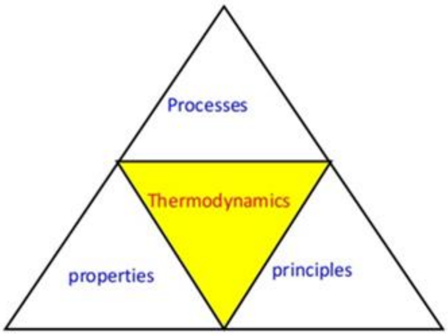
THE UNIVERSITY OF JORDAN

كلية الهندسة
SCHOOL OF ENGINEERING

MECHANICAL ENGINEERING



Engineering Thermodynamics Laboratory Manual

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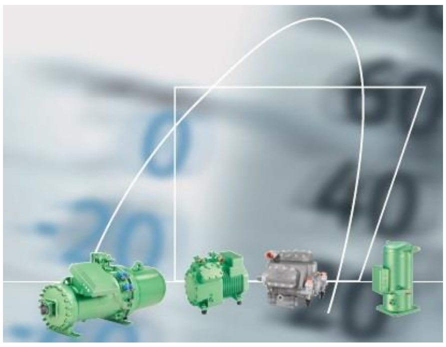
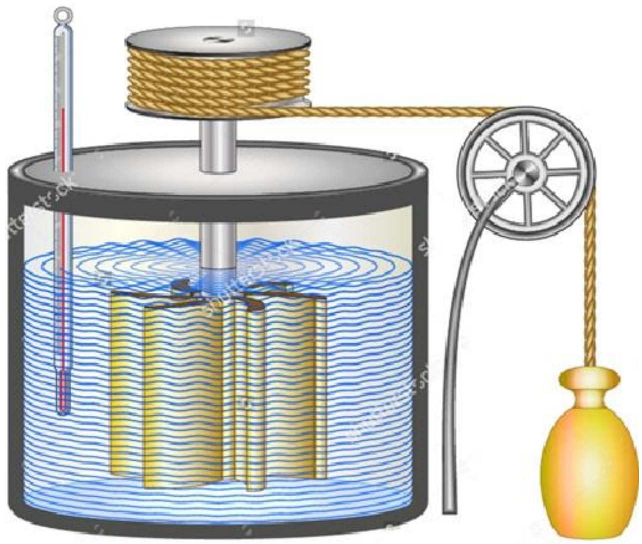
Checked by: *Dr.Jehad Yameen*





Engineering Thermodynamics Laboratory Manual

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This Engineering Thermodynamics Laboratory Manual is based on my experience of teaching at the University of Jordan over the past 14 years, and students input has been valuable and has a direct impact on the format of this manual, and therefore, I would welcome any feedback on the manual, its coverage, accuracy or method of presentation.

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INSTRUCTIONS

Each student should not forget the following when coming to the lab class:

1. The report of the previous experiment. Any report submitted late without an acceptable reason will not be considered for marking.
2. Preparing for the experiment to be done.
3. The laboratory manual.
4. Pen or pencil.
5. An electronic pocket calculator.

- A timetable will be distributed which shows the date on which laboratory groups will perform each particular experiment.
- Each student should read introductory notes to his experiment before coming to the laboratory, and can start work without undue delay.
- This is particularly important in the early part of the session when the theoretical background may not have been covered in lectures, and reference to textbooks is more likely to be necessary.
- Each student must keep a tidy laboratory notebook, recording all measurements exactly as they are taken, and tabulating them where appropriate.
- Where possible, a graph should be drawn as the experiment proceeds to ensure that the results are systematic and that sufficient readings have been obtained, especially in sensitive or particularly important parts of the range of the variables.

SAFETY CODE OF PRACTICE

1. Do not enter the laboratory until the lecturer is present.
2. Bring only necessary items into the laboratory.
3. Do not operate or turn off any machinery until instructed to do so.
4. Do not interfere with any other equipment.
5. Report any breakage to the laboratory supervisor.
6. Always seek advice, either from the lecturer or technician if the equipment is not operating as expected.
7. In the event of a catastrophic failure, try to isolate the equipment from the energy source and / or consult the lecturer or Supervisor.
8. On completion of experiment tidy your working area.
9. Report to the lecturer / supervisor before leaving the laboratory.

LAB REPORTS

1. INTRODUCTION

- You have to carry out nine experiments.

- Your performance will be assessed on the basis of your attitude and skills during the actual experimental stage as well as on the basis of written reports for each experiment.

- The purpose of these experiments is to help you understand some of the concepts discussed in class, and to develop skills in experimentation, measurement, instrumentation and communication skills.

- Student should observe the following guidelines when writing a technical report:

1. **Paper size:** All reports must be presented in standard letter-size paper (A4). Computer paper will not be accepted unless the report is word-processed and / or the graphs are generated by computer.
2. **Margins:** All material within the body of the report (this includes text, tables, and figures) must be within the following margin: 35 mm from the left edge of the paper, 25 mm from the top, right, and bottom edge of the paper.
3. **Orientation:** Every attempt should be made to orientate all text, tables and figures in such a way that they can be read in an upright position that is when the paper is held with its longer edge in the vertical position. Sometimes, wide tables or large figures must be rotated 90°. When doing this makes sure that the bottom of the table or figure is parallel and closer to the right edge of the paper.
4. **Bindings:** binding of the pages should be at the top left corner, when using staples, or at the left edge of the paper when using other means.

2. ELEMENTS OF LAB. REPORT

It must be emphasized here that this is a SHORT REPORT not more than 6 to 8 pages long. Avoid lengthy duplication of text or formulas found in the book and / or in other texts. Give references instead. Avoid artistic renditions of the lab equipment used. Simple line sketches are sufficient. The proper element should be selected from the following in the same order shown:

A. Title (cover) Page

In the first page of the report (not to be numbered), the University, Faculty, Department, Lab, Student and Supervisor Names and Dates should be included. The experiment Title and number should be included as indicated in the Lab. Manual. Use black color only. Use the title page supplied in the beginning of each experiment in the manual.

B. Abstract

A brief description of the experiment should be given. This should include the objectives, the method and a summary of the findings. The abstract should not be more than 100 words. (1/2 page). For example one of the findings of the ratio of specific heat experiment is that it is equal to 1.4 for air. It is recommended to write the Abstract AFTER the report is completed in order to be able to include all important aspects and findings of the experiment.

C. Introduction

After a proper definition of the level of the reader is made, this should introduce the reader into the subject. It is composed of two parts: significance and method. The introduction should not be more than 200 words (1 Page). If a short report is required, only the objectives should be stated to replace the introduction. The objectives are the aims or the goals of the experiment. For example, one of the objectives of the Work-to-Heat experiment is to experimentally find the Joules' work equivalent of heat, which is equal to 4.178 k cal/KJ.

D. Theory

In order to enable the reader to understand the implications of the reported work (experimental or theoretical), the main assumptions should be stated and justified, with the theory written out in sentences, so that the reader is led through the equations without confusion. It should be free from unnecessary details, such as excessively detailed algebraic work. The units used should be defined as they appear. Use SI units where appropriate.

E. Experimental Apparatus and Procedure

Describes the experimental apparatus (if applicable). Tells the reader what was done in brief, and a sketch of the apparatus should be included. The experimental procedure should be also presented.

F. Raw Data

This should include collected data, usually in the format of tables and, possibly as graphs. In either case, as the title indicates, this data should be reported as collected, without treatment or modification. The tables should be numbered and titled at the top.

G. Sample Calculation

The calculation should include all necessary steps to obtain the required results. The equations used should be stated in the theory. All parameters used to obtain the required results should be clear and their symbols and units should be as stated in the theory.

H. Results

This should include all the findings required from the experiment, usually in the form of graphs. All figures should be numbered and titled at the bottom. The coordinates should be defined with proper scale and units. Do not just connect the dots. If you know the trend of the phenomena, use a proper curve-fitting technique to show the plot, which should not be a continuous line, but rather, a dotted line to indicate that it is experimental. Only theoretical curves can be made with a continuous line.

Do not make stupid mistakes such as:

- Irregular Scale: some computer graphing techniques give a scale point at each data point, which may result in an irregular scale (It's like a rule where the first centimeter may be longer or shorter than any other centimeter on the scale).
- The scale increases in the negative direction of x.
- Undefining each plot in a graph that includes several plots.

I. Discussion

This is the most important part of the report. The presented results should be interpreted in view of theoretical background. It should explain why the phenomena look that way. Do not just say, for example, in the Marcet Boiler experiment, that it is noticed that the pressure increases as the temperature increases. Instead, explain why. Show how close the experiment was to the theory and indicate the sources of error which lead to disagreement between experiment and theory. This should include error, or uncertainty analysis. This analysis should tell how much the error is in obtaining each and every parameter in the results.

J. Conclusions

This should tell the reader in brief what was covered in the experiment and what the most important results were. It should not include any thing that was not mentioned before in the previous sections of the report.

K. References

All other related work, either mentioned in Theory or elsewhere should be documented here. All references should be numbered, and those numbers should be indicated in the text at the place they were used. Do not just put a bunch of references without referring to them in the text. This will not impress the reader. The reference format should follow this:

a) Book

Duffie, J.A., and Beckmen, W. A., "Solar Engineering of Thermal Processes", John-Wiley Pub. 1980.

b) Journal

Takeish, K., Aoki, S., Sato, T., and Tsukagoshi, K., 1991. Film Cooling on a Gas Turbine Rotor Blade, ASME Journal of Turbomachinery, Vol. 114, 12-34.

L. Appendices

An Appendix is used to remove all detailed information from the report. The following materials may appear in the appendices.

a- Detailed mathematical derivations.
b- Calibration of instrumentation.
c- Tabulation or graphs of material properties.
d- Detailed computer programs.
e- Calculations and charts obtained from other work.

3. FIGURES

1. Each figure should be given a number and a title, underneath it.
2. The titles should help to explain what the figures show.
3. They should be neatly drawn.
4. They should contain the essential details only.
5. The scales and units should be shown clearly.
6. The points of scale markings should be shown clearly.
7. The size of the figure should be adequate.

A sample figure is shown below

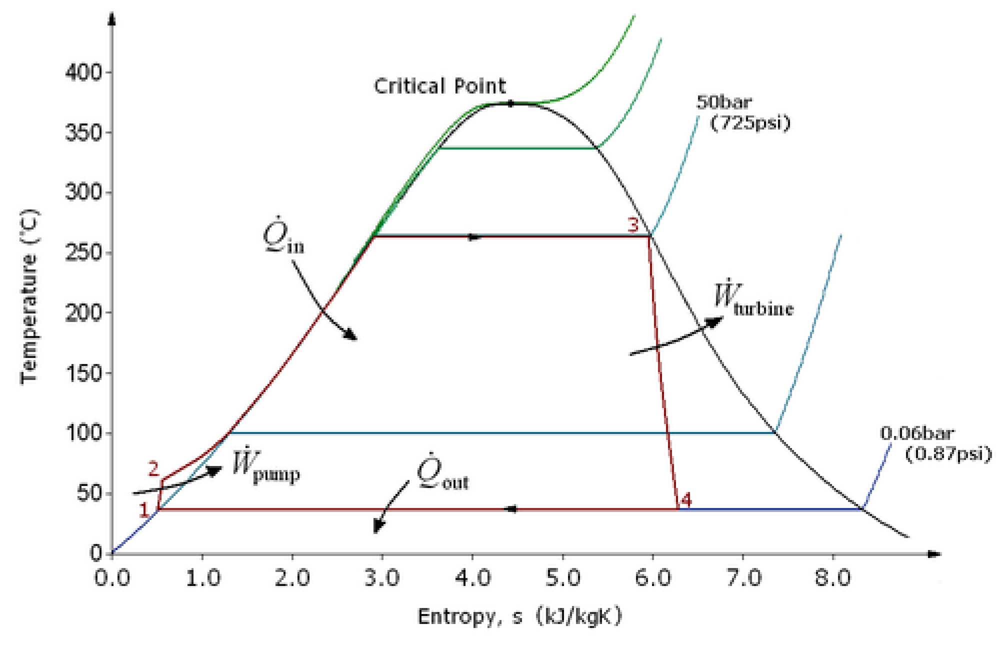

Figure 1:T-S diagram for Rankine Cycle

4. TABLES

1. Each table should be given a number and a title located above it.
2. The title should help to fully explain what information the table contains.
3. The units of the variables should be clearly stated. Use only SI units.

A sample Table is shown below

Table 1: Saturated Water and Steam Table

Pressure, P ***Bar***	***Temperature, T*** ***^0C***	***Specific Volume of Steam, v_g*** ***m^3/kg***	***Latent Heat of Vaporization, h_{fg}*** ***kJ/kg***
1.0	99.6	1.694	2258
2.0	120.2	0.8856	2202
3.0	133.5	0.6057	2164
4.0	143.6	0.4623	2134
5.0	151.8	0.3748	2109

5. ASSESSMENT & EVALUATION

The course assessment is based on the 0 to 100 point scale, and the weighting factors for the various parts are as follows:

Assessment Tool	**Expected Due Date**	**Weight**
Short Reports*	One week after the experiment	30%
Quizzes	Two weeks after the experiment	10%
Midterm Exam	According to the department examination schedule	20 %
Final Exam	According to the university examination schedule	40 %

- ✓ The formal reports must represent an individual work of a student. Obviously, the experimental data and any other material resulting from an experiment, and obtained during the experiment session, may be shared freely and be presented in anyone's report. However, copying a text or graphics from another person's report may be viewed as an attempt of plagiarism, and will be heavily penalized.
- ✓ Students will be awarded points based on performance on their lab work as documented in their laboratory reports.
- ✓ Each lab report can earn a maximum score of 25 points:
- ✓ Each group has to submit one Short Report for each experiment.
- ✓ Late or copied reports are not allowed and will get zero mark.
- ✓ Attendance of classes is obligatory; Absence must be verified according to the university's regulations.

