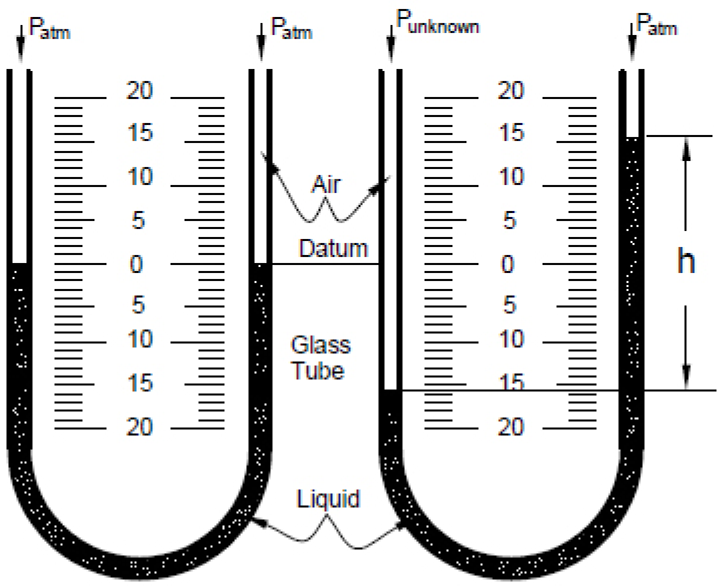

Figure 6: U Tube Manometer

If we know atmospheric pressure, or can accept the errors which occur using the standard value, then we can find $P_{unknown}$ by rearranging the equation,

$$P_{unknown} = P_{atm} + \rho gh \qquad (12)$$

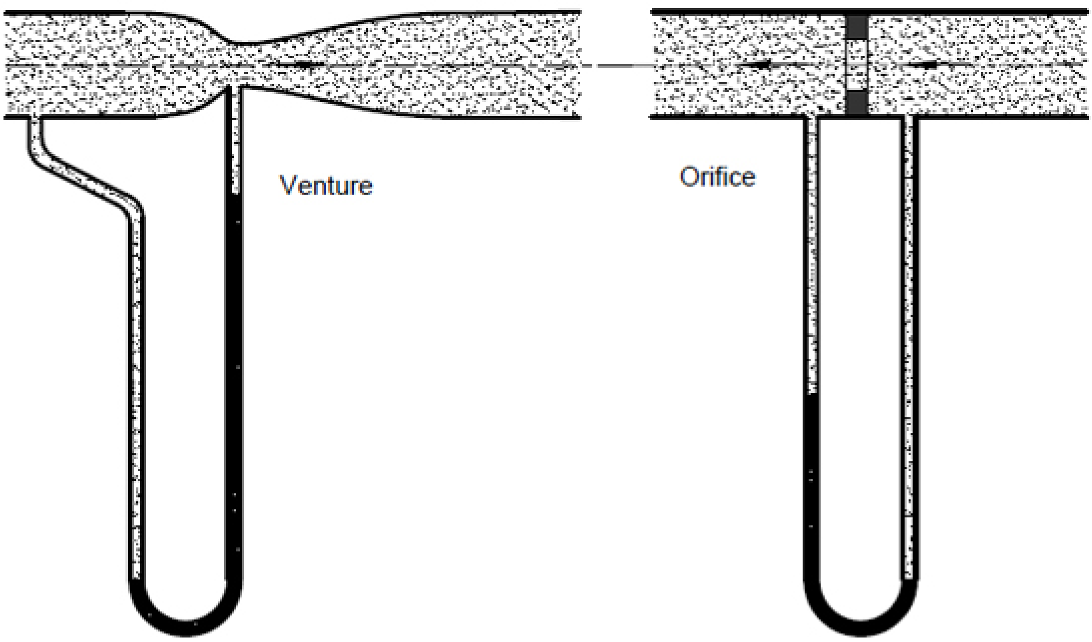

Figure 7:The U tube manometer connected to orifice and venture meter

The U-tube manometer is not in wide use in industry, although it is sometimes used to calibrate other instruments. It is mainly used in laboratories for experimental work and demonstration purposes. It can be used to measure the pressure of flowing liquids as well as gases, but cannot be used remotely. If pressures fluctuate rapidly its response may be poor and reading difficult.

Multi Tube Manometer

The multi-tube manometer consists of 8-16 manometers with a mm scale mounted on a swiveling panel. The panel can be positioned at three inclinations. This permits the units to be used as inclined-tube manometers for measuring very small pressure differences. Water is supplied to the manometers centrally from a water reservoir. At the top of each manometer there are measuring glands for connection of the measuring tubes. Water level before a measurement: Approximately in the middle of the scale (arrow) on the manometers. Push the water reservoir to the level adjacent to the middle of the scale and secure it in place with the knurled screw. Half fill the water reservoir with water. The water is at the same level in all manometer tubes.

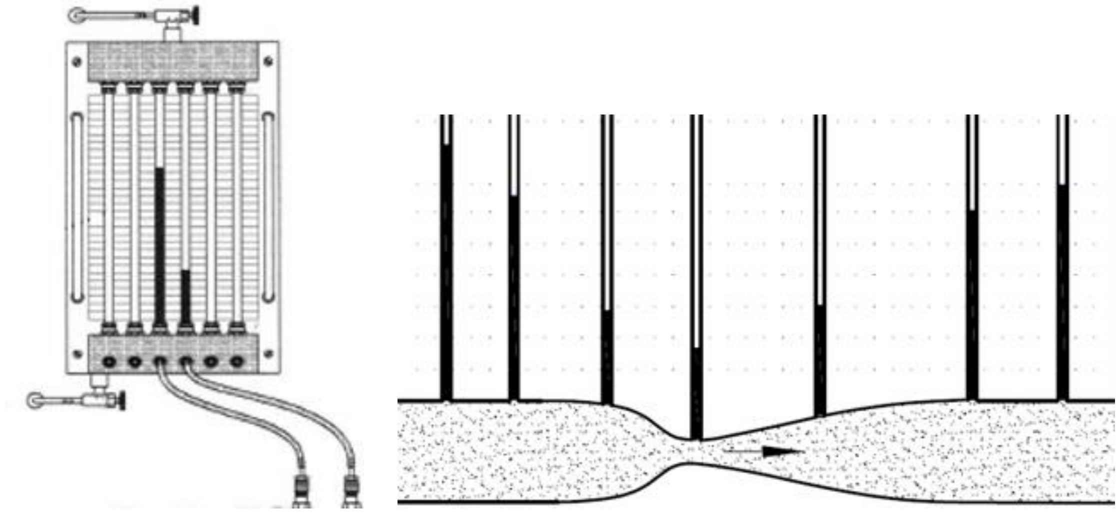

Figure 8: Multi Tube Manometer connected to venture meter

Rotameter:
The rotameter is an industrial flow meter used to measure the flow rate of liquids or gases. It consists of a vertical tapered tube and float, **Figure 11.**

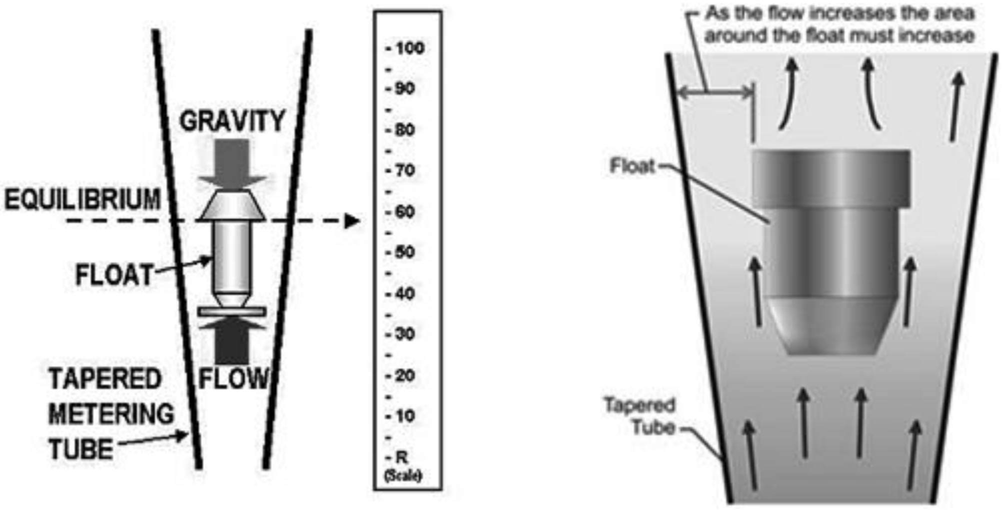

Figure 9: Rotameter

Principle of Operation
The rotameter's operation is based on the variable area principle: fluid flow raises a float in a tapered tube, increasing the area for passage of the fluid. The greater the flow, the higher the float is raised. The height of the float is directly proportional to the flowrate. The float moves up or down in the tube in proportion to the fluid flowrate and the annular area between the float and the tube wall. The float reaches a stable position in the tube when the upward force exerted by the flowing fluid equals the downward gravitational force exerted by the weight of the float. A change in flowrate upsets this balance of forces. The float then moves up or down, changing the annular area until it again reaches a position where the forces are in equilibrium.

Turbine Flow Meters

Turbine type flowmeter is a simple way for measuring flow velocity. Turbine flow meters are used for the measurement of natural gas and liquid flow. A rotating shaft with angular blades is placed inside the flow pipe.

The flowing fluid impinges on the turbine blades, imparting a force to the blade surface and setting the rotor in motion. The flowing fluid will cause rotation of the turbine whose speed of rotation can be a measure of the flow rate. When a steady rotation speed has been reached, the speed is proportional to fluid velocity. The volumetric flow rate, Q can be related with the angular speed, ω as:

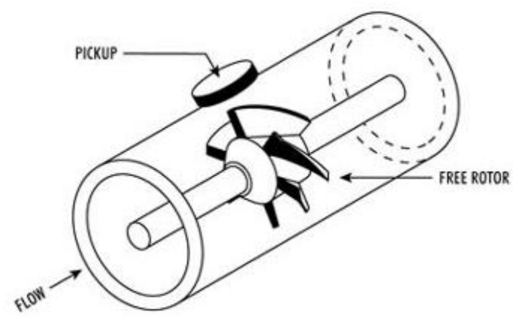

Figure 10:Turbine Flow Meter

$$Q = k\,\omega \tag{13}$$

Open Channel Flowmeters
Open channel flow occurs with a free surface open to the atmosphere, thus meters using change in pressure cannot be used as in pipe flow measurement. For open channel flow measurement, a change in depth of flow at some point is typically measured and correlated with water flow rate. The most common methods of measuring open channel flow rate are with a weir or a flume.

A weir is a small dam or barrier that is built across a river or stream to raise the water level, divert the water, or control its discharge. The weir will cause an increase in the water depth as the water flows over the weir. In general, the greater the flow rate, the greater will be the increase in depth of flow, The height of water above the top of the weir is the measurement usually used to correlate with flow rate. The latter may be computed from a formula expressing the discharge in terms of crest length of the weir, depth of flow above the weir, weir geometry, and other factors.

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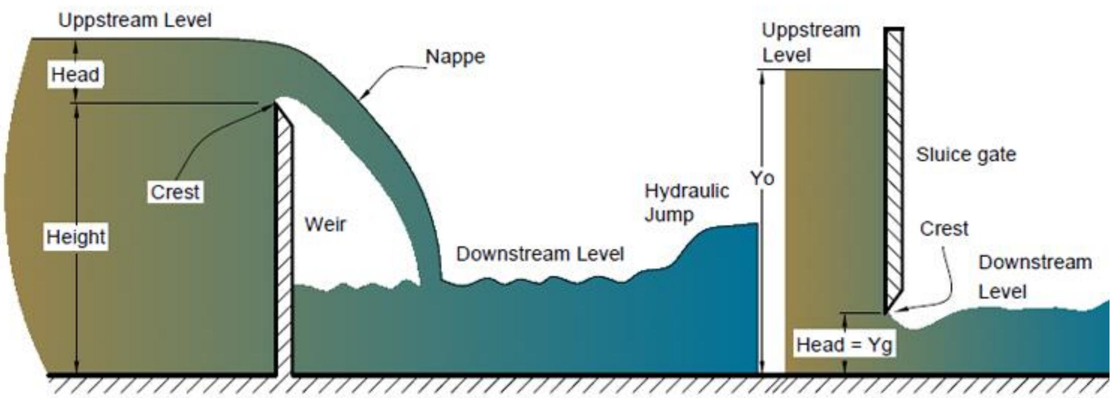


Figure 11: Water flow over a Weir and Sluice gate in open channel

Types of Weirs.

A weir with a sharp upstream corner or edge such that the water springs clear of the crest is a sharp-crested weir. All other weirs are classed as weirs not sharp crested. Sharp-crested weirs are classified according to the shape of the weir opening, such as rectangular weirs, triangular or V-notch weirs, trapezoidal weirs, and parabolic weirs. Weirs not sharp crested are classified according to the shape of their cross section, such as broad-crested weirs, triangular weirs, and trapezoidal weirs.

The discharge over a weir is a function of the weir geometry and of the head on the weir. A weir is an obstruction in an open channel over which liquid flows.

Applying Bernoulli's equation along a streamline between a point upstream of the weir (where the velocity head is neglected) and a point in the plane of the weir, the velocity, V, at the weir is

$$V(h) = 2gh \tag{14}$$

Where g is the gravitational acceleration and h is the elevation of the streamline below the free surface. Assuming that the velocity is constant throughout the cross-section of the weir, the expression for the discharge, Q, over the weir becomes

$$Q = \int_A dQ = \int_A V\,dA = \int_0^H \sqrt{2gh}\, b \times h\, dh \tag{15}$$

Where A is the cross-section of the weir and b(h) is the width of the weir at elevation h. Thus, the general expression for the weir head-discharge relationship is

$$Q = k \times h^n \tag{16}$$

Where k is a flow coefficient and n is an exponent. Both k and n are dependent on the shape of the weir (e.g., rectangular, triangular, trapezoidal or parabolic) and flow conditions (velocity distribution in the approach section, fluid viscosity, surface-tension effects, contraction coefficient).

Fluid Mechanics
Experiment No. 1
Flow measurements of hydraulic systems
Apparatus: Flow measurement apparatus – Fluid Mechanics Lab.

Objectives:

1. To learn the operation principle of a hydraulic bench.
2. To measure flow rate using hydraulic bench
3. To read manometers and calculate pressure differences.
4. Measure flow rate by venture-meter
5. Measure flow rate using an orifice
6. Measure flow rate using Rota meter.
7. Measure pressure drops in fittings and devices.
8. Compare measurements from different devices.

Apparatus description:

The flow measurement apparatus is mounted on a hydraulic bench. The hydraulic bench provides a constant rate flow rate of water through the system. In addition the actual flow rate can be measured by timing and collecting fixed amount of water that flows through the system. Figure (1) shows the system.

Water enters the equipment through a Perspex Venturi-Meter, which consists of a long gradually-converging section, followed by a throat, then by a long diverging section. After a change in cross-section through a rapidly diverging section, the flow continues down a settling length, and through an Orifice plate meter. Then through a further settling length, a right angle bend and a Rota meter. Various manometers along the system gives the pressure at given locations of the system. Using this monometer readings velocity and flow rate can be calculated through the system and major and minor losses can be estimated.

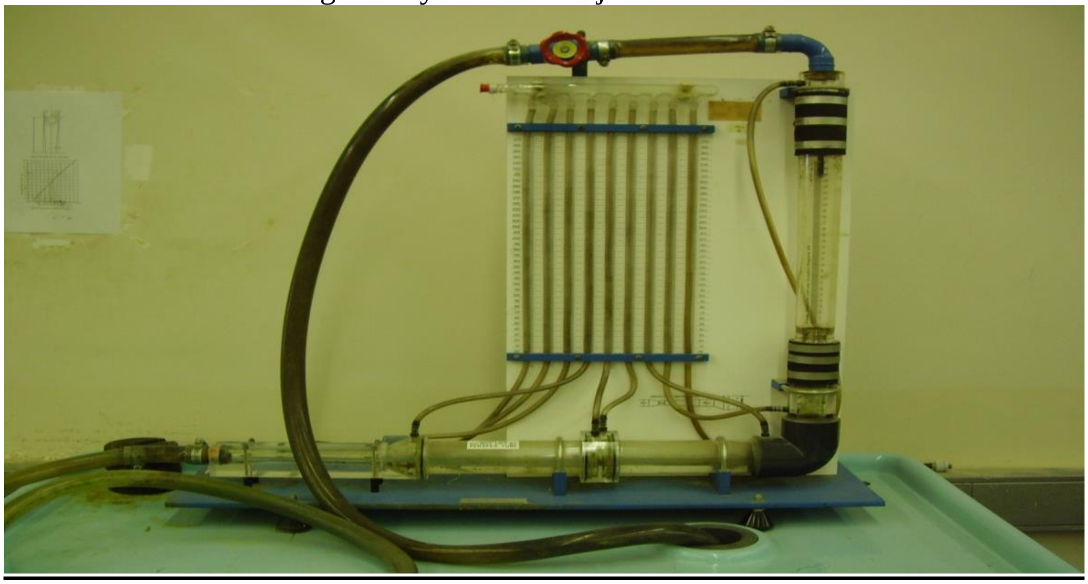


Figure (1) Flow measurement apparatus

Experimental procedure

1. The flow measuring apparatus is connected to the hydraulic bench water supply and the control valve is adjusted until the Rota meter is about mid-position in its calibrated tapered tube.
2. Air is removed from the manometer tubing by flexing it. The pressure within the manometer reservoir is now varied and the flow rate decreased, until, with no flow the manometer height in all tubes is about 280 mm.
3. Open the control valve slightly and start to measure the discharge.
4. Read the manometers and the float height of the Rota meter.
5. Repeat for eight different flow rates.

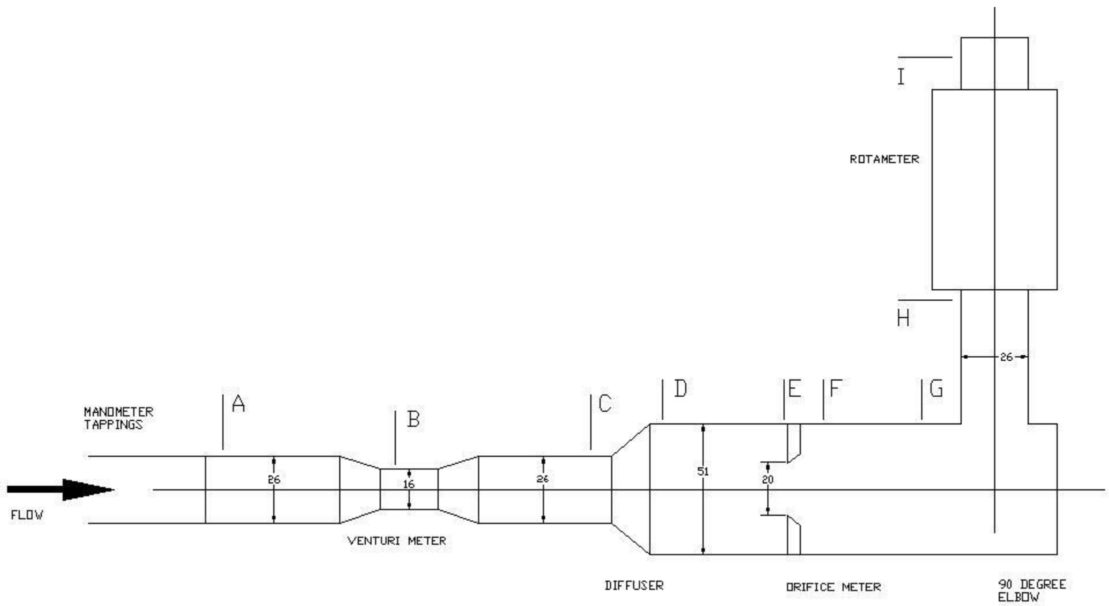


Figure 2: Obstructions and locations of manometers.