Experiments

1. EXPERIMENTS NAMES

Expr. No.	Experiment Name
1	Marcet Boiler- liquid –Vapor Saturation Curve
2	Work to Heat Energy Transfer
3	Ratio of Specific Heats of Air
4	Flow Through a Nozzle
5	Heat Pump and Air Cooler
6	Refrigeration Unit
7	Single Stage Air Compressor
8	Air and Water Heat Pump
9	Thermal Power Plant

2. EXPERIMENTS SCHEDULE

1st and 2nd Week	1- Marcet Boiler 2- Work to Heat
3rd and 4th Week	3- Ratio of Specific Heats of Air 4- Flow through a Nozzle
5th and 6th Week	5- Heat Pump and Air Cooler 6- Refrigeration Unit
7th and 8th Week	7- Single Stage Air Compressor 8- Air and Water Heat Pump
9th Week	9- Thermal Power Plant

3. EXPERIMENTS GROUPS

Week **Group**	1st	2nd	3rd	4th	5th	6th	7th	8th	9th
A	1	2	3	4	5	6	7	8	9
B	2	1	4	3	6	5	8	7	

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Experiment 1

Marcet Boiler WL204

Lab Section

Sunday	Monday	Tuesday	Wednesday	Thursday

Group

A1	**A2**	**B1**	**B2**

+**Group Members**

1. ______________________________

2. ______________________________

3. ______________________________

4. ______________________________

5. ______________________________

You Can Develop Your Grade

____
10

Experiment 2

Work to heat energy transfer

(Mechanical Equivalent of Heat)

Lab Section

Sunday	Monday	Tuesday	Wednesday	Thursday

Group

A1	A2	B1	B2

+**Group Members**

1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________
5. ______________________________

You Can Develop Your Grade

____

10

Experiment 3

Ratio of Specific Heats of Air

Lab Section

Sunday	Monday	Tuesday	Wednesday	Thursday

Group

A1	A2	B1	B2

+**Group Members**

1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________
5. ______________________________

You Can Develop Your Grade

____

10

Experiment 4
Flow through a Nozzle

Lab Section

Sunday	Monday	Tuesday	Wednesday	Thursday

Group

A1	A2	B1	B2

+**Group Members**

1. ____________________
2. ____________________
3. ____________________
4. ____________________
5. ____________________

You Can Develop Your Grade

____ / 10

Experiment 5
Heat Pump and Air Cooler

Lab Section

Sunday	Monday	Tuesday	Wednesday	Thursday

Group

A1	A2	B1	B2

+Group Members

1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________
5. ______________________________

You Can Develop Your Grade

______
10

Experiment 6

Refrigeration Laboratory Unit - R714

Lab Section

Sunday	Monday	Tuesday	Wednesday	Thursday

Group

A1	A2	B1	B2

+Group Members

1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________
5. ______________________________

You Can Develop Your Grade

______
10

Experiment 7

Single Stage Air Compressor

Lab Section

Sunday	Monday	Tuesday	Wednesday	Thursday

Group

A1	**A2**	**B1**	**B2**

+**Group Members**

1. ________________________________
2. ________________________________
3. ________________________________
4. ________________________________
5. ________________________________

You Can Develop Your Grade

____

10

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Experiment 8

Air and Water Heat Pump Unit R832

Lab Section

Sunday	Monday	Tuesday	Wednesday	Thursday

Group

A1	A2	B1	B2

+Group Members

1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________
5. ______________________________

You Can Develop Your Grade

______
10

Experiment 9

Thermal Power Plant

Lab Section

Sunday	Monday	Tuesday	Wednesday	Thursday

Group

A1	A2	B1	B2

+**Group Members**

1. ______________________
2. ______________________
3. ______________________
4. ______________________
5. ______________________

You Can Develop Your Grade

____ / 10

Experiment 1

MARCET BOILER

(UNIT - WL 204)

1.0 OBJECTIVE

- This lab will be carried out to determine the relationship between the steam pressure and heating temperature of saturated steam in equilibrium on an enclosed model steam boiler.
- Besides that, this experiment will also demonstrate the vapor pressure curve and then verify Clapeyron relationship.

2.0 INTRODUCTION & THEORETICAL BACKGROUND

Normally water boils at 100 °C at 1 atm pressure. The heat initially causes water molecules to evaporate. This causes the pressure in the steam chamber, and thus in the water, to rise. As the steam pressure rises the boiling point temperature also increases, because the water molecules encounter increased resistance as they attempt to move from liquid to gas form. Each steam pressure has an accompanying precisely defined boiling point temperature (Fig. 1).

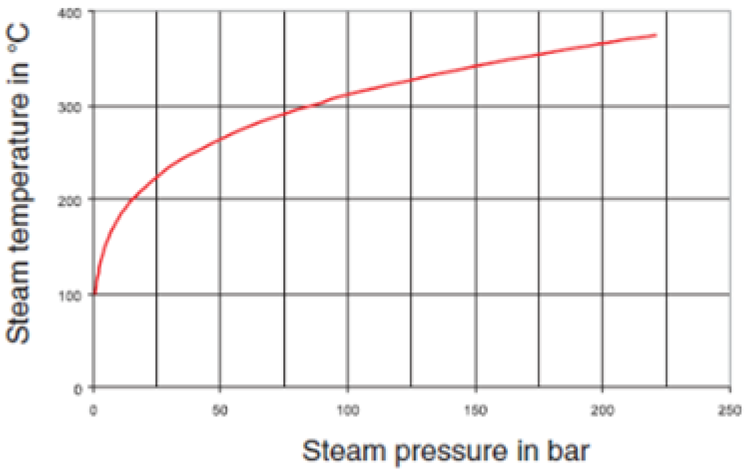


Fig. 1: Boiling Point Curve for Water

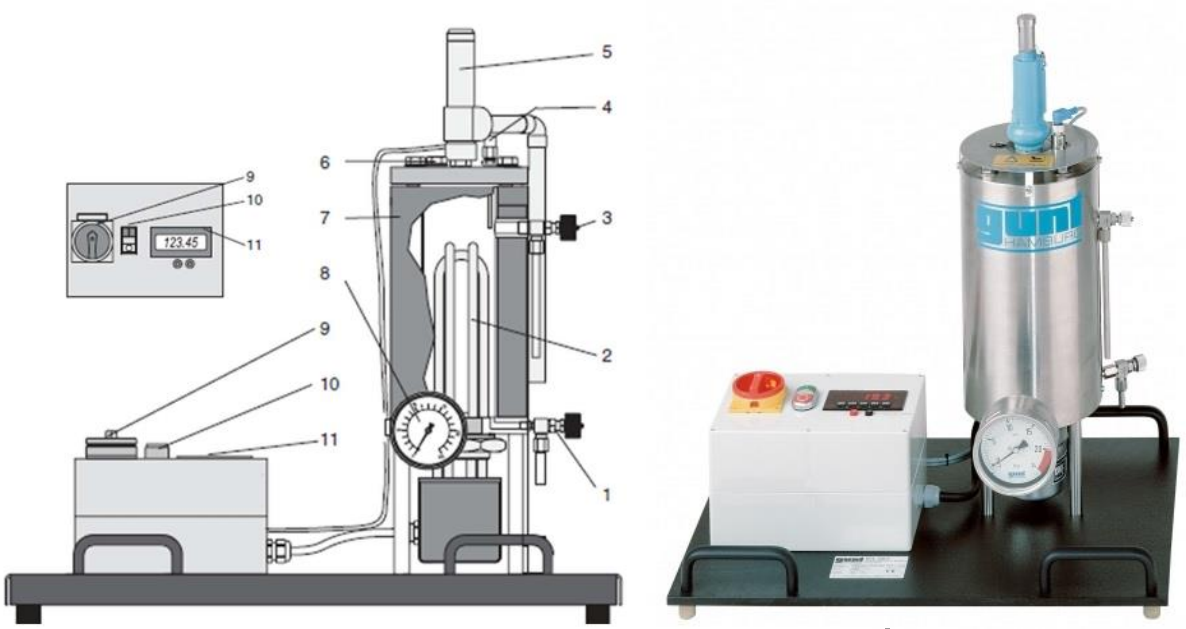
At a given pressure, the temperature at which a pure substance changes phase is called the saturation temperature Tsat. Likewise, at a given temperature, the pressure at which a pure substance changes phase is called the saturation pressure Psat. The amount of energy absorbed or released during a phase-change process is called the latent heat.

Marcet boiler is the device which we use to study the relation between pressure and temperature for a water at saturated liquid phase. We started heating water with constant pressure until it reached boiling point. Then, closing the valve which created a constant volume system. Forcing the pressure to increase as the temperature rises. And thus studying the direct relation between pressure and temperature for water.

We notice that it is essential to close the valve as we reach boiling point to make sure we are now in a constant volume process. We also notice that we closed the valve exactly when we reached boiling temperature (95 ºC at 0.9 bar pressure) and thus keeping water at saturated liquid phase.

3.0 APPARATUS

Marcet Boiler, shown in figure 2, is made of steel and fitted with a pressure gauge, a safety valve, a water cock for testing the water level and a thermo sensor. The boiler is heated by an electrical immersion heater. To minimize losses and to prevent direct contact to the hot surface, the boiler is insulated. The temperature is shown on a digital electronic thermometer. An integrated limit switch prevents the boiler from overheating.



1. Drain Valve

7. Boiler with Insulating Jacket

2. Heater
3. Overflow valve
4. Temperature Sensor
5. Safety Valve
6. Fille Opening

8. Bourdon Tube Pressure Gauge
9. Master Switch
10. Heater Switch
11. Temperatur Gauge

Fig. 2: Marcet Boiler WL204

- The main element of the WL 204 Marcet boiler unit is the stainless steel steam boiler (7). It has a mineral wool insulating jacket.
- The filler opening (6) is used to pour water into the boiler.
- The overflow valve (3), closed off by means of a hand wheel, is used to ensure the vessel is filled to the correct level.
- The drain valve (1) can be used to drain the vessel.
- An electric heater (2) is bolted into the floor of the boiler in such a way that the heating filament protrudes from below into the boiler.
- A manometer (8) is fitted in the lid of the boiler to provide a direct indication of the boiler pressure.
- There is also a Pt-100 temperature sensor (4) to measure the boiler temperature.
- A safety valve (5) to prevent excess pressure build-up in the boiler. If the safety valve is activated, the excess pressure is discharged to the rear of the unit via a drain pipe.
- The boiler temperature can be read from the digital display (11) fitted into the switch cupboard.
- The unit is switched on at the master switch (9).
- The additional heater switch (10) can be used to switch the heater on and off as required during the experiment.

4.0 PROCEDURE

1. Switch on the unit at the master switch.
2. Switch on the heater at the heater switch and heat up the boiler.
3. Record the boiler pressure and temperature values in increments of approximately 0.5 - 1.0 bar (See the experiment worksheet).
4. After the experiment switch off the unit at the master switch.
5. Disconnect the unit from the mains power.
6. Leave the boiler to cool down.

- **SAFETY WARNING!**

Because of high pressure & temperature steam.

- ✓ *Don't touch surfaces during operation!*
- ✓ *Never open valves of the device!*

5.0 OBSERVATIONS

Table 1: DATA OBSERVED

Atmospheric Pressure: ______________ bar					
Pressure, P (bar)		**Temperature, T**			
Gauge	***Absolute***	***Increase*** **(°C)**	***Decrease*** **(°C)**	***Average Tave (°C)***	***Average Tave (K)***
0.00					
0.50					
1.00					
1.50					
2.00					
2.50					
3.00					
3.50					
4.00					
4.50					
5.00					
5.50					
6.00					
6.50					
7.00					
7.50					
8.00					
8.50					
9.00					
9.50					
10.00					

6.0 DATA ANALYSIS

For a pure substance existing as a mixture of two phases, the Clapeyron relationship relates the pressure, heat and expansion during a change of phase provided that the two phases are in equilibrium.

The Clapeyron relationship is:

$$\left(\frac{dT}{dP}\right)_{SAT} = \frac{T(v_g - v_f)}{h_g - h_f} = \frac{T\, v_g}{h_{fg}}$$

As $v_g \gg v_f$

In which,

$v_f = specific\ volume\ of\ saturaed\ liquid$

$V_g = specific\ volume\ of\ saturated\ vapour$

$h_f = enthalpy\ of\ saturaed\ liquid$

$h_g = senthalpy\ of\ saturated\ vapour$

$h_{fg} = latent\ heat\ of\ vaporization$

After the temperature – pressure curve was drawn from data observed in Table 1, the slope of the curve at each pressure was determined by three methods:

1- First Method: The slope $\frac{\Delta T}{\Delta P}$ $using$: The **Central Difference formula**

$\frac{\Delta T}{\Delta P} = \frac{T_{i+1} - T_{i-1}}{P_{i+1} - P_{i-1}}$	(1)

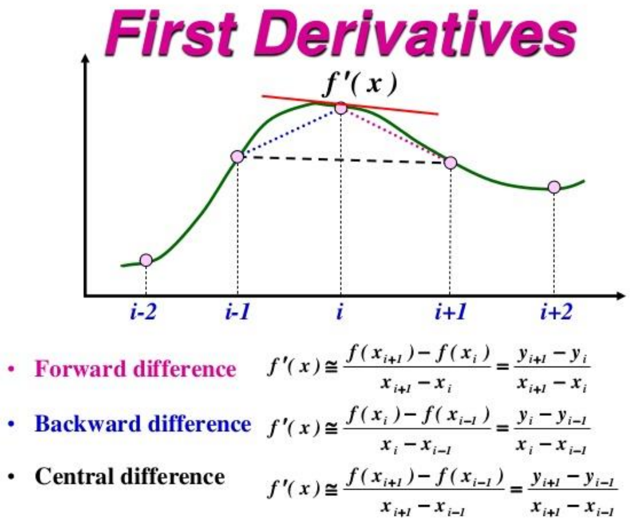
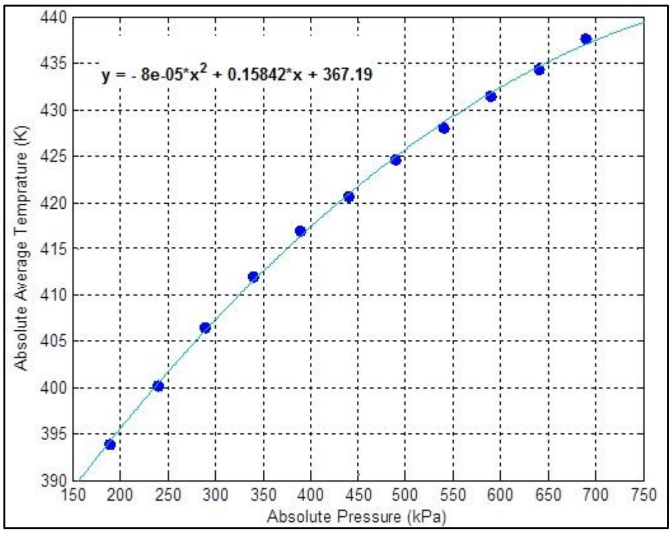


Fig. 3: Central Difference formula

2- Second Method: The slope $\left(\frac{dT}{dP}\right)$ $using$: **Numerical differentiation**

The first derivative of the best fit equation of temperature-pressure curve

$\frac{dT}{dP} = T'(P)$	(2)



$$T(P) = -8 \times 10^{-5}\, P^2 + 0.1584P + 367.19$$

Fig. 4: Best Fit Equation

3- Third Method: The slope $\left(\frac{dT}{dP}\right)_{SAT}$ $using$: Clapeyron relationship.