DATA :

Diameter at section A = 26 mm
Diameter at section B = 16 mm
Diameter at section E = 51 mm
Diameter at section F = 20 mm

Theory

Applying the energy equation between any two locations 1 & 2:

$$\frac{P_1}{\rho g}+\frac{u_1^2}{2g}+Z_1=\frac{P_2}{\rho g}+\frac{u_2^2}{2g}+Z_2+\Delta H_{1-2}$$

Where ΔH_{1-2} is the lost head between 1 & 2

For Venturi-Meter :

Neglecting losses and head difference between locations A & B:

$$\frac{P_A}{\rho g}+\frac{u_A^2}{2g}=\frac{P_B}{\rho g}+\frac{u_B^2}{2g}$$

Continuity equation*:*

$$\dot{m}=u_A\, a_A\, \rho=u_B\, a_B\, \rho$$

Then:

$$\dot{m}=\rho a_B((\frac{2g}{1-(\frac{a_B}{a_A})^2}).(\frac{P_A}{\rho g}-\frac{P_B}{\rho g}))^{\frac{1}{2}}$$

This is the ideal mass flow rate.

The actual mass flow rate can be calculated by:

$$\dot{m}=\rho a_B C_d(\frac{2g}{1-\left(\frac{a_B}{a_A}\right)^2}(h_a-h_B)^2$$

Where Cd is the coefficient of discharge

For the Orifice-Meter*:*

Applying energy equation between sections E & F

$$\frac{u_F^2}{2g}-\frac{u_E^2}{2g}=\frac{P_E}{\rho g}-\frac{P_F}{\rho g}-\Delta H_{E-F}$$

Which can be written as:

$$\frac{u_F^2}{2g}-\frac{u_E^2}{2g}=C_d{}^2(\frac{P_E}{\rho g}-\frac{P_F}{\rho g})$$

Where Cd is the coefficient of discharge

Cd = 1 for ideal mass flow rate.

Solving with the continuity equation:

$$\dot{m}=\rho a_F Cd(\frac{2g}{1-(\frac{a_F}{a_E})^2}(h_E-h_F))^{\frac{1}{2}}$$

which can be read directly from the manometers.

For Rota meter:

The Rota meter is a device that gives directly the fluid flow rate by reading the flow rate from the calibration curves of the device, normally manometer readings versus flow rate.

Minor losses:
Minor losses for fittings can be given as $h_m = K (u^2/2g)$, on the other hand applying energy equation for a fitting as given in equation 1 above, letting $z = 0$, $u1 = u2$ then

$$h_m = (\Delta P)/\rho g,$$

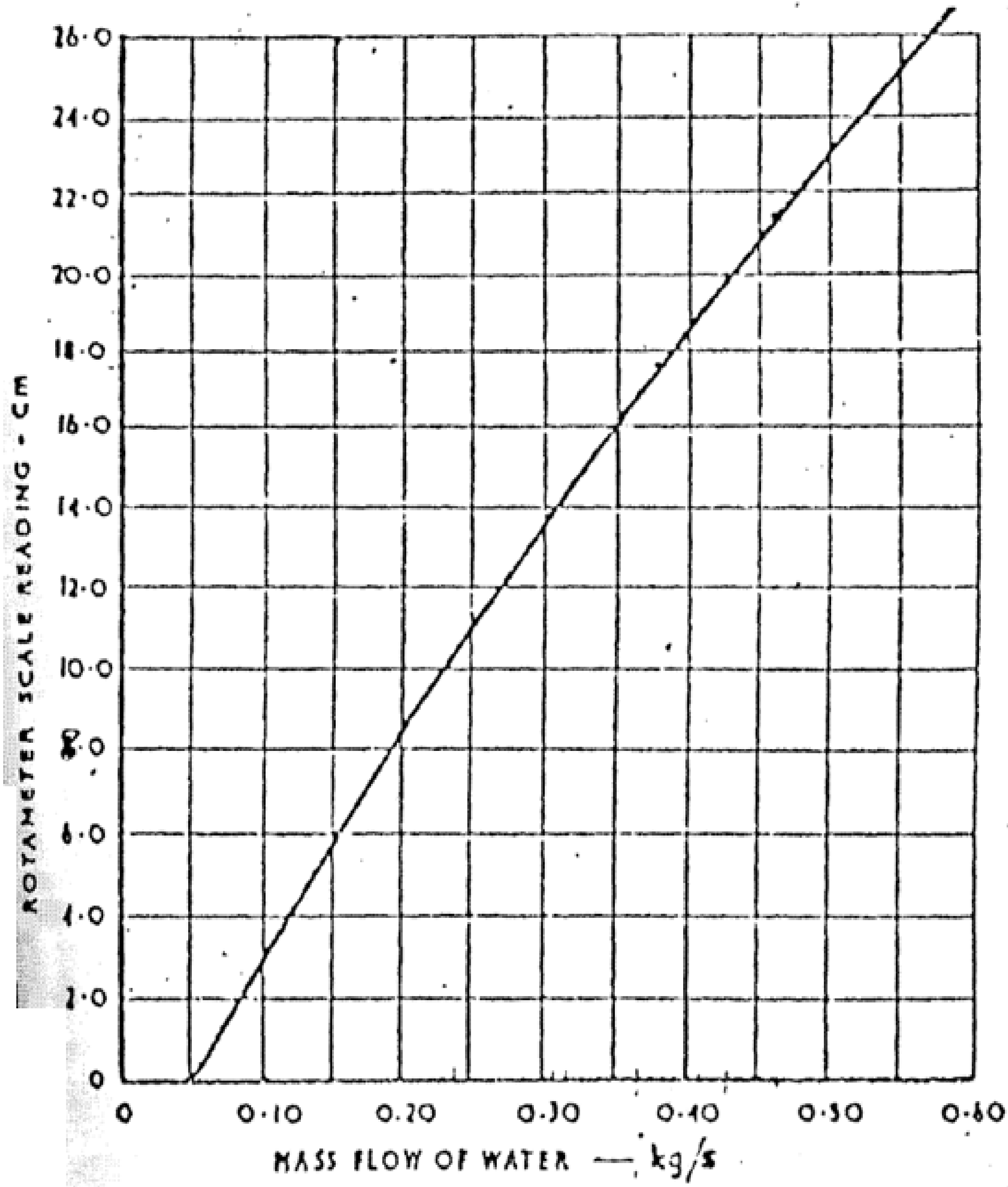
However $P/\rho g$ is the manometer readings.

Analysis & calculations

1. Calculate the ideal mass flow rate for the Venturi meter and Orifice.
2. Compare in a graph the ideal flow rates from venture and orifice with the actual (from hydraulic bench).
3. Find the coefficient of discharge of the orifice and venturi meter (average).
4. Calibrate the Rota meter to give the actual discharge directly by plotting actual flow from bench versus the Rota meter readings.
5. Compute the minor losses h_m for the bend and the loss coefficient K, compare with theoretical values.
6. In a table summaries the flow rate measured including: actual rate, rotometer, ideal orifice, ideal venturi meter over the measured flow rate range.

Appendix:

Data sheet
Calibration rotameter curve.



Rotameter calibration curve

Fluid Mechanics
Experiment No. 2
Friction & pipe flow of compressible systems
Apparatus: Thermo –fluid tutor apparatus – thermodynamic lab.

Objectives:

- Understand Air flow system & fans
- Learn pressure measurements by manometers and pressure gauges
- Measure pressure losses in fittings
- Measure pipe friction losses
- Apply steady flow energy equation.

Apparatus description:

The ductwork is normally designed to pass fluid from point to point such that the total pressure loss in the system is overcome by some type of pump/fan system. The important parameter, from the designer point of view, is therefore the pressure loss down the ductwork for a given flow.

The majority of duct work consists of straight lengths of pipe work, bends and other items such as screen, flow measuring devices……etc. Figure 1 shows the thermo-fluid tutor set up; it contains straight sections of duct ,bends, venturimeter, orifice, heating section, and manometers and thermocouples for temperature measurements, in addition to a fan for air flow.

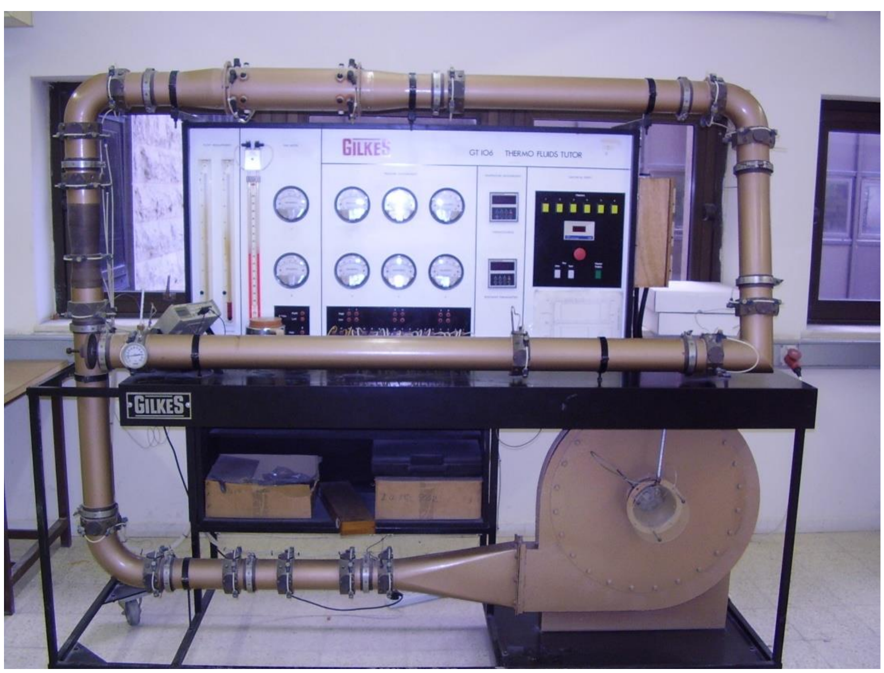


Figure 1: Thermo-fluid tutor device.

Experimental procedure

1. Run the tutor fan at the slow speed, using the differential pressure gage measurement instrument measure the static pressure loss between each pair of traverse position, and the pressure loss between the first and the last sections. From orifice and venture measuring tubes measure hv, and ho
2. Repeat the previous procedure for the fan at high speed.

Section		ΔP_{loss} (mmH_2O)	ΔP_{loss} (mmH_2O)
		Slow speed	High speed
1 – 2	Screen		
2 – 3	Straight duct		
3 – 5	Orifice meter		
5 – 6	Round elbow		
6 – 7	Straight duct		
7 – 10	Venturi meter		
10 – 11	Round elbows		
11 – 12	Heat bank		
12 – 13	Straight duct		
13 – 14	Round elbow		
14 – 15	Straight duct		
15 –16	Right angle elbow		
16 – 18	Straight duct		
1 – 18	Total ΔP_{loss}		

Theory

The total pressure loss through the system is calculated as the summation of the pressure losses of each component in the system.

Consider the schematic ductwork shown in figure (1), the pressure loss in each section in the system can be calculated as:

$$\Delta P_{loss} = K\left(\frac{1}{2}\rho V^2\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(9.1)}$$

Where:

$\frac{1}{2}\rho V^2$ = Dynamic Pressure

ρ = Fluid (air) density Kg/m^3

V = Fluid velocity (m/s)

K = Friction loss factor = $f\,\frac{L}{D}$

ΔP_{loss} = Static Pressure Loss (Pa)

Minor losses calculated as

$$\Delta P_{loss} = K\left(\frac{1}{2}\rho V^2\right)$$

The loss coefficient, K can be found in fluid mechanics text book or in catalogues.

Fluid velocity can be calculated either using the orifice plate or the venture meter.

$$V = \frac{Q_V}{A} \quad \text{m/s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(9.2)}$$

$$V = \frac{Q_o}{A} \quad \text{m/s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(9.3)}$$

Where:

Q_v = flow rate using venture meter.

$= 163.3\sqrt{h_v}$ m^3/hr

Q_o = Flow rate using orifice meter.

$=123.7\sqrt{h_o}$ m^3/hr

$A = \frac{\pi D^2}{4}$ m^2

D = 0.0984 m

Reynolds number = Re = VD/υ

Where υ is the kinematic viscosity of air.

Equivalent length for fittings can be calculated using the formula, Le = KD/f

Analysis & calculations

1. Calculate air flow rate from both venturi and orifice meters.
2. Calculate fluid main velocity.
3. Calculate the pressure loss (drop) for each section in the system, compare with theoretical values for both fittings and major losses.
4. For each section calculate velocity, h_{minor}, K coefficient for fittings, or h_f and f for straight duct sections. In a table list both experimental and theoretical values.
5. Specify the elements which caused the maximum and minimum pressure losses.
6. Which of the flow measuring devices cause more pressure loss?
7. Discuss the results you obtain.
8. Calculate Reynolds number and friction coefficient f using Moody's chart (for steel pipes) and calculate theoretically expected pressure drops, and compare with experimental values.
9. Calculate the equivalent length of the system depending on the total pressure loss.
10. If you know that the total tutor length is L = 7.42 m, comment on your results.

Appendix

Data sheet

Fluid Mechanics
Experiment # 3a
Radial Pumps
Apparatus: Radial pump system– Fluid mechanics lab.

OBJECTIVE :

The purpose of this experiment is to familiarize the student with some basic centrifugal pump characteristics and operation. Figure (1)

Figure (1) Centrifugal Pumps

EXPERIMENTAL PROCEDURE :

1. Make sure the inlet valve is completely open and the discharge valve is closed.
2. Switch the Power on.
3. Run the pump at an angular velocity ; N, of 2500 RPM.
4. Balance the casing of the rotating shaft by the driving screw. This is achieved by having the arm fixed horizontally half way between the restrains.
5. Wait enough time until the system is steady.
6. When the system is steady : Record the following : force, (F), voltage, (V), current, (I), inlet pressure, ($P_1 \equiv P_{in}$), outlet pressure, ($P_2 \equiv P_{out}$), and the volume flow rate, (Q).
7. Open the discharge valve to get a different volume flow rate (Note : Max flow rate = 5 l/s
8. This causes the angular velocity to change. Readjust to 2500 RPM.
9. Repeat the procedure from 4 to 6.
10. Repeat the procedure for 8 volume flow rates
11. Shut the system off.

CALCULATIONS :

1. Calculate the power required to drive the pump, W_e

$$W_e = V\,I$$

Where : $V \equiv$ Voltage
$I \equiv$ Current

2. Calculate the hydraulic power, W_h

$$W_h = Q\Delta P$$

Where : $Q \equiv$ Volume flow rate, m^3/s
$\Delta P \equiv$ Pump pressure difference ($P_2 - P_1$) in Pa.

3. Calculate the mechanical power, W_m

$$W_m = \frac{2\pi N T}{60}$$

Where : $N \equiv$ Angular velocity, RPM
$T \equiv$ Torque, N.m
$T = 0.165\,F$,
$F \equiv$ Force, N

4. Calculate the overall efficiency, η

$$\eta = \frac{\rho g Q H}{W_e}$$

Where : ρ $\equiv$ Water density, kg/m^3

g $\equiv$ gravity, m/s^2

Q $\equiv$ Volume flow rate, m^3/s

H $\equiv$ Head in meters of water

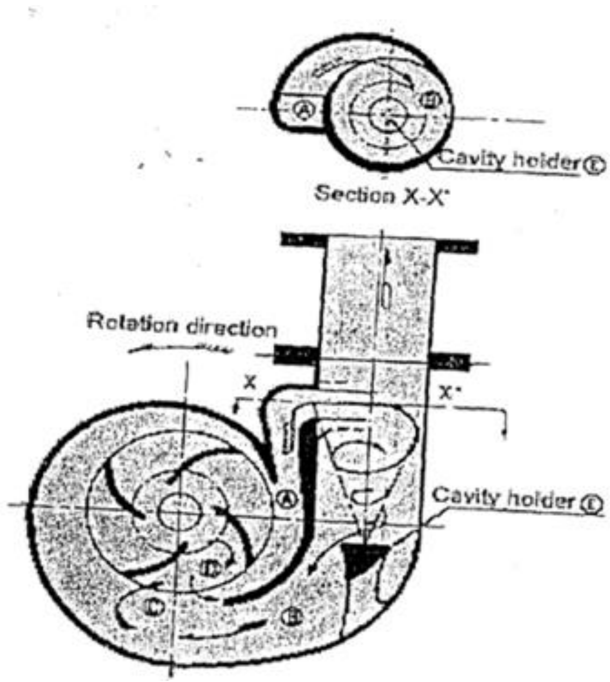
Note: $\Delta P = (P_2 - P_1) = \rho\, g\, H$

RESULTS :

1. On the same graph, plot the electrical power, mechanical power, and hydraulic power vs. the volume flow rate.
2. On the same graph, plot the head & the overall efficiency vs. the volume flow rate.

QUESTIONS :

1. When does the minimum power required to drive the pump occur ?
2. When does the maximum power required to drive the pump occur ?
3. At what point does the maximum pump efficiency occur ? Will this change if the RPM is to change ?



Centrifugal Pump

Data Sheet

N = 2500 RPM

Run	**P_1 (inlet) (bar)**	**P_2 (outlet) (bar)**	**Q (L.P.S)**	**F (N)**	**Voltage (V)**	**Current (A)**
1						
2						
3						
4						
5						
6						
7						
8						

Fluid Mechanics
Experiment # 3b
Positive Displacement Pumps-Piston and Gear Pumps
Apparatus: Positive Displacement system– Fluid mechanics lab.

Introduction

Pumps are mechanical devices that impart energy to fluid. Pumps lift water from one elevation to a highest level, overcome friction and minor losses during the conveyance and add pressure head to the outlet. Many applications involves circulating pumps that circulate a liquid in a given system (e.g central heating system). Pumps use mechanical energy generated from diesel, gasoline or electric motors to increase the pressure and the velocity head of water.

Types of Pump

Rotodynamic pumps use rotating propellers or impellers to accelerate a fluid movement and therefore add pressure. Positive displacement pumps trap and move a known volume of fluid at high pressure. Rotodynamic pumps usually give a steady, smooth output (no pulsations) at lower pressures. Positive displacement pumps usually create pulses in their output flow. These pressure pulses can be high, so designers often fit pulsation dampers in the flow circuit to steady the flow

- Pumps are classified into (1) positive displacement and (2) kinetic pumps.
- Positive displacements are divided into rotary and reciprocating;
- Rotary pumps includes gear pumps, vane pumps, screw pumps, lobe and cam pumps.
- Reciprocating include Radial or centrifugal, axial flow and mixed flow pumps.

Positive displacement pumps
Positive displacement pumps operate by trapping a fixed volume of liquid then releasing it to a higher pressure by means of a piston or rotary gear.
Reciprocating pumps use a piston, plunger, or diaphragm to raise the pressure of a liquid. The pumping chambers are surrounded by one-way valves so that liquid can only move in from the low pressure side and out from the high pressure side. They are classed as "single acting" if fluid is moved only on the down stroke, or "double acting" if fluid is moved by both sides of the piston. Because of the mechanism, these pumps produce a pulsating flow; but since flow is independent of head, they can be used to produce large pressure changes. Reciprocating pumps are best for low volume, high head applications (up to 50000 psi). They cannot be used when pulsating flow is a Rotary pumps use a gear, lobe, screw, cam, or vane to compress liquid. Liquid enters through a gap between the rotating element and pump wall at a low pressure where it is trapped. Then, as the element rotates, it squeezes the liquid out through a one-way valve on the opposite side of the casing.

Typically, rotary pumps are used in high head, low flow applications. They are good for high viscosity and low vapor pressure fluids. The fluid pumped must be "lubricating"; solids cannot be present. A key difference from centrifugal pumps is that discharge pressure variation has little effect on capacity.
Positive displacement rotary pumps also have their weaknesses. Because of the nature of the pump, the clearance between the rotating pump and the outer edge must be very close, requiring that the pumps rotate at a slow, steady speed. If rotary pumps are operated at high speeds, the fluids will cause erosion, much as ocean waves polish stones or erode rock into sand.

Table 1: pump types

Pump	Pulse output magnitude	Relative Cost	Efficiency	Can pump solids in fluid?	Easily damaged by contaminated fluid	Maintenance
Piston Pump (MFP103a)	High	Low	Medium	No	Yes	Medium
Gear Pump (MFP103b)	Low	Low	Medium	No	Yes	Low
Vane Pump (MFP103c)	Medium	Medium	High	Yes	No	Can be high - determined by materials used
Swash-plate Pump (MFP103d)	Low	High	High	No	Yes	Medium

Objectives

General objective of experiment is to study characteristics and performance of reciprocating and gear pumps. In particular student will learn the following;

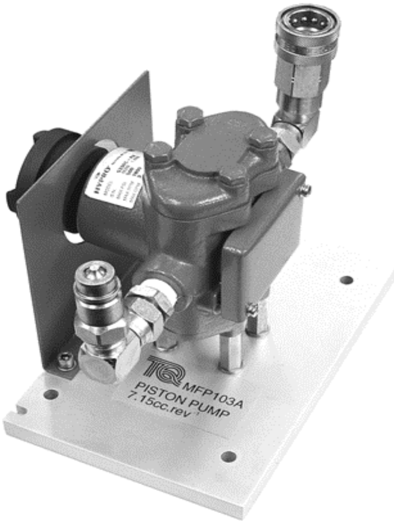
- The Effect of Delivery Pressure at Constant Speed
- The Effect of Speed at Constant Delivery Pressure.
- The Effect of Inlet Pressure on Pump Performance

System Description

Figure 1 shows the main parts of the Positive Displacement Pump Module. It shows the Module fitted with the Universal Dynamometer. The Universal Dynamometer turns the optional pump you fit to the frame. The pump forces oil around a circuit. The oil comes from an oil reservoir, through an inlet valve and through the pump. It then passes through a pressure relief valve (for safety) and a delivery valve. It then passes through a gear-type flowmeter and back to the oil reservoir. The oil reservoir has a level indicator, so you can see how much oil it contains.

Figure 1 Positive displacement pump module

Electronic pressure transducers in the circuit measure the oil pressures at the inlet to the pump and at the outlet of the pump. The delivery pressure transducer measures pressure downstream of the pressure relief valve. To obey good engineering practice, a mechanical pressure gauge also shows the delivery pressure, in case of electrical power failure. The mechanical pressure gauge also helps you to see the pressure pulses at the outlet from the pumps. A thermocouple measures the oil temperature to help find its viscosity. The flowmeter measures the oil flow in the circuit. The electronic pressure transducers, the thermocouple and flowmeter all connect to a digital display that shows the pressures, temperature and flow.
Figure 2 shows the piston pump. This pump is a twin piston industrial pump. It has an off-center cam that pushes two small vertically- opposed pistons up and down alternately in cylinders as shown in figure 4. They move oil through one-way valves from the inlet to the outlet. The swept volume of each cylinder determines the volume of fluid moved for every revolution. Because the pump uses just two pistons, it creates high pressure pulses in the fluid at the output. In most applications, this type of pump has a pulsation damper on its output.



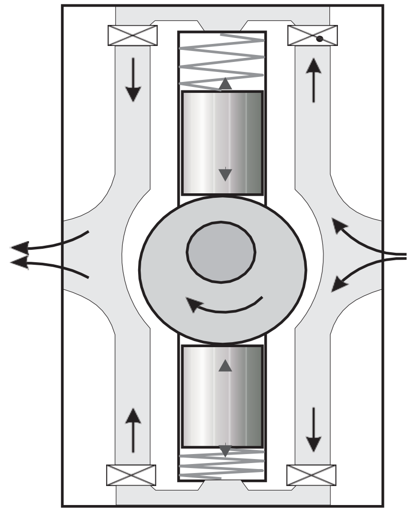


Figure 2 Piston pump

Gear Pump (MFP103b)
This pump is basically two gears that move together in a close-fitting housing as shown in figure 3. As the gears move they create a low pressure area at the input port. Fluid moves into the low pressure area. The gears trap and push small volumes of the fluid around the walls of the housing and to the outlet. The output is reasonably smooth, with small pulses. There are several slightly different designs of gear pump, but the basic principle is the same. The size of the gears determines the volume of fluid moved in each revolution.

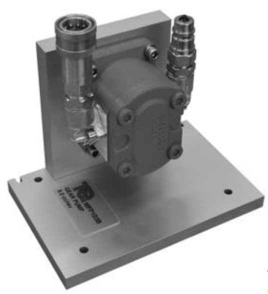
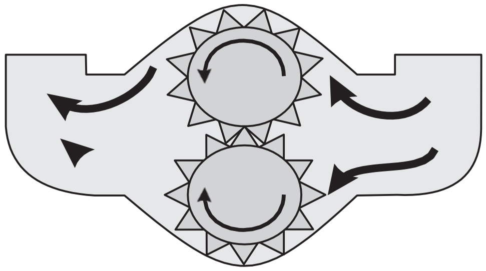


Figure 3 Gear pump.

The Digital Pressure, Temperature and Flow Display

This display connects to the two pressure transducers, the flowmeter and the thermocouple. It displays the oil pressure (at inlet and outlet), its temperature and its flowrate.



In the middle of the Pressure Display is a button marked ‘Press and Hold to Zero Display’. Use this button to zero the pressure readings before each experiment.

The Oval Gear Flowmeter

The oval gear flowmeter is perfect for measuring the oil flow in the oil circuit. It works best with viscous fluids and gives a small pressure loss compared with other flowmeters. It works accurately for a large viscosity range. Its only limitation is that it will only work with clean fluids, as medium to large particles will damage it. It is two oval gearwheels that rotate together, turned by the force of the flow that passes through them. They only allow a fixed volume of fluid to pass for each revolution. A sensor detects the gearwheels rotating. The flow rate is a product of the fixed volume and the gearwheel rotations in a given unit of time (seconds or minutes).

Versatile Data Acquisition System (VDAS)

It is a two-part product (Hardware and Software) that will:

- Automatically log data from your tests
- Automatically calculate data for you
- create charts and tables of your data
- export your data for processing in other software.

Table 2: Piston and gear pumps specifications.

Item	Details
Dimensions (all pumps)	Approximately 300 mm x 300 mm x 300 mm
Piston Pump (MFP103a)	Net Weight: 7.5 kg Twin, vertically-opposed pistons Swept Volume - 0.00715 L.rev^{-1} (7.15 cc.rev^{-}
Gear Pump (MFP103b)	Net Weight: 8 kg Swept Volume - 0.008 L.rev^{-1} (8 cc.rev^{-1})

Theory

The pressure increase (or 'head') and flow rate caused by a pump are its two most important qualities. Next most important are its efficiency and power needs.

Mechanical Power (into the Pump)

This is simply the shaft power at the pump. The Universal Dynamometer couples directly to the shaft of the pumps. So, the shaft power displayed by the Motor Drive is the shaft power at the pump (assuming no losses in the coupling).

Hydraulic Power (from the Pump)

The hydraulic power that the pump adds to the fluid is a product of the flow through the pump and the increase in pressure (or 'head') it gives:

$$Wp = Q(P2 - P1) = \rho g Q \Delta H$$

For a real pump, the hydraulic power it adds to the fluid is always less than the shaft power given to the pump.

Overall Pump Efficiency

Equation below gives the overall efficiency of the pump. It is a simple ratio of hydraulic power out against shaft power input to the pump.

$$\eta = \frac{Whudraulic}{Wmechanical} = \frac{\rho g Q \Delta H}{Wmech}$$

Volumetric Efficiency and the Expected (Theoretical) Flow

Volumetric efficiency is an indication of how well the pump has moved an expected (or theoretical) volume of fluid. It is the ratio of the actual volume of fluid moved in a given time against the expected volume of fluid moved. You normally use the total swept volume (Vs) in the pump to find the expected flow. This is easy to find for piston and cylinder type pumps, but more difficult for gear type pumps. To make this easier you may also use the given volume or displacement for each revolution (cc.rev-1).

The flowmeter measures the actual volume flow (Q_V). The expected volume flow is the product of the swept volume (or cc.rev-1) and the speed of the pump (NP).

Expected volume flow Q_V = Vs x Np

From this, the volumetric efficiency $\eta = \frac{\text{QV}}{\text{Vs x Np}} 100$

For simpler calculations, you can use non-SI units to find the volume flow

$$\eta V = \frac{100000\text{xFlow rate}}{\text{cc/rev x Speed}}$$

Where flow in L/min and speed in rev/min.

Cavitation

When you reduce the inlet pressure to a pump, it can fall to a pressure equal to (or lower than) the vapor pressure of the fluid that it pumps. This creates bubbles of vapor in the fluid, that collapse when the pressure increases as the fluid passes through the pump. The collapsing vapor bubbles cause small pressure waves that can damage the pump. You can usually hear cavitation - the noise from the pump will change or get louder as the inlet pressure decreases. The low pressure areas may also occur inside the moving parts of some pumps under low pressure conditions.

Part 1 - The Effect of Delivery Pressure at Constant Speed

Aim

To find how the pump performs for a range of delivery pressures (varied load) at a constant speed.

Procedure

1. Create a blank table of results, similar to Table 2. If you are to use VDAS, start the software. It will create the results table for you automatically when you take readings.
2. Fully open the inlet and delivery valves.
3. Use the button on the pressure display to zero all pressure readings.
4. Zero the torque reading of the MFP100 Universal Dynamometer (see its user guide for details).
5. Press the start button of the Motor Drive and run the speed to 1600 rev.min^{-1} (+/- 5 rev.min^{-1}) for at least five minutes and monitor the oil temperature until it stabilizes. Check that any air bubbles have moved away from the flowmeter.
6. Record the speed and oil temperature.
7. Slowly shut the delivery valve and maintain the speed until the delivery pressure reaches 2 bar. Allow a few seconds for conditions to stabilize. Record the indicated flow and pressures. If you are using VDAS, click on the record data values button, to record all data automatically.
8. Continue increasing the delivery pressure in 1 bar steps (while keeping the speed constant) to a maximum of 15 bar. At each step, allow a few seconds for conditions to stabilize and record the indicated flow and pressures.
9. Repeat above runs at another speed 1800RPM

Results Analysis

a. From your results, find the pressure difference across the pump and calculate the hydraulic power (remember to convert your readings to SI units).
b. Calculate the expected flow for the speed of your tests (speed x swept volume or cc.rev^{-1}) and the overall and volumetric efficiencies. If you use VDAS, the software will do this for you automatically. Fill the results table below.
c. Plot a different chart for each test speed. On each chart, use two vertical axes and plot curves of flow rate (left axis), overall and volumetric efficiencies and shaft (input) power (right axis) against pressure difference (horizontal axis).
d. Compare the results at the different speeds, and comment on effect of speed on the performance.

Table test results at constant speed.

Pump: cc.rev^{-1}: Oil Temperature: Speed: Expected Flow:							
Delivery Pressure (bar)	Inlet Pressure (bar)	Pressure Difference (head)	Flow (L.min^{-1})	Shaft Power (W)	Hydraulic Power	Overall Efficiency	Volumetric Efficien
2.0							
3.0							
4.0							
5.0							
6.0							
7.0							
8.0							
9.0							
10.0							
11.0							
12.0							
13.0							
14.0							
15.0							

Data sheet for part 1

Table 2 Data for Constant Speed Test

	1600 RPM			1800 RPM		
Delivery Pressur	Inlet Pressure	Flow (L.min^{-1})	Shaft Power (W)	Inlet Pressure (bar)	Flow (L.min^{-1})	Shaft Power (W)
2.0						
3.0						
4.0						
5.0						
6.0						
7.0						
8.0						
9.0						
10.0						
11.0						
12.0						
13.0						
14.0						
15.0						

Part 2 the Effect of Speed at Constant Delivery Pressure

Aim

To find how the pump performs for a range of speeds at a constant delivery pressure (load).

Procedure

1. Create a blank table of results, similar to Table 3. If you are to use VDAS, start the software. It will create the results table for you automatically when you take readings.
2. Fully open the inlet and delivery valves and use the button on the pressure display to zero all pressure readings.
3. Zero the torque reading of the MFP100 Universal Dynamometer (see its user guide for details).
4. Press the start button of the Motor Drive and run the speed to 1600 rev.min^{-1} (+/- 5 rev.min^{-1}) and run the pump for at least five minutes and monitor the oil temperature until it stabilizes.
5. Wait for any trapped air bubbles to move away from the flowmeter before you continue.
6. Slowly shut the delivery valve and maintain the speed until the delivery pressure reaches 15 bar.
7. Allow a few seconds for conditions to stabilize, then record the speed, the oil temperature, the indicated flow (from the display) and pressures. If you are using VDAS, click on the record data values button, to record all data automatically.
8. Reduce the speed by 100 rev.min^{-1} while adjusting the delivery pressure to keep it constant at 15 bar. Allow conditions to stabilize, then record the flow and pressures.
9. Continue decreasing the speed in 100 rev.min^{-1} steps (while keeping the pressure constant) until you reach 800 rev.min^{-1}. At each step, record the indicated flow and pressures.
10. Repeat the experiment at two more (lower) fixed delivery pressures, recommends 10 bar and 5 bar.

Results Analysis

a. From your results, find the pressure difference across the pump and calculate the hydraulic power (remember to convert your readings to SI units).
b. Calculate the expected flow for each speed (speed x swept volume or cc.rev^{-1}) and the overall and volumetric efficiencies. If you use VDAS, the software will do this for you automatically. Fill the results table below
c. Plot a different chart for each tested delivery pressure. On each chart, use two vertical axes and plot curves of flow rate (left axis), overall and volumetric efficiencies and shaft (input) power (right axis), all against pump speed (horizontal axis).
d. Compare the flow rates at the different delivery pressures.

Pump: cc.rev^{-1}: Oil Temperature: Delivery								
Speed (rev.min^{-1})	Inlet Pressure (bar)	Pressure Difference (head)	Flow (L.min^{-1})	Expected Flow	Shaft Power (W)	Hydraulic Power (W)	Overall Efficiency	Volumetric Efficiency
1600								
1500								
1400								
1300								
1200								
1100								
1000								
900								
800								

Data sheet for Part 2

	Delivery pressure 15 bar			Delivery pressure 10 bar		
Speed (rev.min^{-1})	Inlet Pressure (bar)	Flow (L.min^{-1})	Shaft Power (W)	Inlet Pressure (bar)	Flow (L.min^{-1})	Shaft Power (W)
1600						
1500						
1400						
1300						
1200						
1100						
1000						
900						
800						

Part 3: The Effect of Inlet Pressure on Pump Performance

Aim

To show how reduced inlet pressures affect pump performance and cause cavitation.

Procedure

1. Create a blank table of results, similar to Table 4. If you are to use VDAS, start the software. It will create the results table for you automatically when you take readings.
2. Fully open the inlet and delivery valves.
3. Use the button on the pressure display to zero all pressure readings.
4. Zero the torque reading of the MFP100 Universal Dynamometer (see its user guide for details).
5. Press the start button of the Motor Drive and run the speed to 1600 rev.min^{-1} (+/- 5 rev.min^{-1}) and run the pump for at least five minutes and monitor the oil temperature until it stabilizes.
6. Wait for any trapped air bubbles to move away from the flowmeter before you continue.
7. Slowly shut the delivery valve and maintain the speed until the delivery pressure reaches 2 bar.
8. While keeping the speed and delivery pressure constant, use the inlet valve to reduce the inlet pressure to the nearest 0.1 bar.
9. Allow a few seconds for conditions to stabilize, then record the speed, the oil temperature, the indicated flow (from the display) and pressures. If you are using VDAS, click on the record data values button, to record all data automatically.
10. Continue decreasing the inlet pressure in 0.1 bar steps (while keeping the delivery pressure and speed constant) until you can hear a change in the sound from the pump (cavitation). At each step, record the indicated flow and pressures.

Results Analysis

a. From your results, find the pressure difference across the pump and calculate the hydraulic power (remember to convert your readings to SI units).
b. Calculate the expected flow for each speed (speed x swept volume or cc.rev^{-1}) and the overall and volumetric efficiencies. Fill the results table below.
c. Create one chart with two vertical axes. Plot curves of the flow rate (left axis), overall and volumetric efficiency and shaft (input) power (right axis) against the inlet pressure (horizontal axis).
d. Comment on how the low inlet pressures (that can cause cavitation) affect the performance of the pump.