$\left(\frac{dT}{dP}\right)_{SAT} = \frac{T(v_g - v_f)}{h_g - h_f} = \frac{T\, v_g}{h_{fg}}$, $as\;\; v_g \gg v_f$	(3)

All values in the Clapeyron relationship must be taken from table 2.

Table 2: SATURATED WATER AND STEAM TABLES

Pressure (P, bar)	Temperature (T, °C)	Specific volume (v_g, m^3/kg)	Latent heat of vaporization
1.0	99.6	1.694	2258
2.0	120.0	0.8856	2202
3.0	133.5	0.6057	2164
4.0	143.6	0.4623	2134
5.0	151.8	0.3748	2109
6.0	158.8	0.3156	2087
7.0	165.0	0.2728	2067
8.0	170.4	0.2403	2048
9.0	175.4	0.2149	2031
10.0	179.9	0.1944	2015
11.0	184.1	0.1774	2000
12.0	188.0	0.1632	1986
13.0	191.6	0.1512	1972
14.0	195.0	0.1408	1960
15.0	198.3	0.1317	1947
16.0	201.4	0.1237	1935
17.0	204.3	0.1167	1923
18.0	207.1	0.1104	1912
19.0	209.8	0.1047	1901
20.0	212.4	0.09957	1890

7.0 RESULTS & DISCUSSION

Table 3: SUMMARY OF RESULTS

Pressure, P (bar)		**Temperature, T**		**Measured Slope, by *Central Difference***	**Measured Slope, by *derivation***	**Calculated Slope, *by Clapeyron***
Gauge	***Absolute***	***Average Tave (°C)***	***Average Tave (K)***			
0.00						
0.50						
1.00						
1.50						
2.00						
2.50						
3.00						
3.50						
4.00						
4.50						
5.00						
5.50						
6.00						
6.50						
7.00						
7.50						
8.00						
8.50						
9.00						
9.50						
10.00						

1. Fill the table using recorded data and saturated water and steam tables.
2. Plot the curve between measured temperature and absolute pressure (Pressure as x-axis).
3. Compare the measured values with theoretical values, discuss the difference.
4. Calculate the error of measured values.

NOTE: This page is intentionally left blank to identify your important notes

Experiment 2

WORK TO HEAT TRANSFER
(Mechanical Equivalent of Heat)

1.0 OBJECTIVE

- To determine the relationship between energy transferred by heat and the energy transferred by work.

2.0 INTRODUCTION & THEORETICAL BACKGROUND

The principle of the conservation of energy tells if a given amount of work is transformed completely into heat, the resulting thermal energy must be equivalent to the amount of work that was performed. Since work is normally measured in units of Joules and thermal energy is normally measured in units of Calories, the equivalence is not immediately obvious. A quantitative relationship is needed that equates Joules and Calories. This relationship is called the Mechanical Equivalent of Heat. It was not until the experiments of Joule in 1850, however, that Joule performed a variety of experiments in which he converted a carefully measured quantity of work through friction into an equally carefully measured quantity of heat. For example, in one experiment Joule used falling masses to propel a paddle wheel in a thermally insulated water-filled container.

Measurements of the distance through which the masses fell and the temperature change of the water allowed Joule to determine the work performed and the heat produced. With many such experiments, Joule demonstrated that the ratio between work performed and heat produced was constant. In modern units, Joule's results are stated by the expression

(1 calorie = 4.184 Joule).

Joule's results were within 1% of the value accepted today.

(The calorie is now defined as equal to 4.186 Joule.)

Work is done on an object by force acting through a displacement. The energy transferred by work is measured by multiplying the force acting on an object times the displacement over which the force acted: W = F x d. The unit of energy transferred by work is the **joule**. Work done on an object may result in a change in its mechanical energy or a change in its internal energy, or both. A change in an object's internal energy results in a change in its temperature.

Heat is transferred between an object and its environment when there is a temperature difference between the object and its surroundings. The energy transferred is measured as the product of the object's mass, its specific heat, and the temperature change which occurs within the object:

Heat = M x specific heat x ΔT. Specific heat is the amount of energy it takes to raise 1 gram of a substance by 1℃ , the unit of energy transferred through heat is the calorie.

If work is done on an object which results in a change in the temperature of the object, then the work done must be the same as the heat energy that is transferred to the object. The ratio of the work done (in joules) to the heat transferred (in calories) is the "mechanical equivalent of heat".

$$\textit{Mechanical equivaent of heat} = \frac{\textit{work done in joules}}{\textit{heat transferred in calories}}$$

3.0 APPARATUS

The apparatus incorporates a universal electric motor with variable speed control for driving a copper drum calorimeter, two sets of weights, heavy and light, a set of brake belts to encircle the drum, a spring balance, a thermometer and a counter for recording the revolutions of the drum. All items of equipment are mounted on the steel cabinet which contains the motor control gear. (See Figure 1)

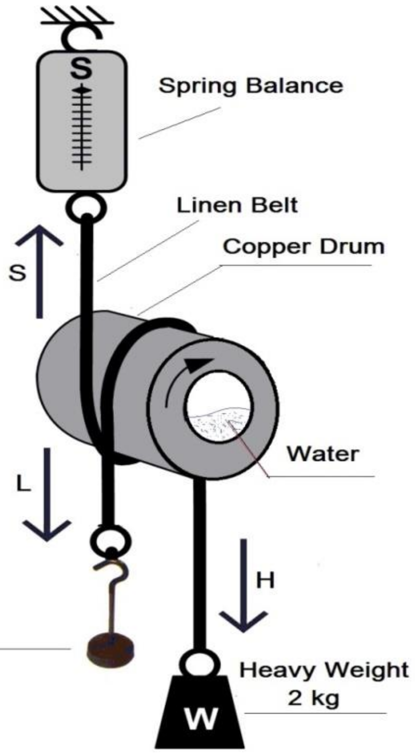


Fig. 1: Work to Heat Apparatus

4.0 PROCEDURE

1. Assemble the double part of the belts suspends the heavier weight of 2 kg, while the single part suspends the carrier for the light weights and the spring balance.
2. Amount of water, approx. 250g, at a temperature approximately 5 or 6 degrees below room temperature is then carefully inserted into the drum taking care not to wet the outside of the drum or the weights.
3. Rotation is then begun at a uniform speed of about 83 rev/min.
4. The light weights are adjusted to keep the heavy weight in floating equilibrium with the spring balance pointer near the center of the scale.
5. After a few revolutions the friction will become practically constant and the water temperature will rise at an approximate rate of 1C per 100 revolutions.
6. Take reading of water temperature at intervals of 100 revolutions of the drum.

5.0 OBSERVATIONS

Table 1: DATA OBSERVED

Initial water & drum temperature, T_i:________ ℃				
Drum revolutions (N)	**Water temperature T_f (ºC)**	**Spring balance S (g)**	**Light weight L (g)**	**Heavy weight H (kg)**
100				2
200				2
300				2
400				2
500				2
600				2
700				2
800				2
900				2
1000				2
1100				2
1200				2
1300				2
1400				2
1500				2
1600				2
1700				2
1800				2
1900				2
2000				2

6.0 DATA ANALYSIS

1- Calculating W, the Work done (kJ)

$$\boldsymbol{W = (H + S - L) \times g \times (2\pi r) \times N/1000} \quad (1)$$

$H = heavy\ weight, 2\ kg$
$L = light\ weight, kg$
$S = spring\ balance, kg$
$g = acceleration\ due\ to\ gravity,\ 9.81\ m/s^2$

$r = drum\ radius, 0.075\ m$

$N = Total\ number\ of\ revolutions\ the\ motor\ was\ turned$

2- Calculating Q, the Heat produced (kcal)

The total heat Q_T produced by friction against the copper cylinder filled with water can be determined from the measured temperature change that occurred.

$$\boldsymbol{Q_T = Q_d + Q_w = (M_d \times C_d \times \Delta T) + (M_w \times C_w \times \Delta T)} \quad (2)$$

$Q_d = heat\ gained\ by\ drum, kcal$

$Q_w = heat\ gained\ by\ water, kcal$

$M_d: mass\ of\ drum = 0.7\ kg$

$C_d: specific\ heat\ of\ copper\ drum = 0.092\ \ kcal/kg.°C$

$M_w: mass\ of\ water\ in\ the\ drum = 0.250\ kg$

$C_w: specific\ heat\ of\ water = 1.0\ kcal/kg.°C$

$\Delta T = rise\ in\ water\ temperature\ after\ agiven\ revolutions = (T_f - T_i),\ °C$

$T_f = final\ water\ temperature, °C$

$T_i = initial\ water\ temperature\ just\ before\ motor\ turning,\ °C$

3- Calculating J, the Mechanical Equivalent of Heat

$$\boldsymbol{Mechanical\ equivaent\ of\ heat = \frac{work\ done\ in\ joules}{heat\ transferred\ in\ calories}} \quad (3)$$
$$\boldsymbol{J = W/Q \qquad kJ/kcal}$$

4- Calculating the % error

$$\%\ \boldsymbol{error} = \frac{\boldsymbol{|theoretical - Measured|}}{\boldsymbol{theoretical}} \times \boldsymbol{100}\% \quad (4)$$

$$Jtheor = 4.186\ \ kJ/kcal$$

7.0 RESULTS & DISCUSSION

Table 2: SUMMARY OF RESULTS

Drum revolutions (N)	$Temp. diff.,$ ΔT °C	$Work\ done,$ W kJ	$Heat\ Produced,$ Q $kcal$	$Joule\ Factor$ $J = W/Q$	Error%
100					
200					
300					
400					
500					
600					
700					
800					
900					
1000					
1100					
1200					
1300					
1400					
1500					
1600					
1700					
1800					
1900					
2000					

1. Plot the graph of work and heat (W versus Q) and calculate the slope (J value).
2. All the results were recorded and tabulated under the results table.
3. Compare (J value) from graph plotted to that calculated from equations.
4. Discuss any discrepancy and the possible causes of errors of the experiment.
5. Write your own opinions about the results. What might be? Discuss about whether the results are acceptable or not?

NOTE: This page is intentionally left blank to identify your important notes

Experiment 3

RATIO OF SPECIFIC HEATS OF AIR

1.0 OBJECTIVE

- The purpose of the experiment is to determine the ratio of the specific heats of air $(K = \frac{C_P}{C_V})$ of a diatomic gas (air) by method of adiabatic expansion.
- The results obtained are compared with the theoretical value.

2.0 INTRODUCTION & THEORETICAL BACKGROUND

This method was devised by Clement and Desormes in 1819. It is based upon the adiabatic expansion of a gas in a large container; the experimental process is shown in Figure 1. A laboratory version of their apparatus is shown in Figure 2.

As we know $(K = \frac{C_P}{C_V})$, where:

Cp: means specific heat of air at constant pressure $(\frac{k_J}{kg.k})$

Cv: means specific heat of air at constant volume $(\frac{k_J}{kg.k})$

Also $H = Cp \times T \quad and \quad U = Cv \times T$

So, $K = H / U = Cp / Cv$

Further $Cp - Cv = R \; then \quad Cp = \frac{K}{K-1} R \quad and \quad Cv = \frac{R}{K-1}$

For diatomic gas (air) $K = 1.4 \ldots\ldots\ldots\ldots\ldots \frac{f+2}{f} \ldots\ldots\ldots f = 5$

For monoatomic gas $K = 1.67 \ldots\ldots\ldots\ldots \frac{f+2}{f} \ldots\ldots\ldots f = 3$

A PV diagram of the experiment is shown in Figure 1

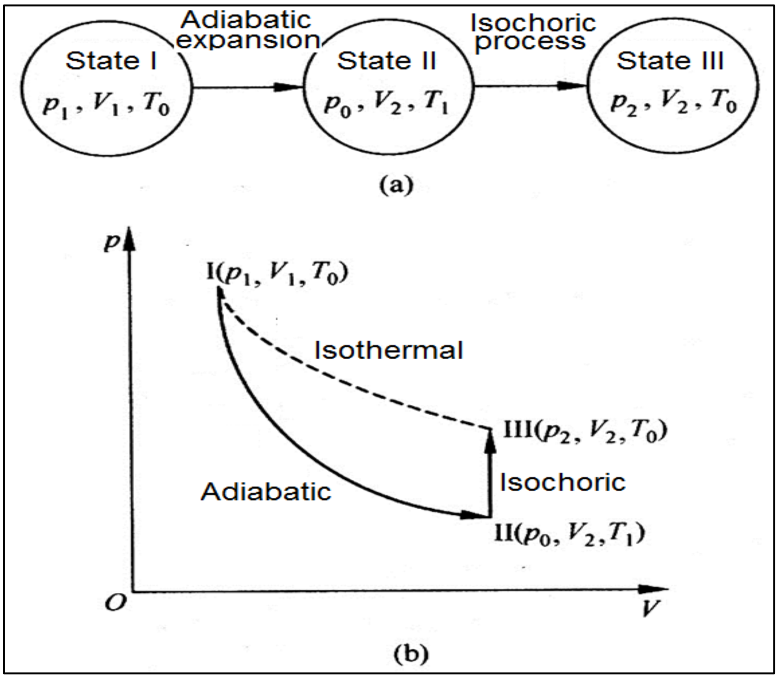


Fig. 1: Experimental process

Stage One: Adiabatic Expansion Process (State I- State II)

$$\frac{P^{K-1}}{T^K} = C$$

$\left(\frac{P_1}{P_o}\right)^{K-1} = \left(\frac{T_o}{T_1}\right)^K$	(1)

Stage Two: Constant volume Expansion Process

(Isochoric Process) (State II- State III) **till** $(T_{air} = T_o)$

$$\frac{P}{T} = C$$

$$\frac{P_o}{T_1} = \frac{P_2}{T_o}, \qquad and \qquad \frac{T_o}{T_1} = \frac{P_2}{P_o}$$

$\frac{P_2}{P_o} = \frac{T_o}{T_1}$	(2)

Combining these two equations (1) & (2) we get:

$$\left(\frac{P_1}{P_o}\right)^{K-1} = \left(\frac{P_2}{P_o}\right)^K$$

With $P_o = P_{\text{atm}}$ $\quad P_1 = \gamma H_1 + P_{atm}$ $\quad P_2 = \gamma H_2 + P_{atm}$ $\quad \gamma = \rho g$

Take $(K-1)\, ln\left(\frac{P_1}{P_o}\right) = (K) ln\left(\frac{P_2}{P_o}\right)$, Then

$K == \frac{ln\left(\frac{P_1}{P_o}\right)}{ln\left(\frac{P_1}{P_2}\right)}$	(3)

3.0 APPARATUS

A large container of at least 10 liters (0.01 m3) capacity contains air at atmospheric pressure. The container is connected with a bicycle tire pump, a large valve and a tube connecting the container to a manometer filled with mercury.

The container is usually surrounded by insulation although this is really unnecessary since the air is a bad conductor of heat and the resulting expansion is rapid. A little concentrated sulphuric acid may be placed in the container to dry the air. (See Figure 2)

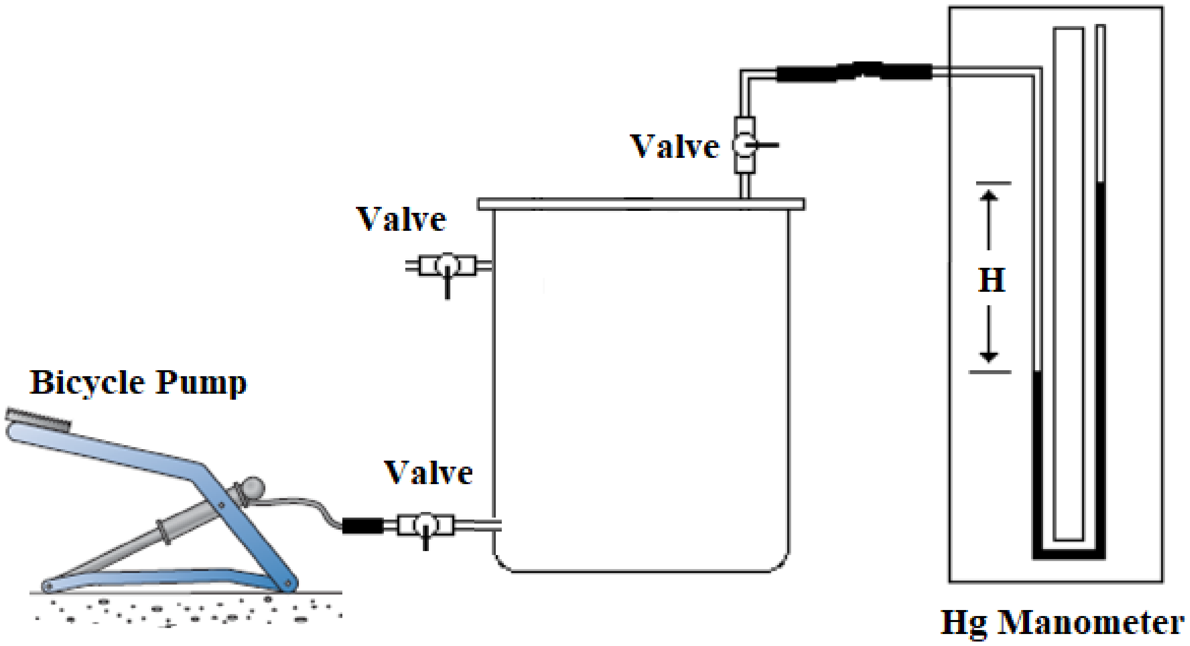


Fig. 2: Apparatus - Schematic Layout

4.0 PROCEDURE

1. The vessel is filled with air at pressure P_1 using the bicycle pump until the manometer reads a pressure **H_1** mm of mercury slightly greater than atmospheric.
2. The vessel is then put in communication with the free air at pressure P_o by opening stopcock valve, so as to equalize the pressures in the sudden, nearly adiabatic expansion.
3. The stopcock is then rapidly closed.
4. The air in the vessel allowed to regain its initial temperature, and the pressure P_2 is then determined from **H_2** .
5. One source of error in this method is the exchange of heat between the air and the walls of the vessel during the expansion.

OBSERVATIONS

Table 1: DATA OBSERVED

Atmospheric Pressure $P_o = P_{atm}$:________ kP_a			
Trial #		**H_1 mmHg**	**H_2 mmHg**
1			
2			
3			
4			
5			

*** All pressures must be in absolute values**

5.0 DATA ANALYSIS

$P_o = P_{atm}$ $\quad$ *All in kP_a*

$P_1 = \rho_{Hg} \times g \times H_1 + P_{atm}$

$P_2 = \rho_{Hg} \times g \times H_2 + P_{atm}$

$$K == \frac{\ln\left(\frac{P_1}{P_o}\right)}{\ln\left(\frac{P_1}{P_2}\right)}$$

6.0 RESULTS & DISCUSSION

Table 2: SUMMARY OF RESULTS

Trial #	P_o	P_1	P_2	$\ln\left(\frac{P_1}{P_o}\right)$	$\ln\left(\frac{P_1}{P_2}\right)$	K	Error %
	kPa	kPa	kPa				
1							
2							
3							
4							
5							

$$\%\ \mathbf{Error} = \frac{|\mathbf{Theoretical}\ - \mathbf{Measured}|}{\mathbf{Theoretical}} \times \mathbf{100}\%$$

The Theoretical value for adiabatic index (K) is equal to 1.4.

$\mathbf{Kair = 1.4}$

1. Plot the graph of $ln\left(\frac{P_1}{P_o}\right)$ versus $ln\left(\frac{P_1}{P_2}\right)$ and using the basic fitting linear, find the slope of the line which = K-value.
2. All the results were recorded and tabulated under the results table.
3. Compare (K-value) from results to that of standard value.
4. Discuss any discrepancy and sources of the possible causes of errors.
5. Write your own opinions about the results. What might be? Discuss about whether the results are acceptable or not?

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Experiment 4
FLOW THROUGH A NOZZLE

1.0 OBJECTIVE

- To study the pressure distribution through a nozzle for different inlet pressures and different flow rates, critical pressure, velocity, mass flow rate of air at the throat.

2.0 INTRODUCTION & THEORETICAL BACKGROUND

A nozzle is a steady state-flow device; whose purpose is to create a high-velocity fluid stream at the expense of its pressure. Nozzles are commonly utilized in jet engines, rockets, space crafts, and even garden hoses. The cross-sectional area of a nozzle decreases in the flow direction for subsonic flows, and increases for supersonic flows, as seen in Figure 1. The rate of heat transfer between the fluid flowing through a nozzle and the surroundings is usually very small ($\dot{Q} \cong 0$), there is little or no change in potential energy($\Delta p \cong 0$), and the process involves no work($\dot{W} = 0$).

Mach Number M: The Mach number is a dimensionless value useful for analyzing fluid flow dynamics. The Mach number can be expressed as $M = v / c$
Where M = Mach number, v = fluid flow speed (m/s), c = speed of sound = 343 (m/s).
Mach number < *1*, the flow is **subsonic**
Mach number = *1*, the flow is **transonic**
Mach number > *1*, the flow is **supersonic**
If the Mach number > *5*, the flow is **hypersonic** (See Figure 1)

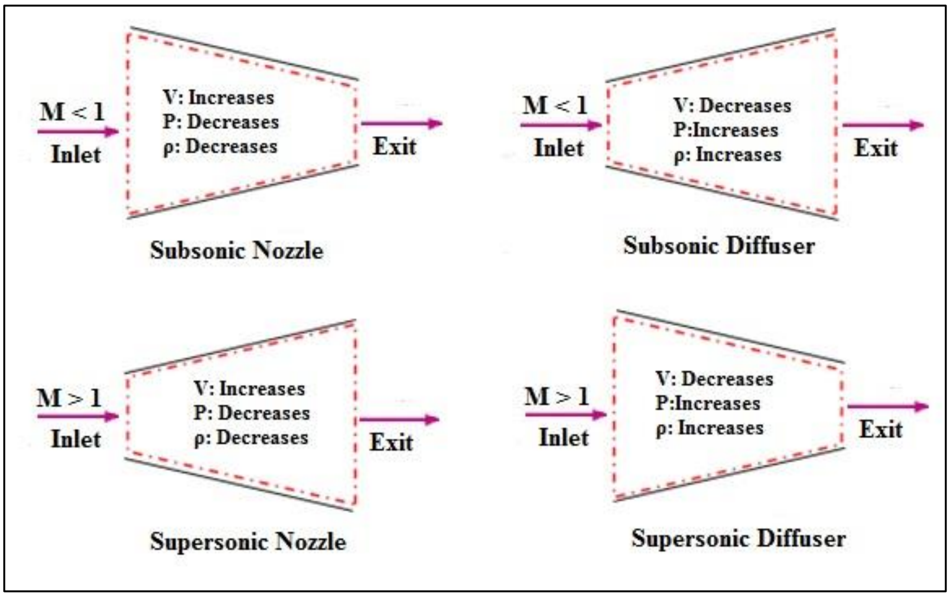

Fig. 1: Shapes of nozzles and diffusers in subsonic and supersonic regimes

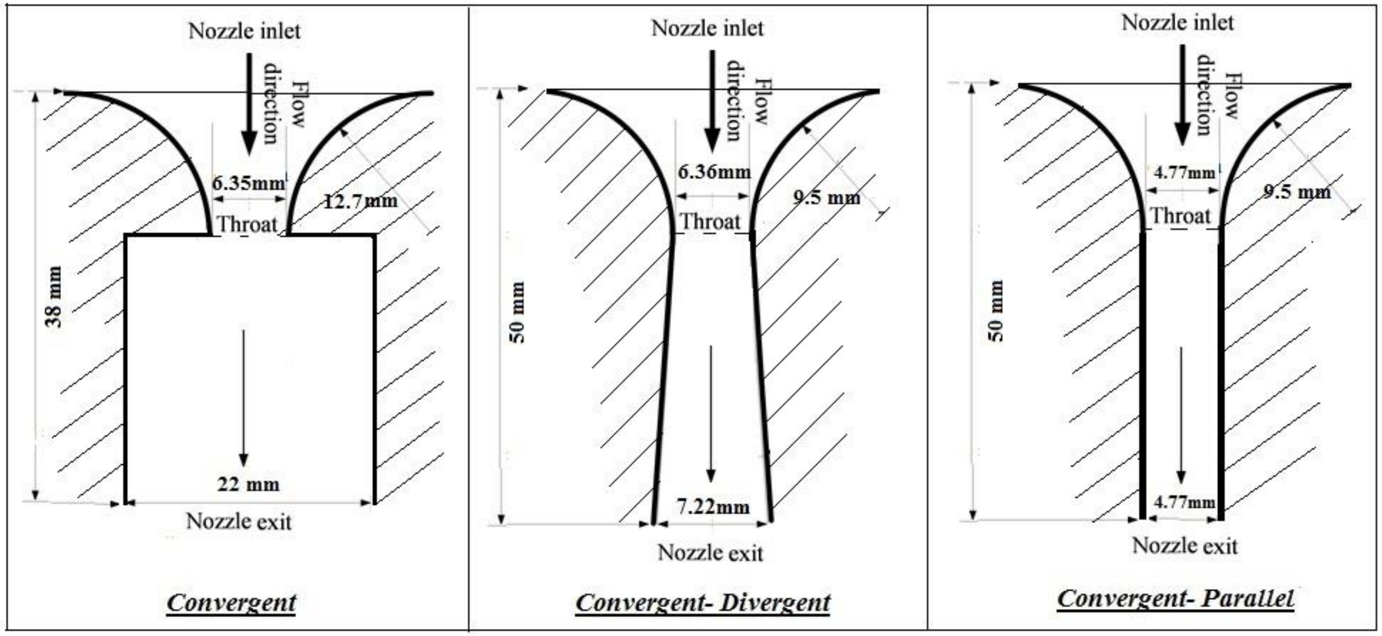

Fig. 2: Nozzle Profiles

TECHNICAL DATA

Nozzle Type	Throat diameter
Convergent:	6.35 mm
Convergent–Divergent:	6.36 mm
Convergent–Parallel:	4.77 mm

Probe diameter: **3.33 mm**

The flow of ideal gas through three different nozzles is shown in Figure 3 & 4. The nozzle discharges into a plenum chamber, in which the pressure is P_b can be regulated. Let P_e be the exit pressure just at the exit cross-section of the nozzle. When P_b is reduced, gas is drawn through the nozzle. As P_b is reduced more, the mass flow rate of gas increases and the velocity increase. The value of the velocity is the highest at the minimum area, and this can't be higher than the critical value i.e. when the velocity reaches the velocity of sound.
At this state the pressure is at its critical value, P*, which is given by:

$$\frac{P^*}{P_o} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$$	(1)

Where P* is the critical pressure kPa

P_o is the stagnation pressure kPa

k is the specific heat ratio

For air k = 1.4, and thus $P^* = 0.528 \times P_o$

For conditions other than the critical condition, the velocity at the throat is given by:

$$V_t = \sqrt{\frac{2kRT_o}{k-1}\left[1-\left(\frac{P_t}{P_o}\right)^{\frac{k-1}{k}}\right]} \quad m/s$$	(2)

Where T_o and P_o are the temperature and pressure in the nozzle chest, and P_t is the pressure at the throat.