Pump: cc.rev^{-1}: Oil Temperature: Delivery Pressure: Speed: Expected Flow:						
Inlet Pressure (bar)	Pressure Difference (head)	Flow (L.min^{-1})	Shaft Power (W)	Hydraulic Power (W)	Overall Efficiency	Volumetric Efficienc

Data sheet part 3
Speed: rpm
Delivery pressure 2 bar

Inlet Pressure (bar)	Flow (L.min^{-1})	Shaft Power (W)
Cavitation		

Fluid Mechanics:
Experiment No. 4
FanTest
Apparatus: Air fan/ Thermodynamic lab

Objectives:

- Distinguish different types of fans
- To see the different components of a centrifugal fan system
- Measure fan head, flow rate, mechanical and electrical power
- Establish the fan performance curves: head versus flow rate, power versus flow rate, efficiency versus flow rate.
- Test the effect of fan speed on fan performance.
- Test the effect of the fan impeller on the fan performance.

Apparatus description:

Figure 1shows the fan test set up, the system consists of AC motor that drives a centrifugal fan. Impeller mounted on the fan can be radial, forward or backward curved. Air flow throw the fan can be adjusted by varying the opening on the fan exhaust (10 – 100% opening). Manometers record the pressure at nozzle inlet, before and after the fan. Mechanical power is measured by measuring the force on the balancing belt. Speed of motor can be adjusted to give different speeds rpms.

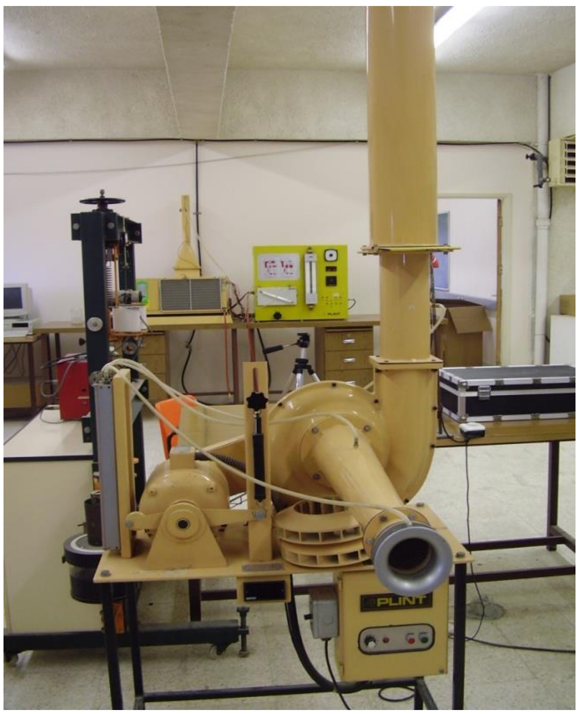


Figure 1: Fan test system.

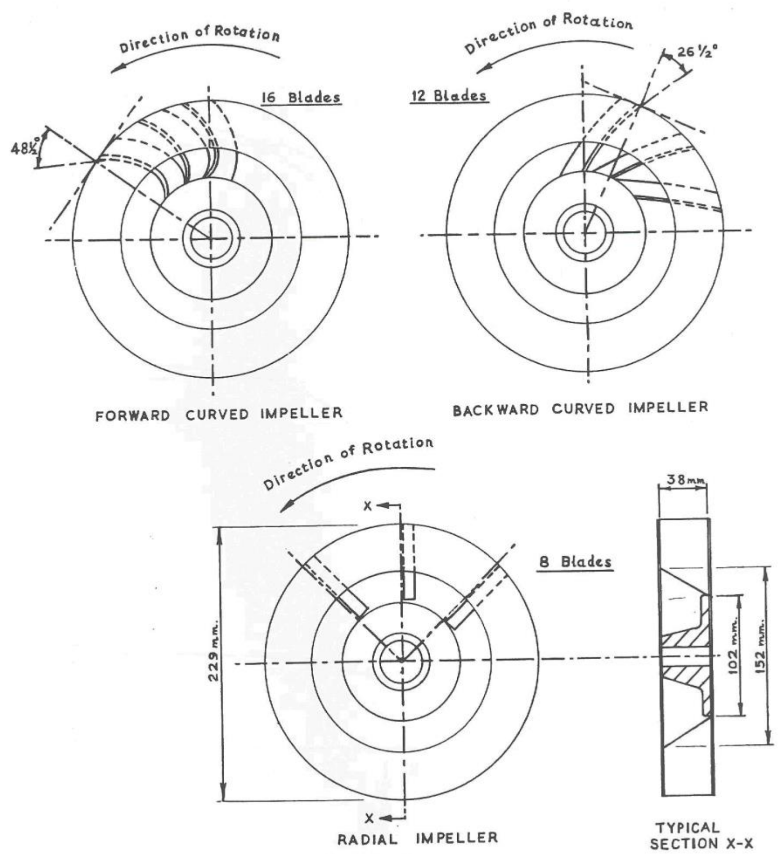


Figure 2: Schematic of impellers.

Experimental procedure

1. Switch on power.
2. Adjust the throttle opening at 100%.
3. Adjust the fan speed to a value of 2400 RPM.
4. Balance the motor case.
5. Read and record the following: Throttle opening (%), the pressure at the throat of the nozzle (h_1), the fan inlet pressure (h_2), the fan outlet pressure (h_3), Load (F).
6. Repeat the above at the same speed but at different openings 10% increments.
7. Install the second impeller blade on the fan (radial, forward or backward). The instructor will show you the proper procedure.
8. Repeat the above test at the same rpm and different openings.
9. Install the third impeller blade on the fan (radial, forward or backward).
10. Repeat the above test at the same rpm and different openings.
11. Make sure that NO impeller is installed on the fan.
12. Measure the force without the impeller at the used speed rpm.
13. For the backward impeller carry out the test at two different speeds 2400, 1200 rpms.

Theory

The fan is belt driven by a 1 horsepower AC motor. The fan is provided with three interchangeable impellers having respectively radial, forward curved and backward-curved blades. By using the inlet nozzle as a flow meter the characteristics of the different impellers may be explored.

The fan test set up, shown in Fig. 1, is supplied with three single column manometers for measuring the pressure at the throat of the measuring nozzle (h_1), the pressure before the fan (h_2), and the pressure after the fan (h_3).

Using the inlet nozzle in the present set-up as a flow meter, the volumetric flow rate, Q, and the mass flow rate, $\dot{m}$, can be obtained :

Volumetric flow rate:

$$Q = 1.006\sqrt{\frac{\Delta PT}{P_a}} \quad , m^3/s$$

Mass flow rate:

$$\dot{m} = 0.00351\sqrt{\frac{P_a \Delta P}{T}} \quad , kg/s$$

where :ΔP is in cm H_2O

$\Delta P = h_o - h_1$

h_o = atmospheric gage pressure, cm H_2O

h_1 = gage pressure at the throat of the nozzle, cm H_2O

T = absolute temp. of the air, K

P_a = atmospheric pressure, N/m^2

The Fan Total Pressure, P_{fan}, is defined as the difference between the total pressures at the fan outlet, and the fan inlet. In the present apparatus the cross sectional areas at the fan inlet and outlet, at which inlet and outlet pressures are measured, are equal. Therefore, the velocity pressures at inlet and outlet are equal to the difference between the corresponding static pressures, h_3 at the outlet and h_2 at the inlet:

$$P_{fan} = h_3 - h_2 \quad ,\text{cm } H_2O$$

$$P_{fan} = \gamma_{H2O}(h_3 - h_2) \quad ,N/m^2$$

The Total Air Power of the fan, TAP_{fan}, or the useful work done, is equal to the product of the Fan Total Pressure, P_{fan}, and the volumetric flow rate; Q :

$$TAP_{fan} = P_{fan}\, Q \quad , J/s \equiv Watt$$

The power input from the dynamometer to the shaft, SP, is given by:

$$\text{Shaft Power,} \quad SP = \frac{2\pi r.F.N}{60} \quad , Watt$$

where: r = torque arm radius (m) = 0.179 m

F = force (N)
N = speed (RPM)

The impeller Power, IP, is equal to the shaft power, SP, minus the losses in the driving belt and the bearings. These losses can be measured by driving the fan with the impeller removed. May use above equation for the finding the losses where F is the measured force while impeller is removed.

The net fan total efficiency, η_{fan}, is defined as the ratio of the total air power of the fan, TAP_{fan}, to the impeller power, IP:

$$\eta_{fan} = \frac{TAP_{fan}}{IP}$$

<u>Analysis & calculations</u>

The performance curves of the tested fan are to be established, including power, versus flow rate, pressure rise (head) versus flow rate and efficiency versus flow rate at certain speed.

1. Calculate the losses in the driving belt and the fan bearings at the tested speed.
2. For the three types of impellers calculate and summaries in a table:
    a. The volumetric flow rate, Q, in m^3/s.
    b. The mass flow rate, $\dot{m}$, in kg/s.
    c. The fan total pressure, P_{fan}, in N/m^2
    d. The total air power of the fan, TAP_{fan}, in Watts.
    e. The shaft power, SP, in Watts.
    f. The impeller power, IP, in Watts.
    g. The net fan total efficiency, η_{fan}.
3. For the three types of impellers at the tested fan speed RPM (plot for the three impeller on the same figure);
    a. Plot the fan total pressure, P_{fan}, vs. the volumetric flow rate, Q
    b. Plot the impeller power, IP, vs. the mass flow rate, $\dot{m}$
    c. Plot the fan efficiency, η_{fan}, vs. the volumetric flow rate, Q
4. For the backward curved impeller blades;
    a. Show the total fan pressure, P_{fan}, vs. the volumetric flow rate, Q, for the two different speeds.
    b. Show the fan efficiency, η_{fan}, vs. the volumetric flow rate, Q, for the two different speeds.
5. Discuss the effect of impeller type on the above performance curves.

Fluid Mechanics:
Experiment No. 5
Reciprocating Compressor
Apparatus: Two Stage Reciprocating Compressor/ I.C.E lab

Objectives:

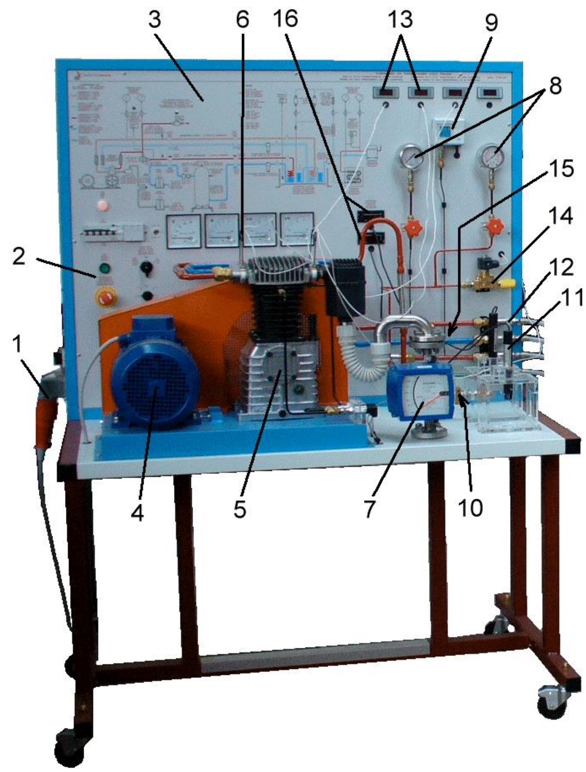
- Distinguish different types of compressors
- Examine parts of a reciprocating compressor.
- To measure air flow rate, pressure rise, power of a compressor
- Analyze p-v diagram of a single and a two stage compressor
- Measure volumetric, mechanical and isentropic efficiency of compressor
- Study the effect of compression ratio on performance
- First law analysis of compressor
- Operate a two stage compressor
- Study the effect of inter cooling on compressor performance
- Thermodynamic analysis of stored air (ideal gas and real gas).
- Study the effect of rpm on compressor performance.

Apparatus description:

The experimental set up includes a reciprocating two stage compressor with optional intercooler and a compressed air storage tank.

The system used to acquire the parameters of the compressed air as shown in figure 1 consists of a series of sensors that transmit the operation data to an electronic interface. The PC and the software take these data and process them. The measured parameters include:

- The air humidity at the circuit inlet and outlet (atmospheric pressure)
- The pressure in the cylinder of the 1st and 2nd stage
- The air temperature at inlet and outlet of 1st and 2nd stage
- The compressor rpm
- An ammeter and a voltmeter to measure the power of the compressor.



1. Power supply: 3-phase with neutral and ground
2. Electrical panel
3. Synoptic diagram in silk-screen aluminum
4. Electrical motor
5. 2-stage compressor
6. Temperature sensors
7. Flow sensor
8. Pressure gauges for high and medium pressure
9. Safety pressostat
10. Pressure regulator
11. Humidity sensors
12. Quick couplings for connection to opt. cooler
13. Digital thermometers
14. Electric safety valve
15. Mechanical safety valve
16. Hygrometers

Figure 1: Two stage reciprocating compressor set up.

The control panel includes switches and read outs as shown in figure 2.

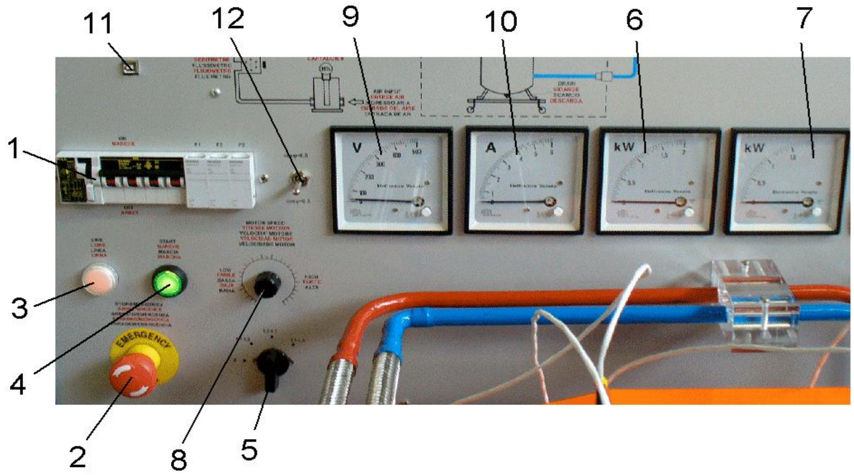


Figure 2: Control panel of system

Dimensions of each stage

1. Magneto-thermal switch, differential switch, fuses
2. Emergency push button
3. Line lamp
4. March button
5. Voltmetric selector
6. Wattmeter1
7. Wattmeter 2
8. Electric motor speed regulating potentiometer
9. Voltmeter
10. Ammeter
11. USB port
12. Voltmetric inverter of wattmeter no. 2

1^{st}. stage diameter = 90 mm
1^{st}. stage stroke = 65 mm
2^{st}. stage diameter = 50 mm
2^{nd} stage stroke = 65 mm

Heat exchanger
For each exchanger
Pipe diameter 12 mm
Pipe length 6.72 m
Surface area =0.255 m^2.

Experimental procedure

The experiments that can be done with this equipment include;

- Study of a compressor.
- Measurement of the cycle pressure and temperature values.
- Determination of the aspired air mass.
- Determination of the specific heat absorbed by the air during the compression in the 1st and 2nd stage.
- Determination of the work done on the air mass.
- Determination of the exchanged heat.
- Calculation of the compressor volumetric efficiency.
- Calculation of the rated power of the 1st and 2nd stage.

Compressor speed, rpm

Through the electric motor speed regulating potentiometer you can modify at your best the motor rotation speed from zero value (when the potentiometer is completely rotated clockwise) to the maximum value (when the potentiometer is completely rotated counter-clockwise). Starting from the configuration corresponding to electric motor still, to increase the rotations of the motor you must rotate the control potentiometer clockwise.

Pressure regulation

The regulation of the system operating pressure is done using the pressure regulator set at the air outlet.

Operation with air tank

The compressor operation is controlled by the pressure switch which interrupts the motor supply when the air pressure in the tank reaches the maximum established value. When the pressure drops under the differential, it is necessary to press run button to start again.

Operation with cooler

If you connect the water tank to an external cooling circuit (shown in figure 3) you can cool the compressed air both at the 1st and 2nd compression stage. The gas cooling is accomplished by heat lost to the water tank from the copper tubing.

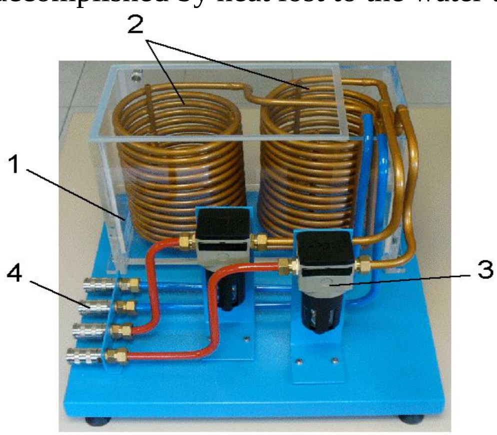


Figure 3: inter-cooling heat exchanger.

1. Tank , 2. Heat exchangers, 3. Automatic water drainage,4. Quick pipe couplings for connection to TTACM/EV

TTACM Software

The bench TTACM/EV application software is given from which the compressor system can be analyzed.

1. Running the program, the trainer's supervision window appears on the display. As shown in figure 4

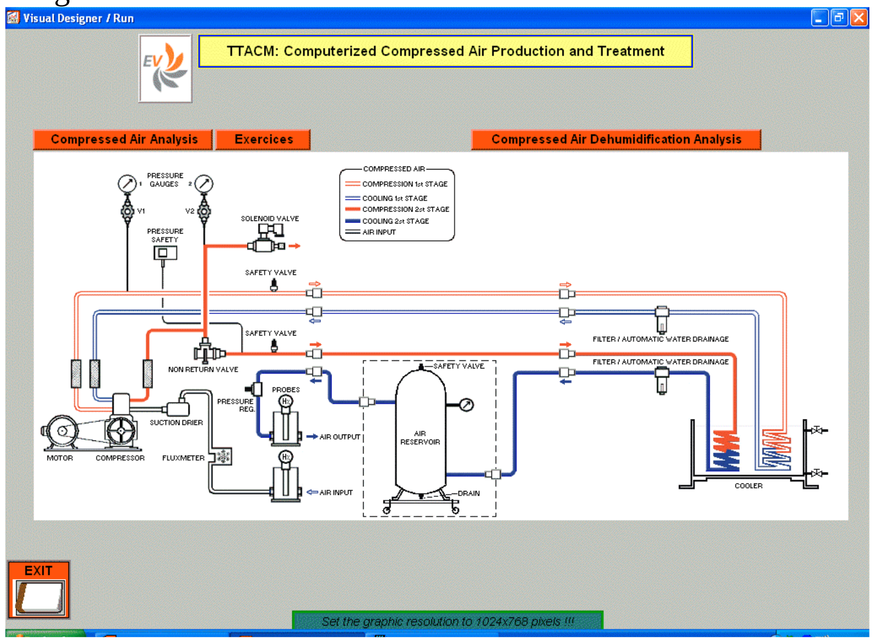


Figure 4: Supervision window.

2. Pressing button "**Compressed Air Analysis**" you enter the following display see figure 5, where you find the main components of the equipment, the temperature values, the pressures, the air relative humidity at the bench inlet and outlet, the value of the suction air flow, the number of turns of the compressor.

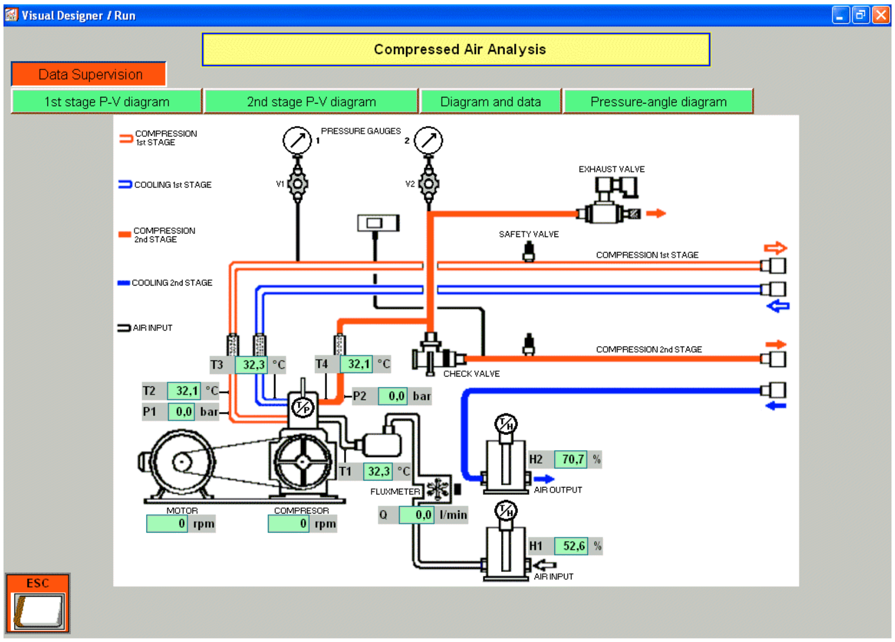


Figure 5: Compressor air analysis window.

On the top of the syn-optical diagram as shown in figure 5, there are four buttons which, when pressed with the mouse, allow to enter the thermodynamics elaborations, based on the values acquired by the probes.
Pressing the key “**1st stage P-V Diagram**”, the pressure data corresponding to each position the first stage piston assumes during its run appear on the P-V diagram, figure 6.

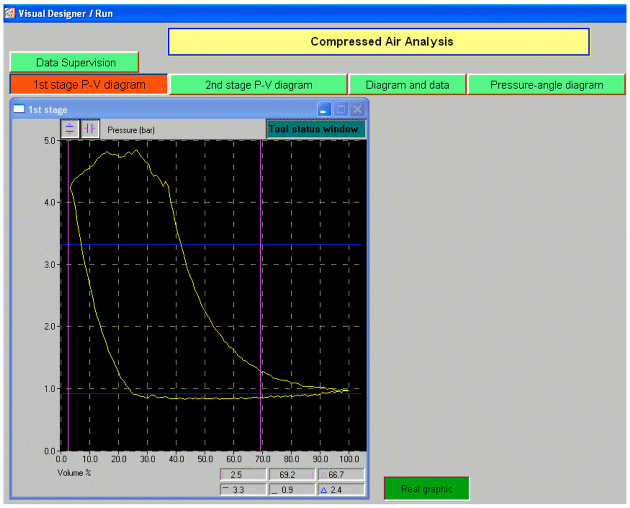


Figure 6: P-V diagram of 1st. Stage.

Pressing the key “**2nd stage P-V Diagram**”, the pressure data corresponding to each position of the second stage piston assumes during its run is drawn in the Pressure – Volume diagram, generating the real compression cycle. The same considerations developed for the first one are valid for this diagram.

Pressing the key "**Diagram and Data**" the two overlapped diagrams are represented, as shown in figure 6, whose forms, amplitudes and reciprocal position, are to be considered for evaluating the correct operation and the construction quality of the machine.

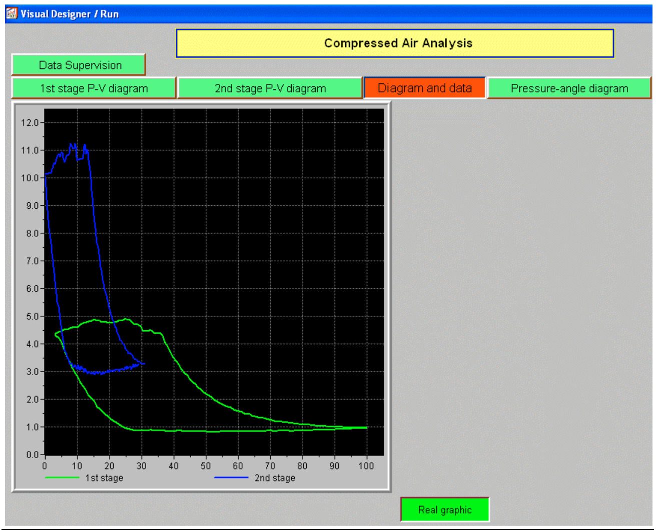


Figure 6: P-V diagram of two stages.

Pressing the key "**Pressure-Angle Diagram**" the pressure diagrams of the first and second states are represented, with reference to the lever.

3. Exercises

From the main screen (figure 4), pressing the button "**Exercises**" you enter the exercises session (figure 7).

Selecting the option "**Practical**" you charge the real data detected by PC for doing the exercises. Note that you must enter via keyboard the room temperature and the atmospheric pressure.

Selecting the option "**Theatrical**" you can develop theoretical exercises based on the data written via keyboard.

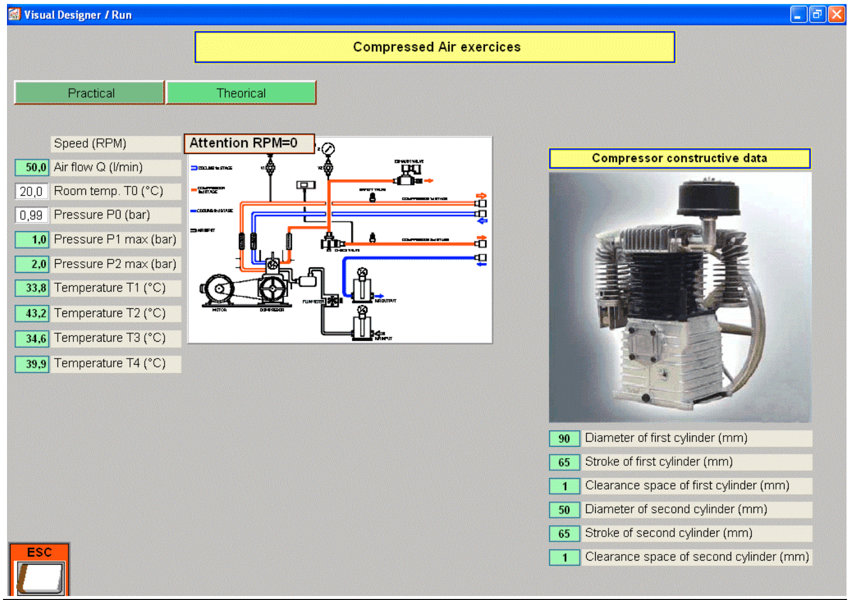


Figure 7: Exercises window.

Theory

The air in the compressor will be treated as ideal gas. Thermodynamic properties of air from thermodynamic tables can be used in the calculations. Figure 8 is a schematic of the two stage compressor with intercooler.

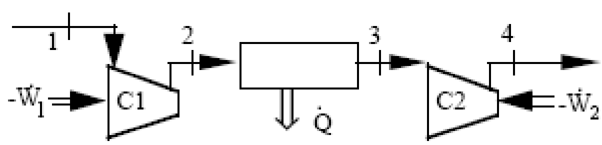


Figure 8: Schematic of the compressors with inter-cooling.

Ideal P-V diagram for a reciprocating compressor is shown in figure 9 and the processes include:
1-2 polytropic compression
2-3 air exhaust at constant pressure
3-4 polytropic of remained air in the clearance volume
4-1 Air intake at constant pressure.

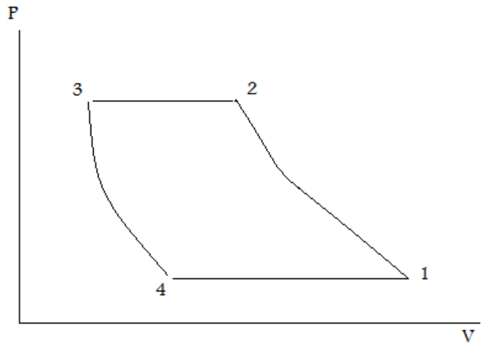


Figure 9: P-V diagram for reciprocating compressor.

The relationship between the pressure and volume during compression or expansion of an ideal gas can be described analytically. One form of this relationship is given by the equation:

$$PV^n = Constant$$

Where n is the Polytropic index.

A thermodynamic process described by the above equation is called a Polytropic process. For a Polytropic process between two states 1-2

$$P_1{V_1}^n = P_2{V_2}^n = Constant$$

- When n =0, p = constant, and the process is a constant pressure or an isobaric process.
- When n=1, pV = constant, and the process is a constant temperature or an isothermal process.
- When n⇒∞, it is called an isometric process, and the process is a constant volume process.
- When n = k, it is an called isentropic process, and pV = constant.
- the case **1 < n < k** , in this process heat and work flows go in opposite directions, This process occurs, for example, in vapor compression refrigeration during compression
- the case **k < n** < ∞, in this process heat and work flows go in the same direction, This process occurs, for example, in an internal combustion engine (e.g. Otto cycle), in which there are heat loses through the cylinder walls during gas expansion (power stroke).

The Polytropic index can be calculated as follow:

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^n$$

By applying the ideal gas law, we can get:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$$

$$\Rightarrow n = \left(1 - \frac{\ln {T_2}/{T_1}}{\ln {P_2}/{P_1}}\right)^{-1}$$

The specific of constant pressure, constant volume, and Polytropic compression can be calculated as given:

$$\mathrm{C}_p = 1009.0188 + 0.1523 \times \frac{\mathrm{T}_1 + \mathrm{T}_2}{2}$$

$$\mathrm{C}_v = 720.1296 + 0.1523 \times \frac{\mathrm{T}_1 + \mathrm{T}_2}{2}$$

$$\mathrm{C}_x = \mathrm{n} \times \mathrm{C}_v - \frac{\mathrm{C}_p}{\mathrm{n} - 1}$$

Where:
C_p: Specific heat of constant pressure in J/kg.K.
C_v: Specific heat of constant volume in J/kg.K.
C_x: Specific heat of Polytropic compression in J/kg.K.
T_1 & T_2: Inlet and outlet temperature in Kelvin.

The first law of thermodynamics states that (by neglecting the kinetic and potential energies):

$$\Delta h = q - w$$

Where:
Δh: Enthalpy absorbed during compression in J/kg.
q: Specific heat exchanged in J/kg.
w: Specific work done in J/kg.

The enthalpy absorbed and the specific heat exchanged during the compression are given as:

$$\Delta h = \mathrm{C}_p(\mathrm{T}_2 - \mathrm{T}_1)$$

$$q = \mathrm{C}_x(\mathrm{T}_2 - \mathrm{T}_1)$$

Thus, the specific work is equal:

$$w = (\mathrm{C}_{x} - \mathrm{C}_{p}) \times (\mathrm{T}_2 - \mathrm{T}_1)$$

In order to calculate the power, the air mass flow rate should be calculated as:

$$\dot{m} = \frac{\mathrm{P}_0 \times \dot{Q} \times M}{R \times T_a}$$

Where:
$\dot{m}$: Air mass flow rate in kg/min.
P_0: The suction pressure in kPa. P_0 = 99 kPa
$\dot{Q}$: The volume flow rate in l/min.
M: The molecular mass of air, M = 28.96
R: The universal constant of gas, R = 8314.5 J/kg.K.
T_a: The ambient temperature in Kelvin.

The power can be calculates as:

$$P = \frac{w \times \dot{m}}{60}$$

The volumetric efficiency can be calculated theoretically by:

$$\eta_{vth} = 1 + c - c\left(\frac{P_2}{P_1}\right)^{1/n}$$

Where:
η_{vth}: The volumetric efficiency.
c: The percentage clearance volume,
$\mathrm{P}_2/\mathrm{P}_1$: The compression ratio.
n: The Polytropic index.

To calculate the experimental volumetric, the compressor displacement is needed and can be calculated by:

$$\dot{V} = \frac{\pi}{4} D^2 \times S \times W_2 \times x \times N \times 1000$$

Where
$\dot{V}$: Compressor displacement in l/min
D: Cylinder bore, meter
S: Cylinder stroke, meter
W_2: Compressor speed rpm
χ: **1** for single acting and **2** for double acting cylinders
N: No. of cylinders
The experimental volumetric efficiency can be calculated by:

$$\eta_{vexp} = \frac{\dot{Q}}{\dot{V}}$$

Where

$\dot{Q}$: The suction air from the compressor in l/min.

$\dot{V}$: The compressor displacement in l/min.

Analysis & calculations

1. Operate the trainer unit without connection to the storage tank (exhausting compressed air to ambient) exhaust valve is fully open and with/without inter-cooling as connected by your instructor.
2. Set rpm of motor at 1500 (or maximum speed) by adjusting knob 8 in control panel (figure 2) for the compressor unit.
3. On a table record the readings of all parameters that appear on the main diagram by selecting data supervision (see figure 5). In addition record electrical power (current and voltage). See the attached data sheet.
4. Examine the P-V diagram for each stage. Record the intake and exhaust pressure for each stage. Also, record the volume % for both stages and for each process including intake, compression, expansion, exhaust (4 values) in addition to the (clearance volume. Compare values with that given in the data supervision.
5. Calculate for each stage compression ratio, intake and exhaust volumes.
6. Calculate air mass flow rate.
7. Assuming ideal gas and constant specific heats calculate polytropic index, specific work for each stage. Compare with values computed by the software- exercises (variable specific heats).
8. Calculate the specific indicated work for each stage from P-V diagrams using software - exercises. Then calculate the power for each stage.
9. Calculate the volumetric efficiency of the first stage, and compare with theoretical value.
10. Repeat experiment at the same rpm but at three different air flow rates. Change air flow by turning the air exhaust valve.
11. Check the effect of the speed on the performance by carrying out analysis for another rpm (half speed).

Heat transfer
Experiment No. 6
Extended surface conduction
Apparatus: Extended surface heat transfer apparatus/ Thermodynamics lab.

Objectives:

- Verify Fourier law of conduction.
- Measure conductivity of metals
- Measure temperature profile along a rod.
- Apply fin theory
- Calculate heat losses from fin rod
- Calculate efficiency of fin
- Apply basic extended surface heat transfer.

Apparatus description:

The extended surface heat transfer apparatus comprises a long horizontal rod, which is heated at one end to provide an extended surface (cylindrical rod) for heat transfer measurements. Thermocouples at regular intervals along the rod allow the surface temperature profile to be measured. By making the diameter of the rod small in relation to the length, thermal conduction along the rod can be assumed to be one-dimensional and heat loss from the tip can be ignored.

The assembly consists of the control panel with read outs and control, and the extended surface or the cylindrical rod as shown in figure 1.

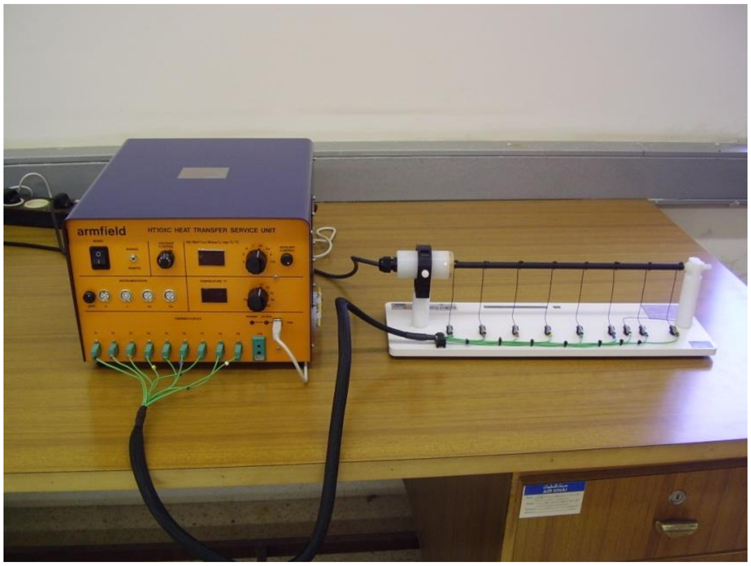


Figure 1: Extended heat transfer apparatus.

Heated rod

The bar is manufactured from a solid brass with a constant diameter of 10 mm and is mounted horizontally with support at the heated end. The bar is coated with black paint which provides a consistent emissivity close to one. The thermal conductivity of the bar is 121 W/m.K.

Heater

The rod is heated by a cartridge electric heating element operating at low voltage and is protected by a thermostat to prevent damage from overheating. The heating element is inserted co-axially into the end of the rod and is rated to produce 20 Watts nominally t 24 Volts DC. The power supplied to the heated rod can be varied and measured on the HT10X.

Thermocouples

Eight thermocouples are attached to the surface of the rod at equal intervals of 50 mm giving an overall instrumented length of 350 mm. Location of each thermocouple is shown in the apparatus. T1 measures the temperature at the hot end of the rod while T9 measures the ambient air temperature. All thermocouples are K type

The heater may be operated manually or remotely using the PC and the software.

For manual operation set the selector switch to the manual position. The voltage supplied to the heater is adjusted using the multi-turn potentiometer from 0 to 24 Volts DC.

The power supplied to the heater is the voltage times the current. Power = IxV Watts.

The temperatures can be read manually by the selecting switch set to the required position and read the value on the panel display. The temperature can be read by the Software and displayed on the mimic diagram of the HT15 software when on the REMOTE operation mode.

Experimental procedure

Part one (Manual)

1. Operate on the manual mode
2. Set the voltage control to 20 Volts. When T1 reaches 80 ^{o}C reduce voltage to 9 volts.
3. Record the temperature of all thermocouples.
4. Repeat every five minutes till reaching steady state (when readings of temperatures remain constant).