While the mass flow rate at the throat is given by:

$$\dot{m}_t = A_t * P_o * \left(\frac{P_t}{P_o}\right)^{\frac{1}{k}} \sqrt{\frac{2k}{(k-1)*R*T_o} * \left[1-\left(\frac{P_t}{P_o}\right)^{\frac{k-1}{k}}\right]} \quad kg/s$$	(3)

Where:

$$Throat\ Area = A_t = \frac{\pi}{4}\left(d_n^2 - d_p^2\right), \quad m^2$$	(4)

In this relation the pressure is in kPa, T_o *in K and* R = 0.287 kJ/kgK

3.0 APPARATUS

A General View and schematic layout of the apparatus is shown in figure 3 and figure 4. Air is admitted to a cast iron pressure chest by way of adjustable vales. A nozzle of highly finished brass is screwed into a seating in the base of the chest and the air or steam expands through the nozzle. To enable the pressure distribution through the nozzle to be plotted, a search tube or probe of stainless steel may be traversed along the axis of the nozzle. A small cross hole in the search tube connects with a high grade pressure gauge which registers the pressure at any point in the nozzle. The search tube is traversed by rotating a calibrated dial and pressures are usually recorded at intervals of 2.5 mm. A pointer moves with the search tube past a replica of the nozzle profile in order to indicate the point in the nozzle at which the pressure is being measured. The nozzle discharges into a vertical pipe of large bore fitted with a throttling valve for controlling the downstream pressure. Other instruments include a second pressure gauge for recording the pressure in the chest (Po) and a thermometer for indicating the temperature of air in the chest. (See Figure 3)

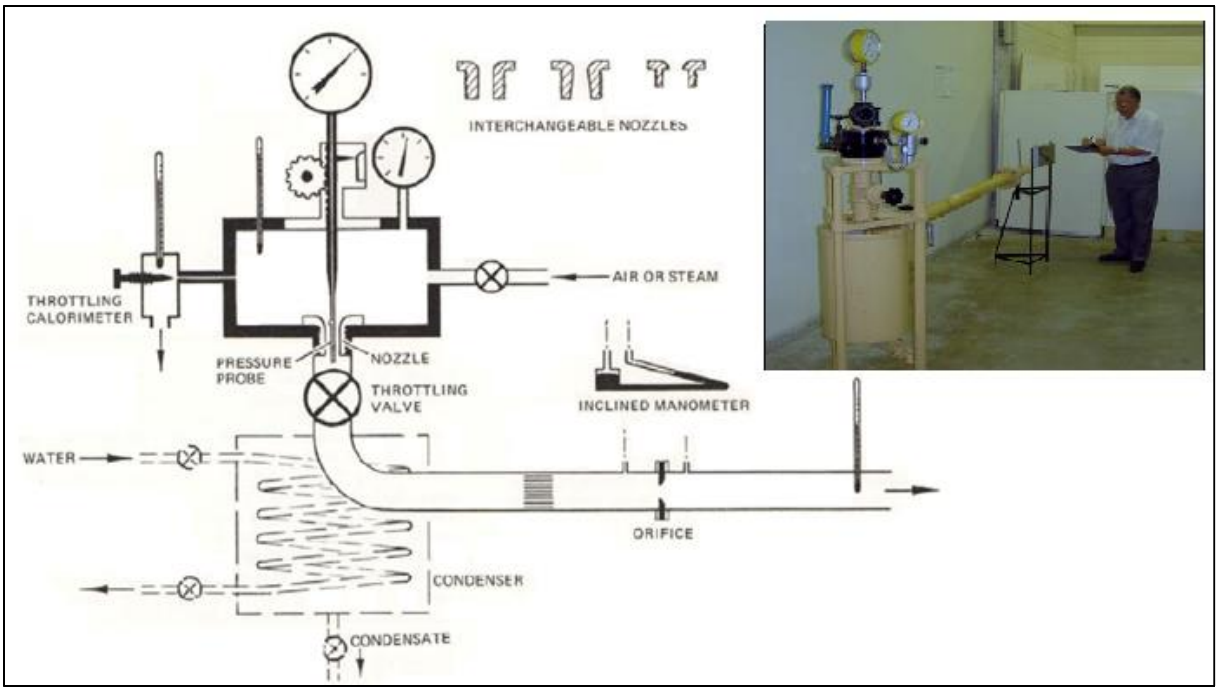

Fig. 3: Nozzle Flow Apparatus

4.0 PROCEDURE

1. Before starting, record the inlet air temperature and the barometer pressure.
2. Open the back pressure valve and return the search tube (pressure probe) to its upper limit, the pressure gauge should indicate the inlet chest pressure.
3. Open the inlet throttling valve by adjusting the chest gage pressure to 300 kPa.
4. Start record the probe pressure at several locations along the nozzle axis by rotating the calibrated dial, the probe is traversed in increments of 2.5 mm
5. The selected inlet chest pressure should remain constant during the experiment, so Chest pressure to be observed and re-adjusted to initial setting if necessary.
6. Record probe pressure at each of the locations shown on the nozzle.
7. At the end of the traverse, search tube should be returned to the upper position.
8. Repeat for other values of chest pressure, 400, and 500 kPa.
9. Check that the pressure at the throat is not lower than that for the condition of choking (critical condition).

Note: there is tendency for the inlet chest pressure to change in the course of the experiment (this may occur when the apparatus is being supplied with air by a compressor of insufficient capacity) a student should be placed in charge of the inlet throttling valve, with the task of maintaining a constant inlet chest pressure by adjusting the throttling valve as necessary.

5.0 OBSERVATIONS

Table 1: DATA OBSERVED

Atmospheric Pressure =______kPa   Atmospheric Temperature = ________ ℃

Part	Probe Position	X/L	Chest pressure P_o (gage)		
			P_o = ------- kPa	P_o = ------- kPa	P_o = -------- kPa
			Position Pressure, Pp, kPa		
Nozzle	7	0.0			
	8	0.25			
	9	0.5			
	10	0.75			
	11	1.0			
Parallel Section	12	1.25			
	13	1.5			
	14	1.75			
	15	2.0			
	16	2.25			
	17	2.5			
	18	2.75			
	19	3.0			
	20	3.25			
	21	3.5			
	22	3.75			
	23	4.0			
	24	4.25			
	25	4.5			
	26	4.75			
	27	5.0			
Outside	28	5.25			
	29	5.5			
	30	5.75			
	31	6.0			
	32	6.25			

Note that: **Position (7): is the entrance of the nozzle**

Position (11): is the location of the throat and exit of nozzle

Position (27): is the end of the parallel section

L = Nozzle length (10 mm), X= Probe increment = 2.5mm, X/L = 0.0, 0.25, 0.50 …6.25mm

6.0 DATA ANALYSIS

When the velocity of air reaches the velocity of sound where Mach number =1, the pressure is at its critical value, P*, which is given by:

$$\frac{P^*}{P_o} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$$

P* is the critical pressure

P_o is the stagnation pressure

K is the specific heat ratio

For air k = 1.4, and thus $P^* = 0.528 \times P_o$

For conditions other than the critical condition, the velocity at the throat is given by:

$$V_t = \sqrt{\frac{2kRT_o}{k-1}\left[1-\left(\frac{P_t}{P_o}\right)^{\frac{k-1}{k}}\right]} \quad m/s$$

T_o and P_o are the temperature and pressure in the nozzle chest, and P_t is the pressure at the throat.

The mass flow rate at the throat is given by:

$$\dot{m}_t = A_t * P_o * \left(\frac{P_t}{P_o}\right)^{\frac{1}{k}} \sqrt{\frac{2k}{(k-1)*R*T_o} * \left[1-\left(\frac{P_t}{P_o}\right)^{\frac{k-1}{k}}\right]} \quad kg/s$$

$$Throat\ Area = A_t = \frac{\pi}{4}\left(d_n^2 - d_p^2\right), \quad m^2$$

In this relation the pressure is in KPa, T_o *in K and* R = 0.287 kJ/kg K

7.0 RESULTS & DISCUSSION

Table 2: SUMMARY OF RESULTS

Throat Area = ________________ m^2

Chest pressure, kpa, (abs.)	Throat Pressure, kpa, (abs.)	Mass Flow Rate @ Throat kg/s	Velocity @ throat m/s	Pressure Ratio	Critical Pressure, kpa, (abs.)

1. For different values of chest pressure, plot the absolute pressure with the probe position along the nozzle (X/L).
2. For different values of pressure ratio across the nozzle, plot the mass flow rate with the pressure ratio.
3. All the results were recorded and tabulated under the results table.
4. Write your own opinions about the results.
5. What might be the possible causes of errors in this experiment? Discuss about whether the results are acceptable or not?
6. The diameter of the pressure probe is 3.33 mm, what is the effect of the probe diameter on the measured pressure distribution? Does it really represent the pressure distribution in the nozzle or a different one?
7. What is the percentage error involved in calculating the mass flow rate?
8. How would you explain the pressure drop downstream of the nozzle exit?
9. What can be done to improve the apparatus or the test procedure?

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Experiment 5

HEAT PUMP AND AIR COOLER

1. OBJECTIVE

- Demonstrate the performance of the equipment in both heating and cooling modes.
- Evaluate the coefficient of performance (COP) when operating as a heat pump.
- Evaluate the coefficient of performance (COP) when operating as an air cooler.

2. INTRODUCTION & THEORETICAL BACKGROUND

An air cooler and a heat pump essentially comprise the same cycle components, however, it is their objectives that differentiate between them. In an air cooler, or a refrigerator, the heat extracted from the air, Q_L (absorbed by the refrigerant in the evaporator) is the required cooling effect.

However, the heat rejected to the circulating water in the condenser, Q_H although necessary, is not the objective.

On the other hand, the heat pump utilizes the heat absorbed from a low-temperature source to maintain a heated space at a higher temperature, thus Q_H is the required heating effect.

The theoretical model with which such a device is compared in order to evaluate its performance is the reversible simple refrigeration cycle shown in Figure 1.

Such a cycle takes in heat isothermally from a reservoir at temperature T_L and rejects heat isothermally to another reservoir at temperature T_H. The intervening processes are adiabatic reversible expansion and compression processes. (See Figure 1)

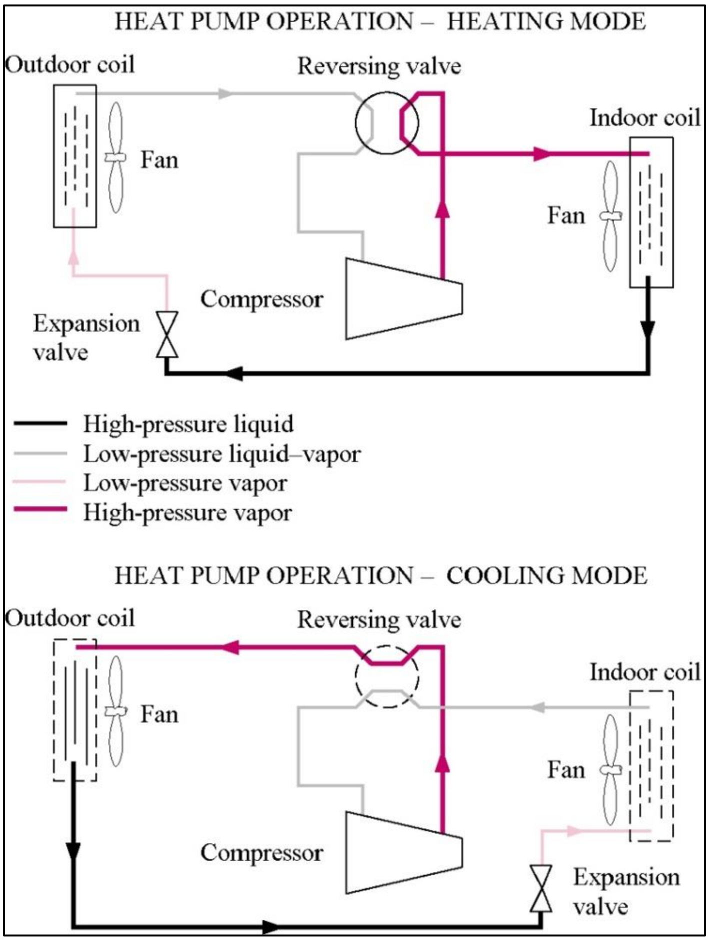


Fig. 1: **Reversible Simple Refrigeration Cycle**

The coefficient of performance of the machine when operating as an air cooler is

$$\boldsymbol{COP_R = \frac{Q_L}{E_C} = \frac{Q_L}{Q_H - Q_L}} \tag{1}$$

And when operating as a heat pump is

$$\boldsymbol{COP_{HP} = \frac{Q_H}{E_C} = \frac{Q_H}{Q_H - Q_L}} \tag{2}$$

However, the numerical values will be less than those corresponding to the ideal reversible engine. For an ideal reversible engine the heat transfer ratio Q_L/Q_H can be replaced by the ratio of the absolute temperature of the two reservoirs as follows:

Thus for a reversible air cooler, the COP is

$$\boldsymbol{COP_R = \frac{T_L}{T_H - T_L}} \tag{3}$$

And for a reversible heat pump the COP is

$$\boldsymbol{COP_{HP} = \frac{T_H}{T_H - T_L}} \tag{4}$$

Note that in all cases, $COP > 1$ and $COP_{HP} = COP_R + 1$

2. APPARATUS

The apparatus consists of two separate units, the air conditioner and the control console. The two units are connected, by electrical cables, thermocouple wires and nylon water pipes. (See Figure 2)

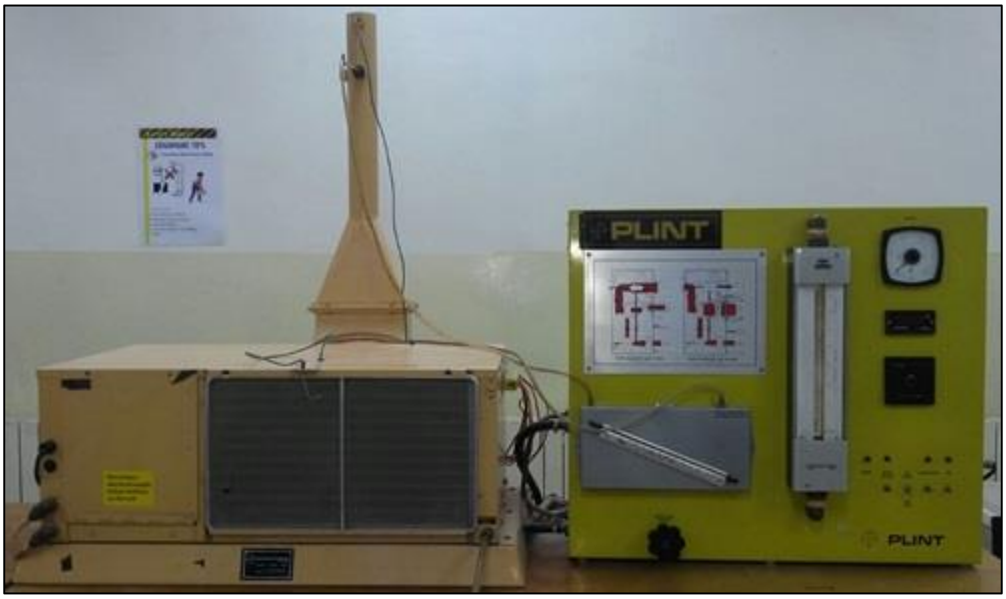


Fig. 2: Apparatus - General View

The air conditioner unit is completely self-contained and consists of a hermetically sealed *refrigeration system driven by a 0.4 kW motor, a refrigerant-to-water heat exchanger, a refrigerant-to-air heat exchanger, reversing valve, fan and motor, condensate collector and electrical controls. The air to be conditioned enters by way of the finned, refrigerant-to-air heat exchanger, passes through the centrifugal fan which is driven by a motor immersed in the air flow. The air is then discharged to a duct of circular cross-section carrying a pitot tube and a thermocouple. When the air is being cooled, and the relative humidity is high enough, moisture is deposited on the heat exchanger and drained off to a measuring vessel.

The control console unit carries all the electrical switches and fuses, a wattmeter and a multi-point digital temperature indicator. It also carries a flowmeter for measurement of water passing through the conditioner, an inclined manometer for use with the Pitot tube for air flow measurement and a vessel containing a 2 kW immersion heater. The latter is sometimes necessary when the conditioner is operating as a heat pump extracting heat from the circulating water since, if the temperature of the water on entry to the conditioner falls below about 10°C, there is a likelihood of freezing taking place.

*refrigerant: R22, Chlorodifluoromethane $CHClF_2$,The boiling point of R22 is -40.8 °C

The following instruments are provided:

1. Wattmeter for measurement of electrical power input to compressor and to fan.
2. Multipoint digital temperature indicator.
3. Whirling psychometer for measurement of relative humidity of air entering and leaving the conditioner.
4. Pitot-static tube and inclined manometer for measurement of air flow.
5. Cooling water flowmeter.
6. Graduated collecting vessel for condensate.
7. Thermocouples for temperature measurement
8. This apparatus uses water as a source and air as a sink in heating mode, and water as a sink and air as a source in cooling mode.

3. PROCEDURE

1. Before starting the machine ensure that the cooling water is turned on and regulated to give a flow of about 4 L/min. If the temperature of the cooling water entering the apparatus is less than 10°C and the machine is to operate as a heat pump, the water must also be switched on to ensure that freezing does not take place in the refrigerant-to-water heat exchanger.
2. Select cooling or heating as desired and switch on the compressor and fan. It takes between thirty minutes and one hour for temperature conditions in the apparatus to stabilize. It is suggested that a set of readings should be taken every ten minutes and continued until two successive readings show a change in air and water temperature of not more than 0.3°C.
3. The wattmeter shows the total electrical input to both the fan and the refrigerator compressor. The input to the fan alone may be measured by momentarily switching off the fan to measure the power to the compressor motor, then subtracting this reading from the reading for both the fan and the compressor.
4. The relative humidity of the air entering the conditioner should be measured by means of the sling hygrometer provided. Ensure that the reservoir in the hygrometer is filled with water and that it is whirled for a sufficiently long period (about thirty seconds) to give steady readings.
5. The relative humidity can be then used to find the humidity ratio ω, with the help of the psychometric chart, given at the end of the experiment.

6. When operating as a heater there will be no moisture deposited in the conditioner, since the relative humidity falls as the air passes through the machine.
7. When operating as a cooler there may or may not be deposition of moisture depending on the relative humidity of the air entering the machine. It may take a considerable time, as much as two to three hours, for the rate of flow of condensate to reach a stable value and, for this reason; it may be desirable when a cooling test is to be made to start up the apparatus several hours in advance of the laboratory period. There is some intrinsic variation in condensate flow rate and the measuring period should be as long as possible.

Record the following temperatures:

T_1 Air at inlet

T_2 Air at discharge

T_3 Circulating water at inlet

T_4 Circulating water at discharge

		Heat Pump	Air Cooler
T_5	Compressor	Discharge	Inlet
T_6	Compressor	Inlet	Discharge
T_7	Refrigerant-to-water heat exchanger	Discharge	Inlet
T_8	Refrigerant-to-water heat exchanger	Inlet	Discharge
T_9	Refrigerant-to-air heat exchanger	Inlet	Discharge
T_{10}	Refrigerant-to-air heat exchanger	Discharge	Inlet

The air flow is measured by means of a pitot tube mounted in the center of the discharge duct. The pressure of air at this point is effectively equal to that of the atmosphere, P_a If H mm H_2O is the velocity head measured by the Pitot tube, the mass flow rate is given by:

$$\dot{m}_a = 0.00105\sqrt{\frac{H \times P_a}{T_2}} \quad kg/s \qquad (5)$$

Where H: Manometer reading in mm H_2O

P_a: Atmospheric pressure in N/m^2

T_2: Air temperature at discharge in K

Part A
Heat Pump

1. THEORY

The machine arrangement when operating as a Heat Pump is shown in Figure 1. The Figure shows the theoretical circuit of apparatus in heating mode, drawing energy from the circulating water and delivering it to the air. The compressor delivers refrigerant under pressure and at high temperature to the refrigerant-to-air heat exchanger, where heat is transferred to the air and the refrigerant condenses in the process. The refrigerant then passes through a restriction tube to the low pressure side of the circuit and to the refrigerant-to-water heat exchanger where it evaporates, taking up heat from the circulating water. It then returns to the compressor. (See Figure 1 & 2)

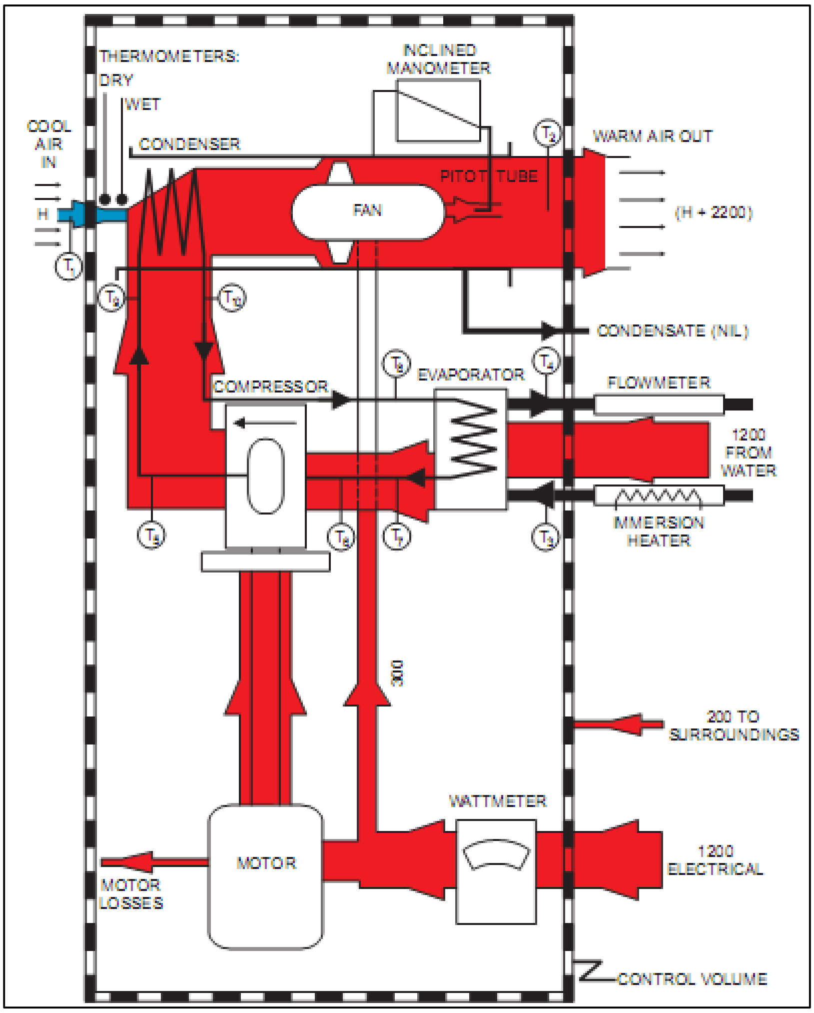


Fig. 1: Heat Pump - Schematic Layout

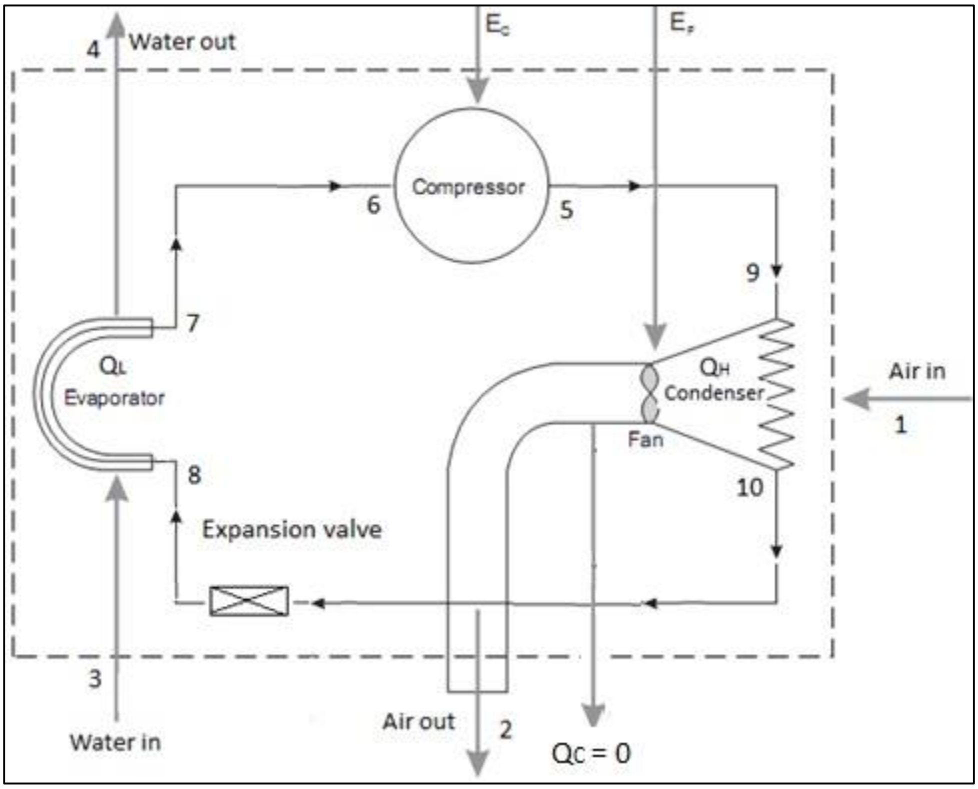


Fig. 2: Energy Flow Diagram for Heat Pump

The steady state steady flow (SSSF) equation for the system, see Figure 2 is the same as for the air cooler and may be written as:

$$Q_H - E_C - E_F = Q_L$$

Where

$$Q_L = \dot{m}_w(\, h_{f4} - h_{f3}\,) = \dot{m}_w C_{Pw}(T_4 - T_3)$$

$$Q_H = \dot{m}_a(\, h_2 - h_1\,) + \dot{m}_a(\, W_2 h_{v2} - W_1 h_{v1}\,)$$

$\dot{m}_a$ = Mass flow rate of dry air (exchange heat with condenser)

$\dot{m}_w$ = Mass flow rate of water (exchange heat with evaporator)

h_1 *and* h_2 = Enthalpy of dry air at inlet and exit (from psychometric chart)

W_1 *and* W_2 = Humidity ratio of air at inlet and exit (from psychometric chart)

h_{v1} *and* h_{v2} = Enthalpy of water vapor in air at inlet and exit

($h_{v1} = h_{g1}$ *and* $h_{v2} = h_{g2}$ From steam table)

$E_C =$ Electrical input to the compressor

$E_F =$ Electrical input to the fan

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

The external coefficient of performance

$$COP_{HP,\ E} = \frac{\dot{m}_a(h_2 - h_1) + \dot{m}_a(W_2 h_{v2} - W_1 h_{v1})}{E_C + E_F} \quad (1)$$

And the corresponding value for an ideal machine operating between the same mean temperatures is:

The max coefficient of performance

$$COP_{HP,\ max} = \frac{(T_1 + T_2)/2}{(T_1 + T_2)/2 - (T_3 + T_4)/2} \quad (2)$$

Where the temperatures in these equations are in Kelvin

The internal coefficient of performance

Again, the performance of the basic heat pump is not identical with the overall performance since the energy supplied to the circulating fan is not chargeable to the heat pump and appears in the discharge air in which the fan and motor are immersed. This leads to the internal coefficient:

$$COP_{HP,\ I} = \frac{\dot{m}_a(h_2 - h_1) + \dot{m}_a(W_2 h_{v2} - W_1 h_{v1}) - E_F}{E_C} \quad (3)$$

This may be compared with an ideal performance based upon the temperature difference across the refrigerator circuit

The ideal max coefficient of performance

$$COP_{HP,ideal\ max} = \frac{T_{10}}{T_{10} - T_8} \quad (4)$$

Where the temperatures in these equations are in Kelvin

In a real machine such as the present one, the coefficient of performance falls short of the ideal for a number of reasons, the most important are:

- Electrical and mechanical losses in both the fan and the compressor.
- The imperfection (irreversibility) of the refrigeration cycle itself.
- The necessity for temperature differences between refrigerant and air, and between refrigerant and water. As a result of which the refrigerant cycle operates between substantially wider temperature limits than those applicable to the water and air forming the source and sink.

2. OBSERVATIONS

Table 1: DATA OBSERVED

Experiential Temperatures			
Location		**Tem p. °C**	**Value**
Air in	Inlet Dry Bulb Temp.	$T_{1,db} = T_1$	
	Inlet Wet Bulb Temp.	$T_{1,wb}$	
Air out	Exit Dry Bulb Temp.	$T_{2,db} = T_2$	
	Exit Wet Bulb Temp.	$T_{2,wb}$	
Water	inlet	T_3	
	outlet	T_4	
Compressor	outlet	T_5	
	inlet	T_6	
Evaporator	outlet	T_7	
	inlet	T_8	
Condenser	inlet	T_9	
	outlet	T_{10}	
Condensate Temp.	at Discharge	T_C	
Manometer Reading	H	mm H_2O	
Mass Flow Rates			
Circulating Water	$\dot{m}_w$	l/min	
Condensate at Discharge	$\dot{m}_C$	ml/min	
Dry Air	$\dot{m}_a$	kg/S	
Power Consumed			
Total Power	E_T	kW	
Compressor Power	E_C	kW	
Fan Power	E_F	kW	

3. RESULTS & DISCUSSION

Table 2: ENTHALPIES

Item	Symbol	Unit	Value
Dry air entering conditioner	h_1	kJ/kg	
Dry air leaving conditioner	h_2	kJ/kg	
Water vapor entering conditioner	h_{v1}	kJ/kg	
Water vapor leaving conditioner	h_{v2}	kJ/kg	
Condensate	h_C	kJ/kg	
Humidity ratio of air at inlet	W_1	kg/kg	
Humidity ratio of air at exit	W_2	kg/kg	
Mass flow rate of dry air	$\dot{m}_a$	kg/s	

Table3: SUMMARY OF RESULTS

Item	$(COP_{AC})_{I}$	$(COP_{AC})_{E}$	$(COP_{AC})_{max}$	$(COP_{AC})_{I,max}$
Value				

1. All the results were recorded and tabulated under the results table.
2. Calculate the COP for the Heat Pump showing your work on psychometric chart and steam table attached and compare it with the ideal theoretical value.
3. Given the diameter of the discharge duct of the heat pump to be D = 0.073 m, derive the mass flow rate of air in kg/s as per the formula below.

$$\dot{m}_a = 0.00105\sqrt{\frac{H \cdot P_a}{T_2}} \quad kg/s$$

And the velocity correction $U = 0.96U$

4. Discuss any discrepancy and the possible causes of errors in this experiment.
5. Write your own opinions about the results. What might be? Discuss about whether the results are acceptable or not?

Part B
Air Cooler

1. THEORY

The machine arrangement when operating as an Air Cooler is shown in Figure 1. The figure shows the theoretical circuit in cooling mode. The direction of flow is now reversed. The refrigerant passes from the compressor to the refrigerant-to-water heat exchanger, where it gives up heat to the cooling water, subsequently passing through the reducing valve to the refrigerant-to-air heat exchanger, where it evaporates, and extracting heat from the air. When the apparatus acts in cooling mode, the air is sometimes cooled to below the dew point and condensate is deposited.

(See Figure 1& 2)

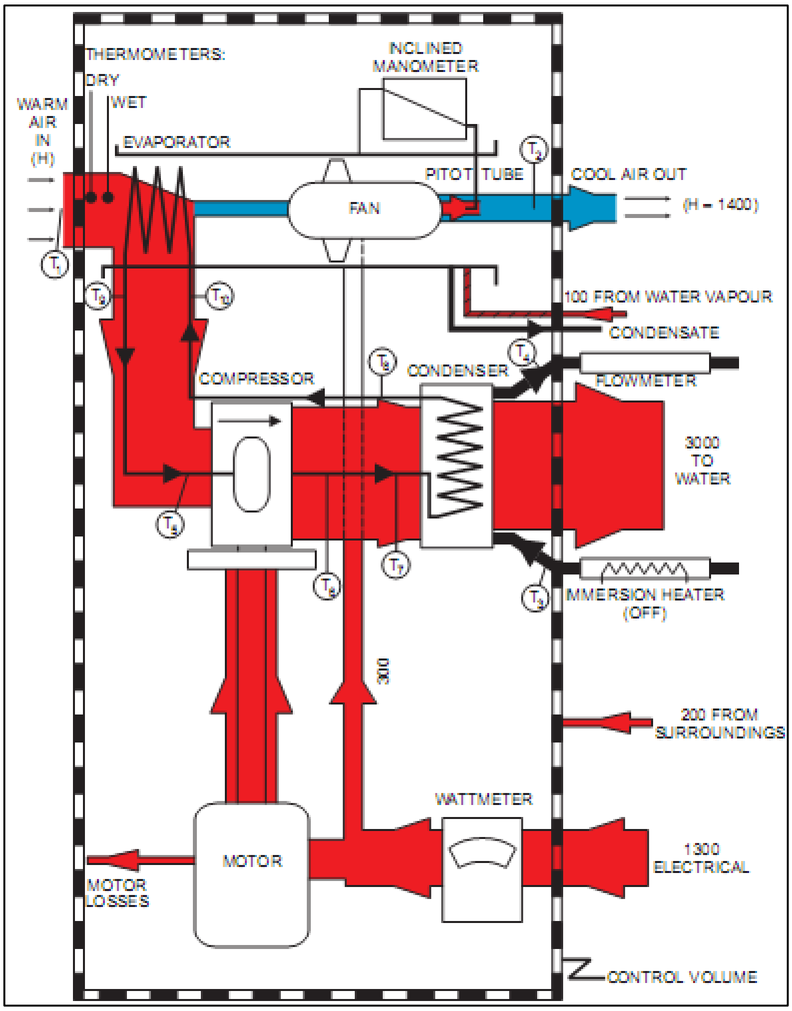


Fig. 1: Air Cooler - Schematic Layout

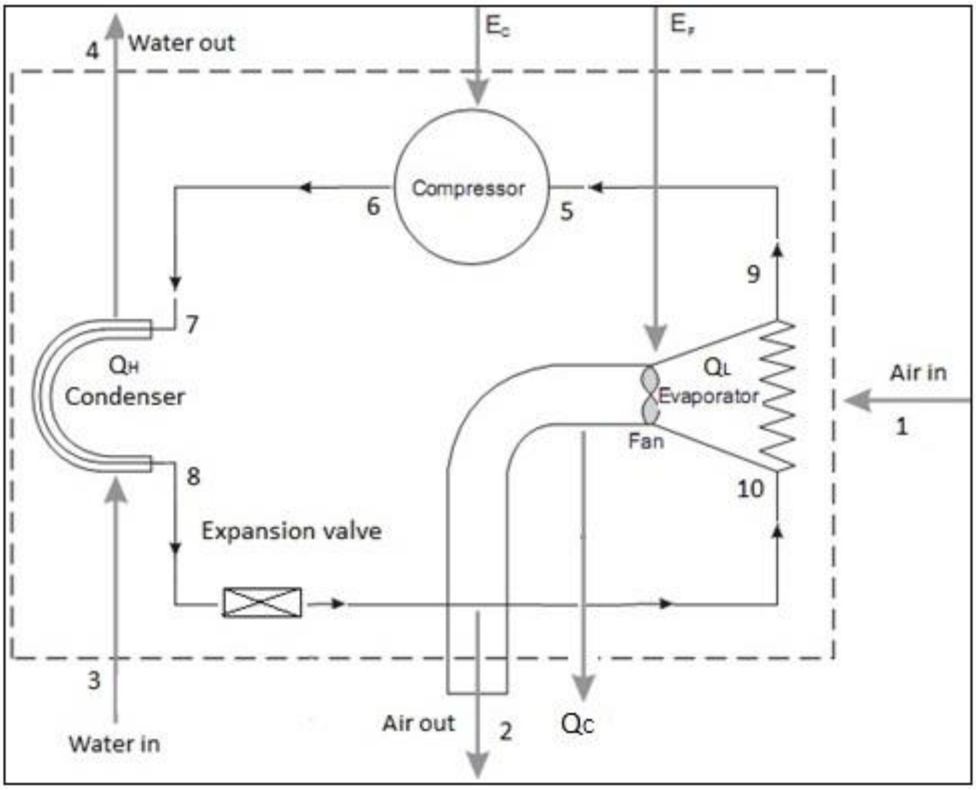


Fig. 2: Energy Flow Diagram for Air Cooler

The steady state steady flow (SSSF) equation for the system may be derived from the energy flow diagram Figure 2, as

$Q_H - E_C - E_F = Q_L$

Where:

$Q_H = \dot{m}_w(h_{f4} - h_{f3}) = \dot{m}_w C_{Pw}(T_4 - T_3)$

$Q_L = \dot{m}_a(h_1 - h_2) + \dot{m}_a(W_1 h_{v1} - W_2 h_{v2}) - Q_C$

$Q_C = \dot{m}_C C_{Pw} T_C$

$\dot{m}_a$ = Mass flow rate of dry air (exchange heat with evaporator)

$\dot{m}_w$ = Mass flow rate of water (exchange heat with condenser)

$\dot{m}_C$ = Mass flow rate of condensate water from the air stream

h_1 *and* h_2 = Enthalpy of dry air at inlet and exit (from psychometric chart)

W_1 *and* W_2 = Humidity ratio of air at inlet and exit (from psychometric chart)

h_{v1} *and* h_{v2} = Enthalpy of water vapor in air at inlet and exit

($h_{v1} = h_{g1}$ *and* $h_{v2} = h_{g2}$ From steam table)

T_C = temperature of condensate water

E_C = Electrical input to the compressor

E_F = Electrical input to the fan

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

The external coefficient of performance

$$COP_{AC,\ E} = \frac{\dot{m}_a(h_1 - h_2) + \dot{m}_a(W_1 h_{v1} - W_2 h_{v2}) - \dot{m}_C C_{Pw} T_C}{E_C + E_F} \qquad (1)$$

And the corresponding value for an ideal machine operating between the same mean temperatures is:

The max coefficient of performance

$$\boldsymbol{COP_{HP,\ max} = \frac{(T_1 + T_2)/2}{(T_3 + T_4)/2 - (T_1 + T_2)/2}} \qquad (2)$$

Where the temperatures in these equations are in Kelvin

The internal coefficient of performance

The performance of the basic refrigerator is not identical with the overall performance since the energy supplied to the circulating fan is not chargeable to the refrigerator and appears in the discharge air in which the fan and motor are immersed. This leads to the internal coefficient:

$$\boldsymbol{COP_{AC,\ I} = \frac{\dot{m}_a(h_1 - h_2) + \dot{m}_a(W_1 h_{v1} - W_2 h_{v2}) - \dot{m}_C C_{Pw} T_C - E_F}{E_C}} \qquad (3)$$

The ideal max coefficient of performance

This may be compared with an ideal performance based upon the temperature difference across the refrigerator circuit

$$\boldsymbol{COP_{HP,ideal\ max} = \frac{T_{10}}{T_8 - T_{10}}} \qquad (4)$$

Where the temperatures in these equations are in Kelvin

In a real machine such as the present one, the coefficient of performance falls short of the ideal for a number of reasons, the most important are:

- Electrical and mechanical losses in both the fan and the compressor.
- The imperfection (irreversibility) of the refrigeration cycle itself.
- The necessity for temperature differences between refrigerant and air, and between refrigerant and water. As a result of which the refrigerant cycle operates between substantially wider temperature limits than those applicable to the water and air forming the source and sink.