Part two (Software)

1. Select REMOTE setting, and set the voltage to zero Volts using the control box.
2. From the PC and software click **load** to start the program. Then go into **view** and schematic of rod - temperature. Enter into computer control and click *power on*.
3. From heater control adjust the heater to give 10 volts.
4. Go to **view** then *tables* click **Go** *to* see the temperatures, repeat this every 5 minutes until reaching steady state. Clicking *sample* then *next results*.
5. To view the graph click **view** then **graph**, adjust the *temperature axis*
6. Repeat at another voltage 14 Volts.
7. You can save your results as excel files and copy to the USB

THEORY

- Heat transfer from a cylindrical rod:

$$h_{conv} = 1.32 \times \left\{\frac{(T_S - T_\infty)}{D}\right\}$$

Where:
h_{conv}: Convection heat transfer coefficient in W/m^2.K.
T_S: Average surface temperature in K.
T_∞: Ambient temperature in K.
D: Rod diameter = 0.01 m.

$$h_{rad} = \varepsilon\sigma \left\{\frac{\left({T_S}^4 - {T_\infty}^4\right)}{(T_S - T_\infty)}\right\}$$

Where:
h_{rad}: Radiation heat transfer coefficient in W/m^2.K.
T_S: Average surface temperature in K.
T_∞: Ambient temperature in K.
ε: Emissivity = 0.95.
σ: Stefan –Boltzmann constant = 56.7x10^{-9} W/m^2. K^4.

The combined heat transfer coefficient $h_{Total} = h_{rad} + h_{conv}$

The electrical power, conduction and convection heat transfer can be calculated as shown below:

$$q_{el} = VI$$

Where:
q_{el}: Electrical power in Watt.
V: Electric voltage in Volt.
I: Electric current in Ampere.

$$q_{cond} = kA_c \frac{(T_1 - T_2)}{x}$$

Where:
q_{cond}: Conduction heat transfer in Watt.
k: Thermal conductivity = 121 W/m.K.
A_c: Rod cross sectional area in m^2.
T_1: Temperature at x_1 in K.
T_2: Temperature at x_2 in K.
x: Distance between T_1 and T_2 in m.

$$q_{conv} = h_{conv} A_s (T_s - T_\infty)$$

Where:

q_{conv}: Convection heat transfer in Watt.

h_{conv}: Convection heat transfer coefficient in W/m^2.K.

T_S: Average surface temperature in K.

T_∞: Ambient temperature in K.

A_s: Rod surface area in m^2, where the rod length = 0.35 m.

- Extended surface analysis:

Refer to heat transfer book for convection –conduction systems.

Rectangular or pin (circular) fins have constant cross section area A_c=const=A

$$\Rightarrow \frac{dA_c}{dx} = 0$$

Base temperature T_b=T(x=0)

Fluid temperature T_p

Surface area $A_s = P_x$ or $dA_s = Pdx$

Where P: perimeter, then $\frac{dA_c}{dx} = 0$ and $\frac{dA_s}{dx} = P$ simplifying fin equation

$$\frac{d^2T}{dx^2} - \frac{h}{kA_c} P(T - T\infty) = 0$$

$$\text{Let } \theta = T - T\infty = T(x) - t\infty \rightarrow \frac{d\theta}{dx} = \frac{dT}{dx}$$

$$m^2 = \frac{hP}{A_c K}$$

$$\mathrm{m_{th}} = \sqrt{\frac{\mathrm{h_{total}} \times \mathrm{P}}{\mathrm{Area} \times \mathrm{k}}}$$

$$\frac{d^2\theta}{dx^2} - m^2\theta = 0$$

General solution : $\theta(x) = c_1 e^{mx} + c_2 e^{-mx}$

constants c_1 and c_2 evaluated from first B.C at the base (x=0) where T=T_b

$T(x=0) = T_b$ and $\theta(x=0) = T_b - T_\infty = -\theta_b$

$$\theta_b = c_1 + c_2$$

Second B.C depends on physical condition at other end.

Case A: convection at the tip (x=0)

$$q_{conv} = q_{const_{x=L}} \Rightarrow hA_c(T_l - T_\infty) = -kA_c \left.\frac{dT}{dx}\right|_{x=L}$$

$$\text{or :}\quad h\theta(L) = -k\left.\frac{d\theta}{dx}\right|_{x=L}$$

Case B: Negligible convection (insulated) tip

$$\left.\frac{d\theta}{dx}\right|_{x=L} = 0$$

Case C: finite temperature at tip $T(x=L) = T_l$ or $\theta(L) = \theta L$

Case D: very long fin $L \to \infty$ $T \to T_\infty \Rightarrow \theta L \to 0$

Apply B-C 2 for case D:

$$\theta_l = 0 = c_1 e^{-\infty} + c_2 e^{\infty} \to c_2 = 0$$

$$\text{B-C 1 :}\quad c_1 + c_2 = \theta_b \Rightarrow c_1 = \theta_b$$

$$\text{Then}\quad \theta = \theta_b e^{-mx}$$

$$m_{exp} = \frac{\left|\ln\left\{\frac{T_x - T_\infty)}{T_b - T_\infty)}\right\}\right|}{x}$$

Total heat transfer from fin for case D

$q_f = q_{constatbase}$ from energy balance over entire fin

$$q_f = -kA_c \left.\frac{dT}{dx}\right|_{x=0} = -kA_c \left.\frac{d\theta}{dx}\right|_{x=0}$$

$$q_f = -kA_c\left[-m\theta_b e^{-m(0)}\right] = kA_c m\theta_b = kA_c\sqrt{\frac{hP}{kA_c}}\theta_b$$

$$q_f = \sqrt{hPkA_c}\,\theta_b$$

$$\text{Fin efficiency} = \frac{q_f}{q_{\max}}$$

q_f : Heat lost from fin

$q_{\max}$: Maximum possible heat from fin.

Maximum heat transfer from fin could occur if entire fin is at base temperature, where maximum driving for ΔT exist. Actually $T_{(x)}$ decrease along the fin and $T_{(x)} - T_\infty$ is decreasing.

$$\gamma_f = \frac{q_f}{hA_f\theta_b}$$

A_f : is the fin surface area.

Case B: adiabatic fin (no convection at tip)

Temperature distribution along the fin is given as:

$$\frac{(Tx - T9)}{(T1 - T9)} = \frac{\cosh m(L - x)}{\cosh mL}$$

T1 = base temperature, and T9 is the ambient temperature.

The heat transfer from the fin is given as;

$$q_f = \sqrt{hPkA_c}\,\theta_b \tanh(ml)$$

The fin efficiency is given as;

$$\gamma_f = \frac{\sqrt{hPkA_c}\,\theta_b \tanh(ml)}{hA_f\theta_b} = \frac{\sqrt{hPkA_c}\tanh(ml)}{hLP}$$

since $A_f = LP$

$$\gamma_f = \frac{\tanh(ml)}{L\sqrt{\frac{hP}{kA_c}}} = \frac{\tanh(ml)}{mL}$$

<u>Analysis & calculations</u>

1. In a table list the temperature in all locations (T1 to T9)
2. Estimate the convection and radiation coefficients and the heat transfer from surface at each thermocouple location.
3. Calculate the heat lost from the rod from the power supplied to the rod?
4. Calculate the heat lost from the rod by the conduction at the base (heated end).
5. Find the value of **m** in the fin profile. You can find value of **m** for each location by solving the distribution in each location. Then calculate an average value. You may try different values to get closer to the measure profile (starting value m=7.4).
6. Plot the values of temperature at the various locations of the rod (T1 to T8).
7. Show both experimental and theoretical temperature curves on the same figure. Using the temperature distribution along the fin equation.
8. Comment on the shape of the curve.
9. Calculate the heat transfer using the theoretical equations for fins given in theory.
10. Compare the value of total heat lost from rod calculated by different methods, and comment on the difference and which one you think gives the best answer? Why?
11. Calculate the fin efficiency and compare it with theoretical values.
12. Would doubling the length of the rod double the lost heat from it? Why?

Heat transfer
Experiment No. 7
Forced and Free Convection
Apparatus: Cross flow heat exchanger/ Thermodynamics lab.

Objectives:

- Measuring time dependent temperature of a rod
- Verify lumped capacitance method.
- Measure forced convection coefficient
- Investigating effect of air speed & flow on cooling rate
- Investigating effect of air speed on convection coefficient
- Measure free convection heat transfer coefficient

Apparatus description:

The set-up for this experiment is shown in Fig. 1.
The apparatus consists of the following:

1. Perspex working section through which air may be drawn by a centrifugal fan.
2. Perspex rods, inserted into the working section with their axes at right angles to the direction of flow.
3. A pure copper rod, 10 cm in length.
4. A cylindrical electrical heater which raises the temperature of element to a maximum of 80^{o}C.
5. Centrifugal fan driven by 1 hp electric motor.
6. The fan discharges to a graduated throttle valve by means of which the air velocity through the apparatus may be regulated.
7. A total head tube to permit exploration of the flow pattern upstream of the tube bank and this may be traversed in a direction perpendicular both to the air flow and to the axes of the element.
8. Static tapping so that the velocity head may be recorded by a manometer.
9. Inclined manometer for measurement of pressure drop and velocity heads.
10. Thermocouples in the element and at the air inlet are of copper and constantan for measurement of temperature difference.

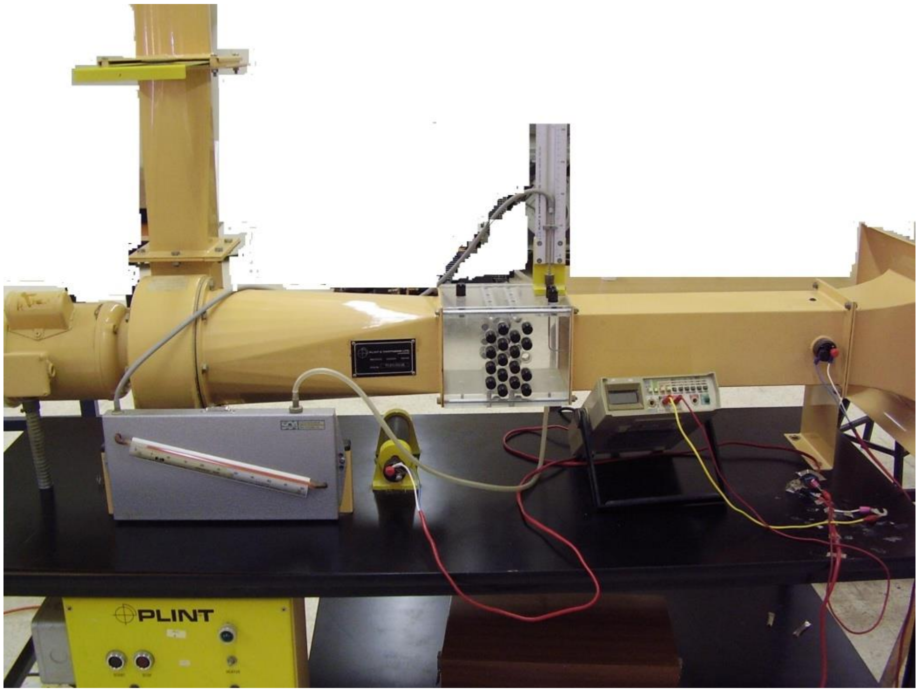


Figure 1: Cross flow het transfer apparatus

<u>Experimental procedure</u>

1. Make sure there are no perspex rods in the working station.
2. Set the throttle opening as (10%) open.
3. Insert the copper rod into the cylindrical heater.
4. Switch the cylindrical heater on.
5. When the temperature difference between the copper rod and the air temperature is in between 2.2 ~ 2.4 mV, remove the copper rod from the heater and place it in the center of the front raw.
6. Switch the fan on.
7. Once the copper rod is in place, read and record; time, t, temperature difference, $\Delta T = T - T_\infty$, every 10 seconds until the temperature difference reaches about 0.4 mV. In addition record air temperature, T_∞, and the velocity head, H_1.
8. Repeat the heating and the cooling of the rod for throttle openings of 20%, 40%, 60%, 80% and 100%.
9. For free convection repeat 1 through 3 above but don't switch the fan on, you may record temperature every 30 seconds.

Theory

Using the lumped capacity method for transient cooling, the following relation can be derived:

$$\ln\left[\frac{T - T_\infty}{T_o - T_\infty}\right] = -mt \quad ----(1)$$

$$where, m = \frac{hA_e}{\rho C V_e}$$

$$m = \frac{h}{\rho C L_s} \quad -----(2)$$

$$where, L_s = \frac{V}{A_e}$$

T	: the temp. of the heated element, ^oC.
T_∞	: air temp., ^oC.
T_o	: initial temp., ^oC.
t	: time, seconds.
h	: convective heat transfer coefficient, $\frac{W}{m^2.^o C}$
A_e	: effective surface area of heated element, m^2.
r	: density of heated element, kg/m^3.
C	: specific heat, $J/kg.^oC$
V_e	: effective volume of heated element, m^3.
L_s	: characteristic length, m

A certain amount of heat is conducted from the heated copper element into the plastic extension pieces. Due to this an addition to the true length of the heated element to give an effective length to be used in the calculations.

$$l_e = l + 0.0084$$

where : l : length of the copper heated element in m.
l_e : effective length of heated element in m.

For the lumped capacity system analysis to be valid, the value of the Biot number, Bi :

Bi < 0.1

where $Bi = \frac{hL_s}{K}$

K : thermal conductivity of the heated element, W/m. ^oC

Equation (1) represent the equation of a straight line, with a slope of -m. Plotting $\ln\left[\frac{T - T_\infty}{T_o - T_\infty}\right]$ vs. t, the slope of the line can be determined. Once the value of m is known, the convective heat transfer coefficient , h, may be calculated from equation (2). Recorded thermocouple mV to be converted to temperature using conversion tables, noting that recorded mV measures the temperature difference between the rod and the ambient air.

The velocity, V, in the test section may be determined from the following relation :

$$V = 237.3\sqrt{\frac{H_1 T_\infty}{P_a}} \quad ----(3)$$

where, H_1 : upstream velocity head, cm H_2O

P_a : atmospheric pressure, N/m^2

T_∞ : absolute temp.

To determine the velocity of the flow in the transverse plane where the heated element is located, the conservation of mass is used:

$$\dot{m}_1 = \dot{m}_2$$
$$\rho_1 V_1 A_1 = \rho_2 V_2 A_2$$
$$\rho_1 = \rho_2$$
$$V_2 = \frac{V_1 A_1}{A_2}$$

Note that, the diameter of the heated element and the perspex rods is 1.25cm, and the height of the working section is 12.5cm.

Nusselt number, Nu, is a non-dimensional heat transfer number and it is defined as:

$$Nu = \frac{hd}{K}$$

where: h : convective heat transfer coefficient

d : diameter of the heated element

K : thermal conductivity of air

Nusselt number is a function of parameters: Reynolds number, Re and Prandtl number, Pr Defined as:

$$\mathrm{Re} = \frac{Vd}{\nu}$$

$$\mathrm{Pr} = \frac{C_p \mu}{K}$$

where: V : air velocity

d : heated element diameter

ν : kinematic viscosity of air

C_p : specific heat of air

K : thermal conductivity of air

μ : dynamic viscosity of air

<u>For pure copper:</u>

Density, ρ_C= 8933 kg/m3, Specific heat, C_C = 385 J/kg.K

Thermal conductivity of the heated element, K_C = 401 W/m.oC

Diameter of rods, D =12.5 mm, L = 100 mm

For air:
Thermal conductivity of air, K_{air} = 0.0263 W/m.oC,
Specific heat of air. Cp_{air} = 1007 J/kg.K
Dynamic viscosity, μ_{air} = 0.00001846 kg/m.s, &
Kinematic viscosity,ν_{air} = 0.00001589 m2/s

Analysis & calculations

1. Plot $\ln\left[\frac{T-T_\infty}{T_o-T_\infty}\right]$ vs. time. For each of throttle opening of 10-100%.
2. Calculate heat transfer coefficient h for each opening.
3. Calculate Biot number and check the validity of the LCM
4. Calculate the air velocity and the Reynolds number for each opening.
5. Calculate the Nusselt number based on the experimentally found h.
6. Calculate the theoretical Nu from empirical forced convection correlation of a cylinder in cross flow: $Nu = 0.24\ (Re)^{0.6}$
7. Plot Nusselt number vs. Reynolds number. For both experimental and theoretical on the same graph.
8. From your experimental results obtain a correlation similar to the above one as Nu = f(Re)
9. Plot the transient heat Q flow vs. time. Both cases on the same graph. (For natural and 80% throttle opening). Q to be calculated from measured temperature as Q=m Cp (T at time t- T at previous time)
10. For free convection case repeat 1 through 5 above however use the free convection correlations for comparison with theoretical values. Remember you need Rayleigh number in this case.

❖ You can convert the voltage to °C degree using the table below:

ITS-90 Table for Type K Thermocouple (Ref Junction 0°C)

°C	0	1	2	3	4	5	6	7	8	9	10
						Thermoelectric Voltage in mV					
0	0.000	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798
20	0.798	0.838	0.879	0.919	0.960	1.000	1.041	1.081	1.122	1.163	1.203
30	1.203	1.244	1.285	1.326	1.366	1.407	1.448	1.489	1.530	1.571	1.612
40	1.612	1.653	1.694	1.735	1.776	1.817	1.858	1.899	1.941	1.982	2.023
50	2.023	2.064	2.106	2.147	2.188	2.230	2.271	2.312	2.354	2.395	2.436
60	2.436	2.478	2.519	2.561	2.602	2.644	2.685	2.727	2.768	2.810	2.851
70	2.851	2.893	2.934	2.976	3.017	3.059	3.100	3.142	3.184	3.225	3.267
80	3.267	3.308	3.350	3.391	3.433	3.474	3.516	3.557	3.599	3.640	3.682
90	3.682	3.723	3.765	3.806	3.848	3.889	3.931	3.972	4.013	4.055	4.096

Heat transfer
Experiment No. 8
Plate Heat exchanger
Apparatus: Heat exchanger/ Thermodynamics lab.

<u>Objectives:</u>

- Distinguish types of heat exchangers
- Apply basic heat exchanger theory
- Investigate flow arrangement (co and counter flows)
- Measuring log-mean- temperature difference
- Measuring the overall heat transfer coefficient U -value
- Effect of flow rate on the U-value
- Investigating heat exchanger efficiency.

<u>Apparatus description:</u>

The heat exchanger unit consists of a plate heat exchanger, heating reservoir, thermostat to control the hot water temperature, thermocouples that measure temperature of flowing liquid, a flow meter sensors and the data acquisition system, figure 1 shows the unit.

The connecting hoses can be easily unlocked and connected to the exchanger allowing easy change of flow arrangement form co current to counter current flow.

Figure 1 shows the experimental heat exchanger.

Experimental procedure

Priming:

1. To priming the hot and cold water circuits connect the heat exchanger hot water inlet (appropriate flexible tube with red collar) to the quick release cold water outlet connector (blue collar with arrow pointing left) at the rear of HT30X.
2. Connect the heat exchanger hot water outlet (appropriate flexible tube with red collar) to the quick release hot water inlet connector on HT30X (red collar with arrow pointing right at the front of HT30X.
3. To prime the hot water circuit first ensure the by pass valve in the hot water circuit is fully closed (right-hand valve with black handle 90 degree to valve body).
4. Ensure that the cold water pressure regulator is set to minimum pressure (pull the grey knob upwards – towards the right – the turn the knob fully anticlockwise, looking at the end of the knob).
5. Open the cold water pressure regulator valve fully (left-hand valve with black handle in line with valve body). Gradually adjust the pressure regulator by turning the grey knob clockwise until cold water is heard / seen to flow steadily through the flexible tubing of the hot water circuit.
6. wait until water flows in to the clear plastic priming vessel and all air bubbles have been expelled from flexible tubing. ***Note:*** water will flow from the hot water outlet connector at the front of HT30X before priming is complete, this is normal and the water will drain in the central canal.
7. When the system has primed, close the cold water flow control valve (left hand valve with black handle at 90 degrees to valve body).
8. Disconnect the flexible tube (to the heat exchanger) from the cold water outlet connector (blue collar with arrow pointing left) then reconnect the same flexible tube to the hot water outlet connector (red collar with arrow pointing left).
9. Fill the clear plastic priming vessel with clean water to the level of over flow the replace the lid on vessel.
10. Switch on the hot water circulating pump. Any remaining air bubbles will be expelled via the priming vessel. Open and close the hot water bypass valve (right-hand valve with black handle) several times until no air bubbles are seen traveling along the flexible tubing. If the level falls below mid height in priming vessel the it will be necessary to top it up with clean water.
11. Reconnect as in figure 1.

Cocurrent

1. Close the cold water flow control valve V_{cold} the reverse the cold water connections to the shell of the heat exchanger. Note : the connection to the heat exchanger are now configured for cocurrent operation where the hot and cold water fluid streams flow in the same direction across the heat transfer surface (the two fluid streams enter the heat exchanger at the same end). See figure 2.
2. Open the cold water control valve V_{cold} and adjust it to give a reading of 1 liter/min (hot and cold water flow rates the same as before).

3. when the temperature are stable record the following: T_1,T_2, T_3, T_4, F_{hot}, F_{cold}.
4. Check the cold fluid flow rate by collecting certain amount of water in graduated cylinder and dividing by the time it took to collect this amount of water.
5. Repeat for another 4 flow rates of the hot/cold water.

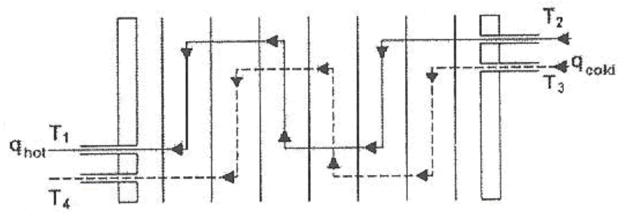
<u>Counter current</u>

1. Set the temperature controller to a set point approximately 45°C above the cold water inlet temperature (T_4) . (e.g If T_3 = 15°C the set controller to 60°C, then switch the hot water circulator.
2. Set the flow indicator switch to F_{cold} then adjust the cold control valve V_{cold} (not the pressure regulator $V_{reg)}$ to give 1 liter/min.
3. Set the flow water indictor switch to F_{hot} then adjust the hot water control valve V_{hot} to give 2 liters/min.
4. Allow the temperature to stabilize (monitor the temperature using the switch / temperature meter).
5. When the temperature are stable record the following: T_1, T_2, T_3, T_4, F_{hot}, F_{cold}.
6. Repeat experiment for another 4 flow rates of hot/cold water.

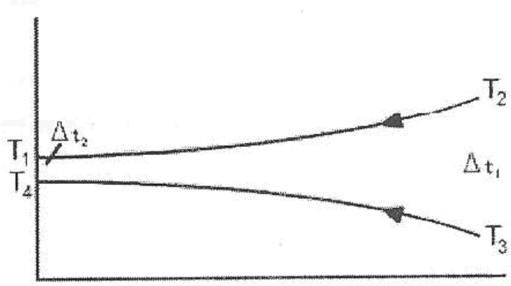
Theory

When the heat exchanger is connected for countercurrent operation the hot cold fluid streams flow in opposite directions across the heat transfer surface (the two fluid streams enter the heat exchanger at opposite ends). Figures 2 and 3 are showing the co-current and counter-current arrangements and their temperature profiles.

The hot fluid passes through the seven tubes in parallel, the cold fluid passes across the tubes three times, directed by the baffles inside the shell.



Cocurrent diagram



Cocurrent

Figure 2: Co-current arrangement and its temperature profile.

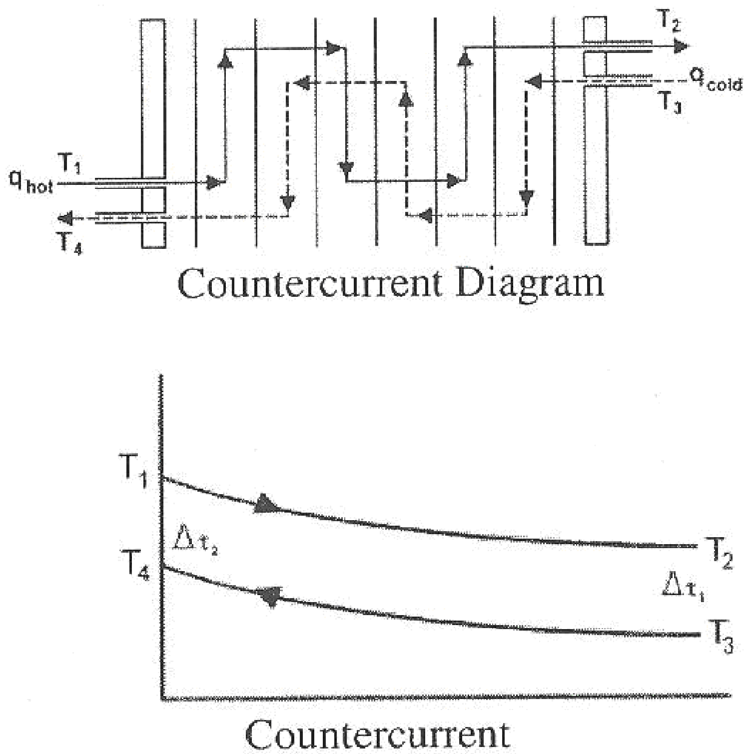


Figure 3: Countercurrent arrangement and its temperature profiles.

Because the temperature difference between the hot and the cold fluid streams varies along the length of the heat exchanger it is necessary to derive an average temperature difference (driving force) from which the heat transfer calculations can be performed. This average temperature difference is called the Logarithmic Mean Temperature Difference (LMTD) Δt_{1m}

Where
(LMTD) $\Delta t_{1m} = [(\Delta t_1 - \Delta t_2) / \ln (\Delta t_1 / \Delta t_2)]$
And
$\Delta t_1 = (T_1 - T_4)$, $\Delta t_2 = (T_2 - T_3)$ (°C)

Note this equation cannot produce any results for the case where $\Delta t_1 = \Delta t_2$

(LMTD)
$\Delta t_{1m} = [(T_1 - T_4) - (T_2 - T_3)] / \ln[(T_1 - T_4) / (T_2 - T_3)]$ (°C)
In this experiment the equation for LMTD is the same for both countercurrent and cocurrent operation because the temperature measurement points are fixed on the exchanger. Two

different equations will result if the temperature points are related to the fluid inlets and outlets.

Heat transfer in the exchanger is given by the equation;

$Q = UA\ F\ \Delta t_{1m}$

Where U is the overall heat transfer coefficient
A area of heat exchange
F correction factor for shell in tube equals 0.95
Δt_{1m} is the log –mean temperature – difference.

The heat exchange area for the shell and tube exchanger must be calculated using the arithmetic mean diameter of the inner tubes.

Arithmetic mean diameter	$d_m = (d_o + d_i) / 2$	(m)
Heat transmission length	$L = n \cdot s$	(m)

Where
n = number of tubes = 7
s = heat transmission length of each tube = 0.144 (m)

L = 1.008

Heat transmission area $A = \pi \cdot d_m \cdot L$ (m^2)

For plat heat exchanger the total area of all plates is 0.4 m^2

Also the heat exchanged can be calculated based on the heat lost by the hot fluid or the heat gained by cold fluid as
$Q = mC(T_{out} - T_{in})$

It is known that's the reduction in the hot fluid temperature
$T_{hot} = T_1 - T_2$ (^oC)

And the increase in the cold fluid temperature
$T_{cold} = T_4 - T_3$ (^oC)

And the heat power emitted from fluid
$Q_e = m_h \cdot (Cp)_h (T_1 - T_2)$ (in Watt)

Where:

Hot fluid inlet temperature	T_1	(^oC)
Hot fluid outlet temperature	T_2	(^oC)

Cold fluid inlet temperature	T_3	(^oC)
Cold fluid outlet temperature	T_4	(^oC)
Hot fluid volume flow rate	V_{ho}	
Specific heat for hot fluid	$(Cp)_h$	(kJ/kg ^oK) from table 1
Mass flow rate (hot fluid)	m_h	(kg/s)

A useful measure of the heat exchanger performance is temperature efficiency of each fluid stream, the temperature change in each fluid stream is compared with the maximum temperature difference between the two fluid streams given a comparison with an exchanger of infinity size.

Temperature efficiency for hot fluid

$\eta_h = [(T_1 - T_2) / (T_1 - T_3)] \times 100$ (%)

Temperature efficiency for cold fluid

$\eta_c = [(T_4 - T_3) / (T_1 - T_3)] \times 100$ (%)

Mean temperature efficiency

$\eta_m = (\eta_h + \eta_c) / 2$ (%)

Analysis & calculations

1. In a table present your results as flow rates of hot and cold fluids, temperatures of all streams, for both cases co and counter current arrangements.
2. Calculate the log mean temperature differences, the overall heat transfer coefficient, U.
3. Calculate the hot fluid, cold fluid, and average efficiencies for all runs.
4. Plot efficiencies versus cold /hot fluid flow rates, comment on results.
5. Plot U –value versus cold/hot fluid flow rates, comment on results.
6. Discuss the difference between the co and the counter current arrangements.

Heat transfer
Experiment No. 9
Heat Pump
Apparatus: Heat Pump/ Thermodynamics lab.

OBJECTIVES :

The objective of this experiment is to test the performance of an experimental heat pump, this includes;

- Know components of a vapor compression cycle
- Distinguish cooling and heating modes of heat pump
- Measuring cooling/ heating capacity of the unit
- Measuring COP of the unit
- Investigate effect of heat removal on unit performance
- Determining air properties and the use of psychrometric chart

APPARATUS DESCRIPTION :

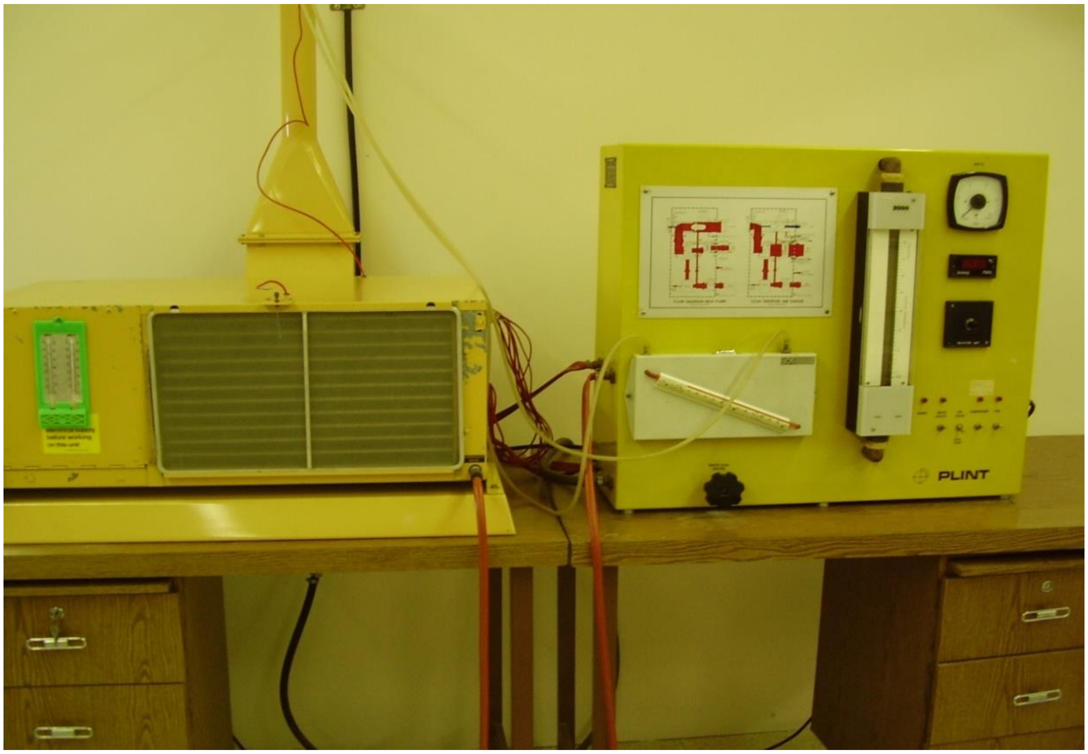


Figure (1) Heat pump unit

EXPERIMENTAL PROCEDURE :

1. Turn on the circulating water and adjust the flow rate to a value of 4 liter/min using Rotameter.
2. Read the inlet circulating water, T_3.
3. If T_3 is less than 10^oC, switch the water heater on.
4. Choose heating to operator as a heat pump.
5. Switch on the compressor and the fan.
6. Note : The wattmeter reading is the total electrical power input to both the fan and the compressor. To get the input power to the individual units, switch off the fan momentarily at which the wattmeter reading is the input power to the compressor.
7. Every 5 minutes, read and record the following : The temperatures T_1, T_2,...,T_{10}, Pitot tube velocity head, H_1, the total input power to the compressor and the fan, E_{total}, the input power to the compressor, E_c.
8. Measure the relative humidity Φ of air entering the unit using the sling hygrometer.
9. When steady state condition is recorded (i.e., the temp. is not changing any more).
10. Adjust the circulating water flow rate to 5 liter/min and wait approximately 5 minutes and then read and record only once all the values you recorded in step 6.
11. Repeat step 9 for circulating water flow rates of 6, 3 and 2.

THEORY:

The notation below is used in the theory explained in this experiment.

Temperatures

T_1	Air at inlet
T_2	Air at discharge
T_3	Circulating water at inlet
T_4	Circulating water at discharge
T_5	Compressor discharge
T_6	Compressor inlet
T_7	Refrigerant-to-water heat exchanger discharge
T_8	Refrigerant-to-water heat exchanger inlet
T_9	Refrigerant-to-air heat exchanger inlet
T_{10}	Refrigerant-to-air heat exchanger discharge

Mass Flow Rates

Dry air	m_1 kg/s
Circulating water	m_3 kg/s

Thermal Quantities

Specific heat of water	C_w J/kg ^oC
Specific heat of air at constant pressure	C_p J/kg ^oC

Specific enthalpy of water vapor	h_v J/kg

Enthalpy Flow Rates

Dry air entering conditioner	Q_1 J/s
Water vapor entering conditioner	Q_2 J/s
Dry air leaving conditioner	Q_3 J/s
Water vapor leaving conditioner	Q_4 J/s
Circulating water at inlet	Q_6 J/s
Circulating water at outlet	Q_7 J/s
Radiation and stray losses	Q_8 J/s

Electrical Input

Refrigerator compressor	E_c W
Fan	E_F W

Psychrometer Data

Relative humidity at inlet	Φ
Density of saturated water vapor at inlet	ρ_W kg/m^3
Density of dry air at inlet	ρ_a kg/m^3
Specific humidity at inlet	γ

Ideal Heat Pump

Power input	W J/s
Input from cold source	q_2 J/s
Output to hot sink	q_1 J/s

The machine is shown schematically in Fig.3, which shows the various energy flows through the system boundary. They are defined as below :
Use absolute temperature in Kelvin for all temperature below.

Enthalpy of dry air entering conditioner

$$Q_1 = m_1 C_p T_1$$

Enthalpy of water vapor entering conditioner

$$Q_2 = \gamma m_1 h_v$$

Enthalpy of dry air leaving conditioner

$$Q_3 = m_1 C_p T_2$$

Enthalpy of water vapor leaving conditioner

$$Q_4 = \gamma m_1 h_v$$

Enthalpy of circulating water at inlet

$$Q_6 = m_3 T_3 C_w$$

Enthalpy of circulating water at outlet

$$Q_7 = m_3 T_4 C_w$$

Radiation and stray losses

$$Q_8$$

Electrical input to fan

$$E_F$$

The Steady flow energy balance for the system :

$$(Q_6 - Q_7) + (E_c + E_F) = (Q_3 + Q_4) - (Q_1 + Q_2) + Q_8$$

The coefficient of performance, COP, may be defined in two different ways :

1. The overall of external coefficient

$$COP_{external} = \frac{(Q_3 + Q_4) - (Q_1 + Q_2)}{(E_c + E_F)}$$

The corresponding ideal value,

$$COP_{external)ideal} = \frac{\frac{1}{2}(T_1 + T_2)}{\frac{1}{2}(T_1 + T_2) - \frac{1}{2}(T_3 + T_4)}$$

2. The internal coefficient :

$$COP_{internal} = \frac{(Q_3 + Q_4) - E_F - (Q_1 + Q_2)}{E_c}$$

The corresponding ideal value,

$$COP_{internal)ideal} = \frac{T_{10}}{T_{10} - T_8}$$

The air flow through the unit is measured using a Pitot-static tube mounted in the center of the discharge duct.

The volumetric flow rate, $\dot{V}$, of air in the duct :

$$\dot{V} = 0.3014\sqrt{\frac{H_1 T_2}{P_a}}\ m^3/s$$

Where :

H_1	: velocity head in mm H_2O
T_2	: absolute air temp. at discharge
P_a	: atmospheric pressure, N/m^2

The mass flow rate, m_1, of air in the duct :

$$m_1 = 0.00105\sqrt{\frac{H_1 P_a}{T_2}}\ kg/s$$

The specific humidity of the air entering the unit :

$$\phi = \frac{\Phi\,\rho_w}{\rho_a}$$

Where :

Φ	: relative humidity
ρ_w	: density of saturated water vapor entering the unit
ρ_a	: density of air entering the unit

When the device is reversible (i.e. operating in Carnot cycle) as shown in Fig.4, which is considered the ideal cycle.

The coefficient of performance of a heat pump, COP_{hp}, is defined as :

$$COP_{hp} = \frac{q_2}{W}$$

Where :

q_2	: is the input from a cold source
W	: power input

$$q_2 = (Q_3 + Q_4) - (Q_1 + Q_2)$$

$$W = (W_c + W_F)$$

When the unit is operating in a Carnot cycle (i.e., ideal), the ideal coefficient of performance for heat pump is defined as:

$$COP_{hp)ideal} = \frac{T_2}{T_2 - T_3}$$

ANALYSIS AND CALCULATIONS :

1. Find inlet and exit air specific humidity using equations and psychrometric chart, also find for inlet air the specific volume, and enthalpy.
2. Calculate the volumetric flow rate of air in the duct.
3. Calculate the mass flow rate of air in the duct.
4. Calculate the heat added or removed from air.
5. Calculate the heat from circulating water.
6. Calculate the heat lost to surroundings.
7. Find the actual and ideal of both the overall external and the internal coefficients of performance.

8. Draw the Heat Pump/Air Cooler Vapor Compression Cycle.
9. Plot T2, compressor power versus time, and comment on the curve.
10. Plot the total power of compressor and fan against experimental time, and comment on graph.
11. Plot Heat Pump rejected and added heat against time, and comment on graph.
12. Plot the total power of compressor and fan against water flow rate, and comment on graph.
13. Plot the Heat Pump rejected and added heat against water flow rate, and comment on graph.

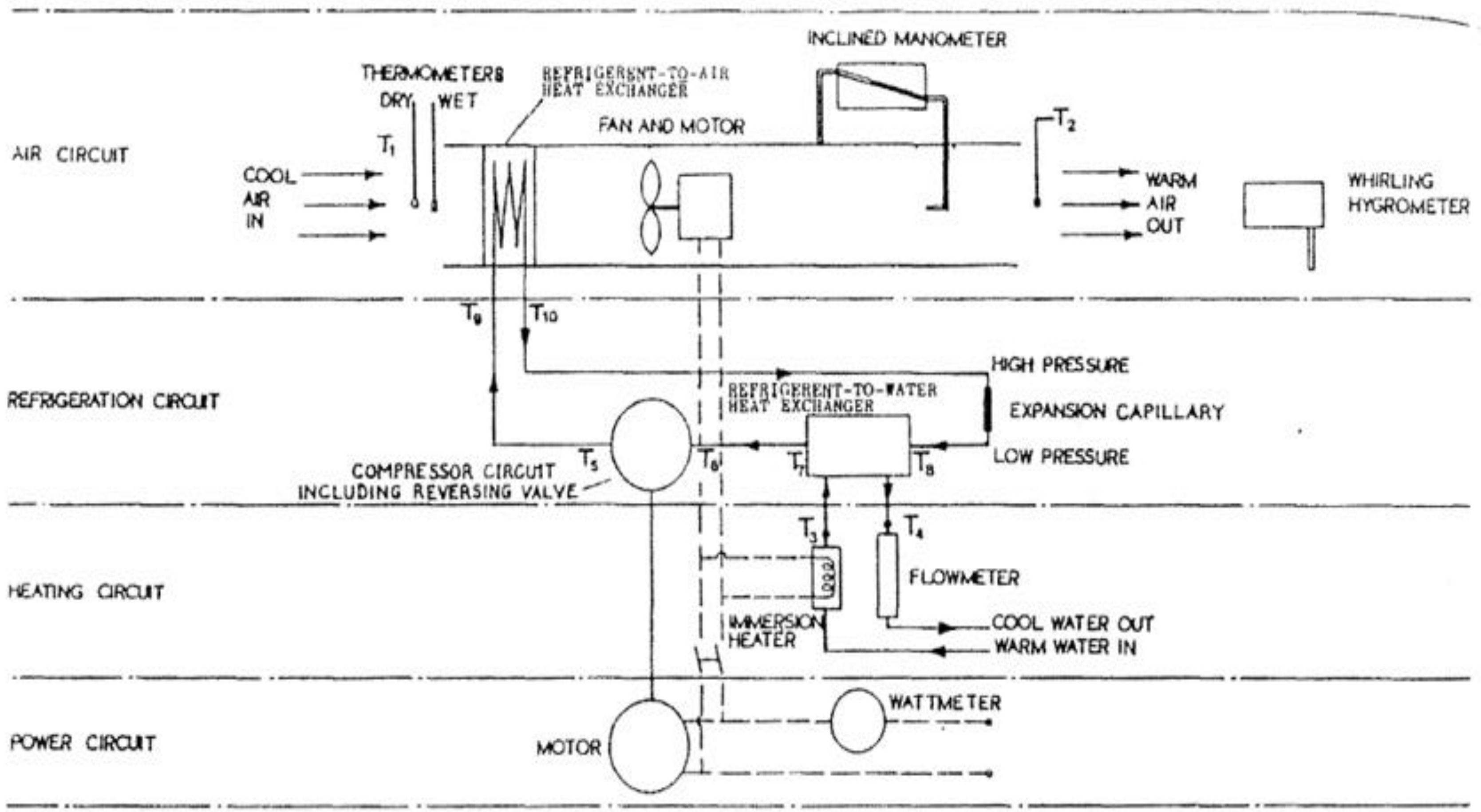


Fig. 2 FLOW DIAGRAM, HEAT PUMP

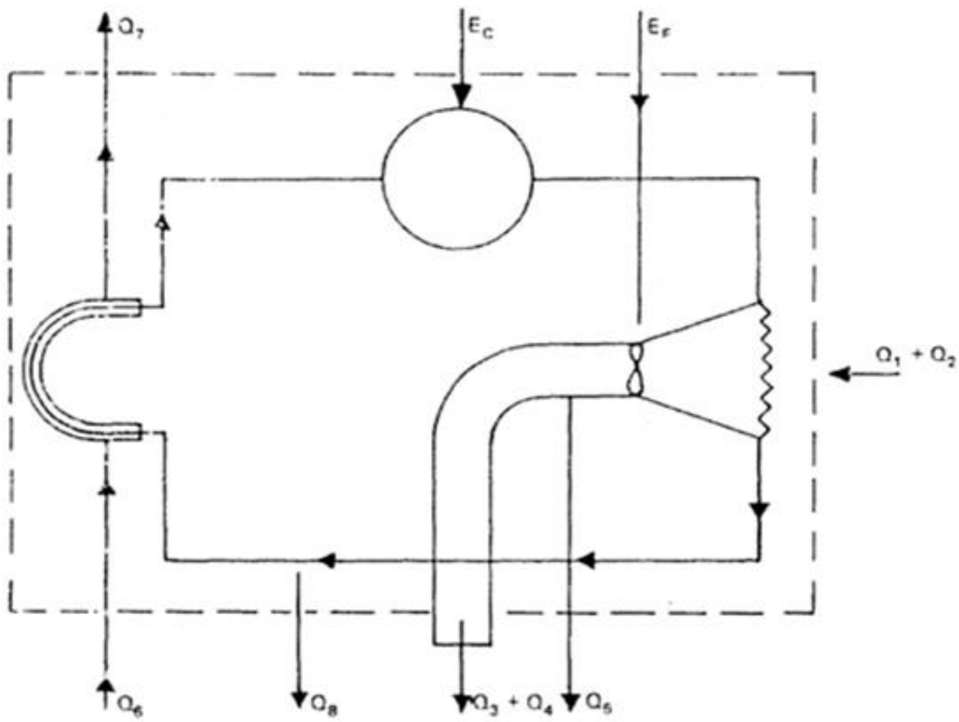


Fig. 3 ENERGY FLOW DIAGRAM

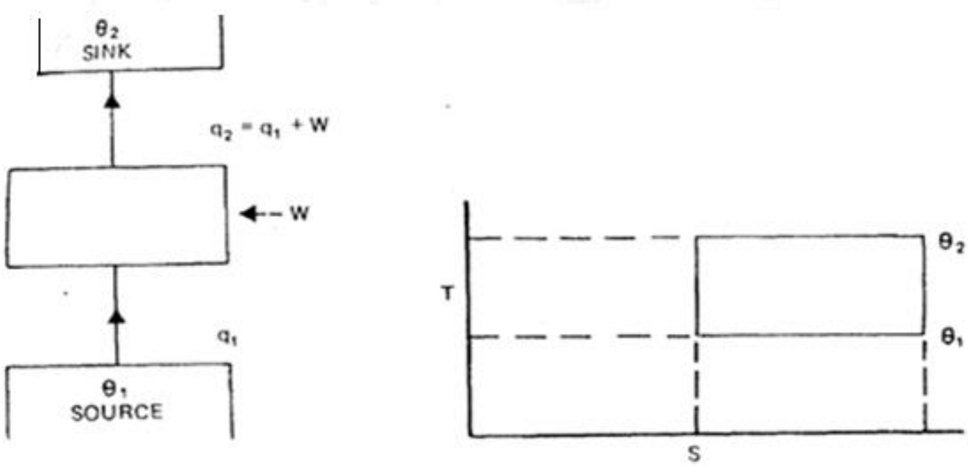


Fig. 4 IDEAL REVERSIBLE ENGINE

DEPRESSION OF WET BULB

DRY BULB READINGS

°C	·5	1·0	1·5	2·0	2·5	3·0	3·5	4·0	4·5	5·0	5·5	6·0	6·5	7·0	7·5	8·0	8·5	9·0	9·5	10·0
+20	96	91	87	83	78	74	70	66	63	59	55	51	48	44	41	37	34	30	27	24
21	96	91	87	83	79	75	71	67	64	60	56	52	49	46	42	39	36	32	29	26
22	96	92	88	83	80	76	72	68	64	61	57	54	50	47	44	40	37	34	31	28
23	96	92	88	84	80	76	72	69	65	62	58	55	51	48	45	42	39	36	33	30
24	96	92	88	84	80	77	73	69	66	63	59	56	53	49	46	43	40	37	34	31
25	96	92	88	84	81	77	74	70	67	63	60	57	54	50	47	44	41	38	36	33
26	96	92	88	85	81	78	74	71	67	64	61	58	55	52	48	46	43	40	37	34
27	96	92	89	85	81	78	75	71	68	65	62	59	55	52	50	47	44	41	38	36
28	96	93	89	85	82	78	75	72	68	65	62	59	56	53	50	48	45	42	40	37
29	96	93	89	86	82	79	76	72	69	66	63	60	57	54	51	49	46	43	41	38
30	97	93	89	86	83	79	76	73	70	67	64	61	58	55	52	50	47	44	42	39
31	97	93	89	86	83	79	77	73	70	67	64	61	59	55	53	50	48	45	43	40
32	97	93	89	86	83	80	77	74	71	68	65	62	60	56	54	51	49	46	44	41
33	97	93	90	86	84	80	77	74	71	68	66	63	60	58	55	52	50	47	45	42
34	97	93	90	87	84	80	77	74	71	68	66	64	61	58	56	53	51	47	46	42
35	97	93	90	87	85	81	78	75	72	69	66	64	61	59	56	54	51	49	47	44
36	97	93	90	87	85	81	78	75	72	69	67	64	61	59	57	55	52	50	48	45
37	98	93	91	87	86	82	79	76	73	70	67	65	62	60	58	55	53	51	48	46
38	98	93	91	88	86	82	79	76	73	70	67	65	62	60	58	56	53	51	48	46
39	98	94	91	88	86	82	79	76	74	71	68	66	63	61	58	57	54	52	50	48
40	98	94	91	88	86	82	79	77	74	71	68	66	63	61	59	57	54	52	50	48
41	98	94	91	88	86	83	79	77	74	72	69	67	64	62	59	57	55	53	51	49
42	98	94	92	88	86	83	80	78	75	72	69	67	64	62	60	58	56	54	51	49
43	98	94	92	88	86	83	80	78	75	73	69	68	65	63	60	58	56	54	52	50
44	98	94	92	88	87	83	80	78	75	73	70	68	65	63	61	59	57	55	53	51
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49	98	94	92	89	87	84	81	79	76	74	71	70	67	66	63	61	58	57	55	53
50	99	94	92	89	87	84	81	79	76	74	71	70	67	66	63	62	59	58	56	54

°C	10·5	11·0	11·5	12·0	12·5	13·0	13·5	14·0	14·5	15·0	15·5	16·0	16·5	17·0	17·5	18·0	18·5	19·0	19·5	20·0
+20	21	18	15	12	9	6	3	0												
21	23	20	17	14	11	8	6	3	0											
22	25	22	19	16	13	11	8	5	3	0										
23	27	24	21	18	16	13	10	8	5	3	0									
24	28	26	23	20	18	15	12	10	7	5	3	0								
25	30	27	25	22	19	17	14	12	10	7	5	3	0							
26	32	29	26	24	21	19	16	14	12	9	7	5	3	0						
27	33	30	28	25	23	21	18	16	14	11	9	7	5	3	0					
28	34	32	29	27	25	22	20	18	15	13	11	9	7	5	3	1				
29	36	33	31	28	26	24	21	19	17	15	13	11	9	7	5	3	0			
30	37	34	32	30	27	25	23	21	19	17	15	13	11	9	7	5	3	1		
31	38	35	33	31	29	27	24	22	20	18	16	14	12	10	8	7	5	3	0	
32	39	37	34	32	30	28	26	24	22	20	18	16	14	12	10	8	7	5	3	1
33	40	38	36	33	31	29	27	25	23	21	19	17	15	14	12	10	8	7	5	3
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35	42	40	38	36	33	31	29	27	26	24	22	20	18	16	15	13	11	10	8	7
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39	46	44	42	40	37	35	33	31	30	28	26	25	23	21	20	18	17	15	14	12
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41	47	45	43	41	38	36	34	32	30	29	28	26	25	23	22	20	19	18	16	15
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43	48	46	44	43	40	38	36	34	32	30	29	27	27	25	23	22	21	20	19	17
44	49	47	45	44	41	39	37	35	33	30	29	28	27	25	24	22	22	20	19	18
45	49	47	45	44	41	39	37	35	33	31	30	28	27	25	24	23	22	21	20	19
46	50	48	46	44	42	39	37	35	34	31	30	28	27	26	25	24	23	22	21	20
47	50	49	47	45	42	40	38	36	34	32	31	29	28	27	26	25	24	23	22	21
48	51	49	47	45	42	40	38	36	34	32	31	30	29	28	27	26	25	24	23	22
49	51	49	47	45	42	40	38	36	35	34	32	31	30	29	28	27	26	25	24	23
50	52	50	48	46	43	41	39	37	36	35	34	32	31	30	29	28	27	26	25	24

DEPRESSION OF WET BUL

DRY BULB READINGS °C	·25	·5	·75	1·0	1·25	1·5	1·75	2·0	2·25	2·5	2·75	3·0	3·25	3·5	3·75	4·0	4·25	4·5	4·75	5·0	5·25	5·5	5·75	6·0	6·25	6·5	6·75	7·0	7·25	7·5	7·75	8·0	8·25	8·5	8·75	9·0	9·25	9·5	9·75	10·0	10·25	10·5	10·75
−5	94	88	83	77	71	66	60	54	49	43	38	32	29	26	23	20																											
4	95	89	84	78	73	67	62	57	51	46	41	36	31	27	24	22	20																										
3	95	89	84	79	74	69	64	59	54	49	44	39	34	29	25	23	21	19																									
2	95	90	85	80	75	70	66	61	56	52	47	42	37	33	28	24	22	19	17																								
1	96	91	86	81	76	72	67	63	58	54	49	45	40	36	32	27	24	21	19	17																							
0	96	91	86	82	78	73	69	65	60	56	52	48	43	39	35	31	27	24	20	18	16																						
+1	96	91	87	83	79	75	71	66	62	58	54	50	46	42	38	34	30	26	22	19	17	15																					
2	96	92	88	84	80	76	72	68	64	60	56	52	49	45	41	37	33	30	26	22	20	17	15																				
3	96	92	88	84	81	77	73	69	66	62	58	54	51	47	44	40	36	33	30	26	23	20	17	15																			
4	96	92	89	85	82	78	74	70	67	63	60	56	53	49	46	42	39	35	32	29	26	23	20	17	15																		
5	97	93	89	86	83	79	75	72	69	65	62	58	55	51	48	45	42	38	35	32	28	24	21	19	17	15	12	10															
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7	97	93	90	87	84	80	77	74	71	67	64	61	59	55	53	49	46	43	40	37	35	31	28	26	23	20	17	14	12	10													
8	97	94	91	87	85	81	78	75	72	69	66	63	60	57	54	51	48	45	42	40	37	34	31	29	26	23	20	18	16	13	11												
9	97	94	91	88	85	82	79	76	73	70	67	64	62	58	56	53	50	47	44	42	39	36	33	31	29	26	23	21	18	16	13	11											
10	97	94	91	88	86	82	79	76	74	71	68	65	63	60	58	54	52	49	46	44	41	39	36	34	31	29	26	24	22	19	16	14	12	10									
11	98	94	91	88	86	83	80	77	75	72	69	66	64	61	58	56	54	51	48	46	43	41	38	36	33	31	28	26	24	22	19	17	15	12	10								
12	98	94	91	89	87	83	80	78	75	73	70	68	65	62	59	57	55	53	50	48	45	43	40	38	35	33	31	29	26	24	22	20	18	16	14	11							
13	98	95	91	89	87	84	81	79	76	74	71	69	66	64	61	59	56	54	51	49	47	45	42	40	37	36	33	31	29	27	24	23	21	18	16	14	12						
14	98	95	92	90	87	84	81	79	77	74	72	70	67	65	62	60	57	56	53	51	49	46	44	42	39	38	35	33	31	29	27	25	23	21	19	17	15	12					
15	98	95	92	90	88	85	82	80	77	75	72	71	68	66	63	61	59	58	54	52	50	48	46	44	41	40	38	36	34	42	29	27	25	23	21	20	18	16	14	12			
16	98	95	92	90	88	85	83	81	78	76	73	71	69	67	65	63	61	58	56	54	52	50	47	46	43	42	39	37	36	34	32	30	28	26	24	22	20	18	16	15	13	11	9
17	98	95	92	90	88	86	83	81	78	77	74	72	70	68	66	64	62	59	57	55	53	51	49	47	45	43	41	39	38	36	33	32	30	28	26	24	22	21	19	17	16	14	12
18	98	95	93	91	89	86	83	82	79	77	75	73	71	69	67	65	63	61	58	56	54	53	50	49	47	45	43	41	39	37	35	34	32	30	28	27	25	23	21	20	18	16	14
19	98	95	93	91	89	86	84	82	80	78	76	74	72	70	67	65	64	62	59	58	56	54	52	50	48	46	44	43	41	39	37	36	34	32	30	29	27	25	23	22	20	19	17

RELATIVE HUMIDITY TABLE

INSTRUCTIONS FOR OBTAINING RELATIVE HUMIDITY WITH WHIRLING PSYCHROMETER

The psychrometer is whirled rapidly for 15 or 20 seconds while held well in front of the body facing into the wind, and shaded in bright sunshine. Then it is stopped and the wet bulb quickly read first. This is repeated until at least two successive readings are within 0.1°. The wet bulb reading is subtracted from the dry bulb reading giving the depression of the wet bulb and the relative humidity obtained from the tables.

DISTILLED WATER ONLY should be used and the muslin wick renewed as soon as it becomes dirty or greasy; as a rough guide, in a smoky town atmosphere after 1 hour's use; in clean air, after 50 hours' use.

TEMPERATURES BELOW FREEZING. If the wet bulb temperature falls below freezing point, but the water remains in the liquid state, no error is caused if the minimum temperature is reached. If, however, ice forms during whirling extra whirling is necessary to lower the temperature to the minimum since on freezing the temperature of the wet bulb is temporarily raised to 0°C.