2. OBSERVATIONS

Table 1: DATA OBSERVED

Experiential Temperatures			
Location		**Temp. ℃**	**Value**
Air in	Inlet Dry Bulb Temp.	$T_{1,db} = T_1$	
	Inlet Wet Bulb Temp.	$T_{1,wb}$	
Air out	Exit Dry Bulb Temp.	$T_{2,db} = T_2$	
	Exit Wet Bulb Temp.	$T_{2,wb}$	
Water	inlet	T_3	
	outlet	T_4	
Compressor	inlet	T_5	
	outlet	T_6	
Condenser	inlet	T_7	
	outlet	T_8	
Evaporator	outlet	T_9	
	inlet	T_{10}	
Condensate Temp.	at Discharge	$\mathbf{T_C}$	
Manometer Reading	H	mm H_2O	
Mass Flow Rates			
Circulating Water	$\dot{m}_w$	l/min	
Condensate at Discharge	$\dot{m}_C$	ml/min	
Dry Air	$\dot{m}_a$	kg/S	
Power Consumed			
Total Power	E_T	kW	
Compressor Power	E_C	kW	
Fan Power	E_F	kW	

3. RESULTS & DISCUSSION

Table 2: ENTHALPIES

Item	Symbol	Unit	Value
Dry air entering conditioner	h_1	kJ/kg	
Dry air leaving conditioner	h_2	kJ/kg	
Water vapor entering conditioner	h_{v1}	kJ/kg	
Water vapor leaving conditioner	h_{v2}	kJ/kg	
Condensate	h_C	kJ/kg	
Humidity ratio of air at inlet	W_1	kg/kg	
Humidity ratio of air at exit	W_2	kg/kg	
Mass flow rate of dry air	$\dot{m}_a$	kg/s	

Table3:COP RESULTS

Item	$(COP_{AC})_{I}$	$(COP_{AC})_{E}$	$(COP_{AC})_{max}$	$(COP_{AC})_{I, max}$
Value				

1. All the results were recorded and tabulated under the results table.
2. Calculate the COP for the Heat Pump showing your work on psychometric chart and steam table attached and compare it with the ideal theoretical value.
3. Given the diameter of the discharge duct of the heat pump to be D = 0.073 m, derive the mass flow rate of air in kg/s as per the formula below.

$$\dot{m}_a = 0.00105\sqrt{\frac{H \cdot P_a}{T_2}} \quad kg/s$$

And the velocity correction $U = 0.96U$

4. Discuss any discrepancy and the possible causes of errors in this experiment.
5. Write your own opinions about the results. What might be? Discuss about whether the results are acceptable or not?

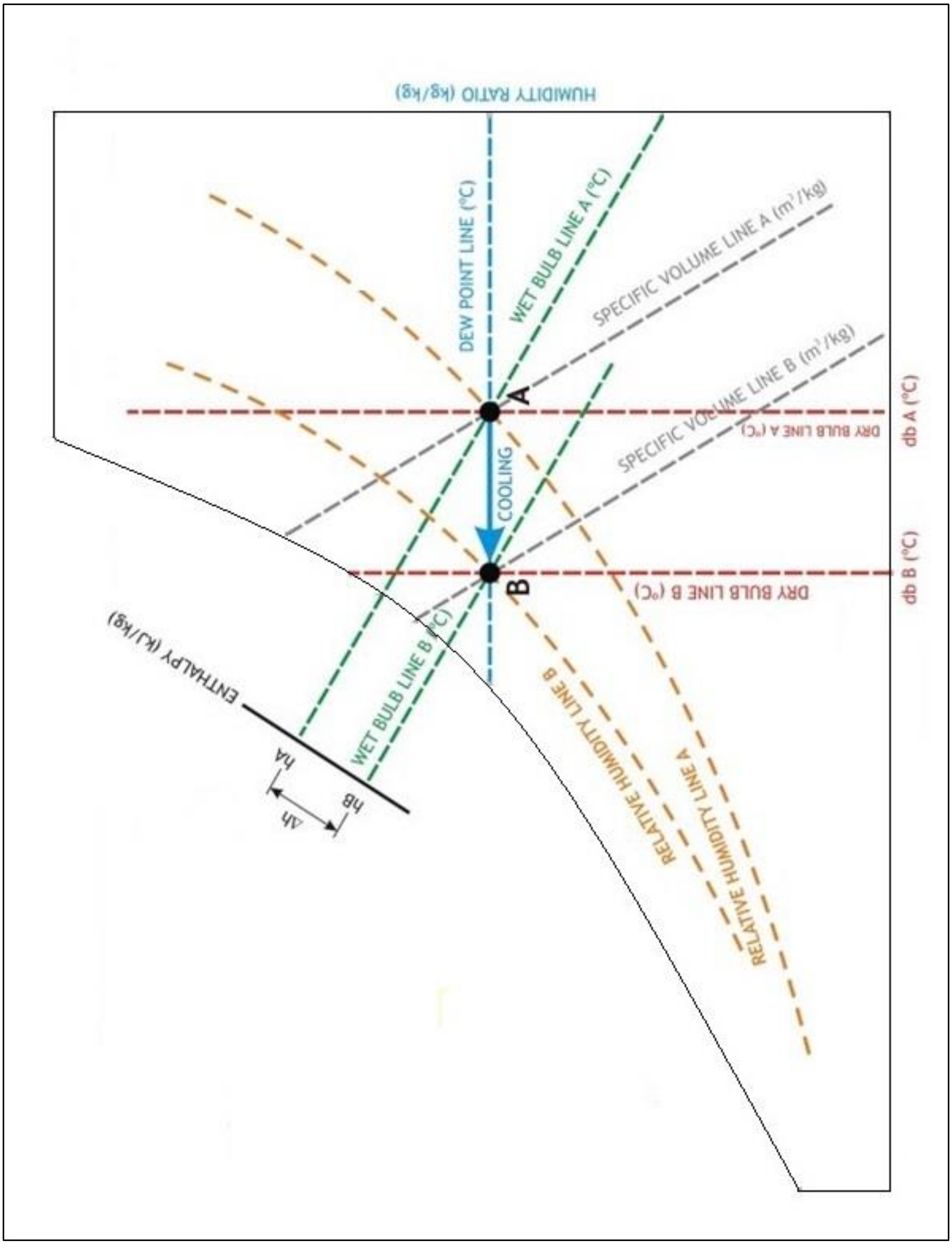
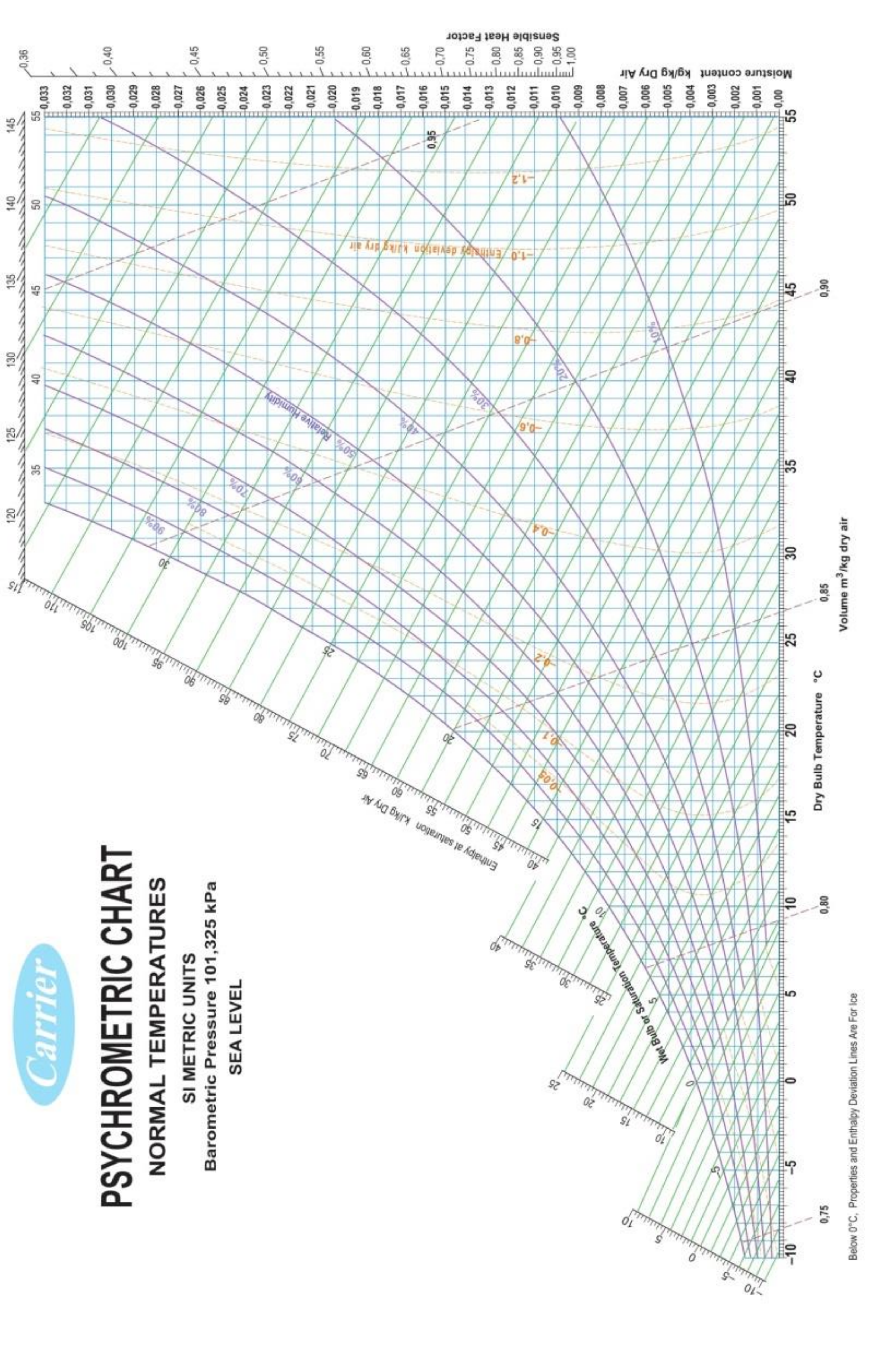


Fig. 2: Psychometric Chart (Basics)


Carrier
PSYCHROMETRIC CHART
NORMAL TEMPERATURES
SI METRIC UNITS
Barometric Pressure 101,325 kPa
SEA LEVEL
Sensible Heat Factor
Moisture content kg/kg Dry Air
Dry Bulb Temperature °C
Volume m3/kg dry air
Enthalpy at saturation kJ/kg Dry Air
Wet Bulb or Saturation Temperature °C
Relative Humidity
Enthalpy deviation kJ/kg dry air
Below 0°C, Properties and Enthalpy Deviation Lines Are For Ice

SATURATED STEAM - TEMPERATURE TABLE

		Spec. vol. m 3/kg		Enthalpy kJ/kg	
T °C	P bar	Sat liq. vf X1000	Sat. Vap. vg	Sat. liq. hf	Sat vap. hg
0.01	0.0061	1.0002	206.1	0.01	2501
4	0.0081	1.0001	157.2	16.79	2509
5	0.0087	1.0001	147.1	21	2511
6	0.0093	1.0001	137.7	25.21	2512
8	0.0107	1.0001	120.9	33.61	2516
10	0.0123	1.0001	106.4	42.01	2520
11	0.0131	1.0007	99.86	46.19	2522
12	0.0140	1.0007	93.79	50.4	2523
13	0.0150	1.0007	88.13	54.59	2525
14	0.0160	1.0007	82.85	58.8	2527
15	0.0170	1.0007	77.93	62.99	2529
16	0.0182	1.0013	73.34	67.17	2531
17	0.0194	1.0013	69.05	71.36	2533
18	0.0206	1.0013	65.04	75.57	2534
19	0.0220	1.0013	61.30	79.76	2536
20	0.0234	1.002	57.79	83.94	2538
21	0.0249	1.002	54.52	88.13	2540
22	0.0264	1.002	51.45	92.32	2542
23	0.0281	1.0026	48.58	96.5	2544
24	0.0298	1.0026	45.89	100.7	2545
25	0.0317	1.0032	43.36	104.9	2547
26	0.0336	1.0032	41.00	109.0	2549
27	0.0357	1.0032	38.78	113.2	2551
28	0.0378	1.0038	36.69	117.4	2553
29	0.0401	1.0038	34.73	121.6	2554
30	0.0425	1.0045	32.90	125.8	2556
31	0.0450	1.0045	31.17	130.0	2558
32	0.0476	1.0051	29.54	134.1	2560
33	0.0503	1.0051	28.01	138.3	2562
34	0.0532	1.0057	26.57	142.5	2563
35	0.0563	1.0057	25.22	146.7	2565
36	0.0595	1.0063	23.94	150.8	2567
38	0.0663	1.007	21.60	159.2	2571
40	0.0738	1.0076	19.52	167.5	2574
45	0.0959	1.010	15.26	188.4	2583
50	0.1235	1.012	12.03	209.3	2592
55	0.1576	1.015	9.569	230.2	2601
60	0.1994	1.017	7.671	251.1	2610
65	0.2503	1.020	6.197	272.0	2618
70	0.3119	1.023	5.042	293.0	2627
75	0.3858	1.026	4.131	313.9	2635
80	0.4739	1.029	3.407	334.9	2644

NOTE: This page is intentionally left blank to identify your important notes

Experiment 6

REFRIGERATION LABORATORY
(UNIT - R714)

1. OBJECTIVE

- To study the performance of an actual vapor compression refrigeration cycle, and perform energy balances on its different components [i.e. Evaporator, Compressor, and Condenser].
- To evaluate the coefficient of performance using Direct Measurements.
- To evaluate the coefficient of performance using Enthalpy Change Rate after drawing the refrigeration cycle on the (P-h) diagram, and to determine the state of refrigerant at the ending of various processes.

2. INTRODUCTION & THEORETICAL BACKGROUND

Refrigeration is playing an important role in all sectors of industry, commerce and household usage. A domestic refrigerator or any refrigeration system work on the vapor compression cycle. A Refrigeration Unit is a device which allows transport of heat from lower temperature level to a higher one (in a direction that is opposite of spontaneous flow), by using external energy (European Renewable Energy Council, 2008). The Refrigeration Unit being used in this experiment relies on the vapor compression cycle which needs a small work input to transfer heat from electric heater source evaporator to a water cooled condenser. (See Figure 1)

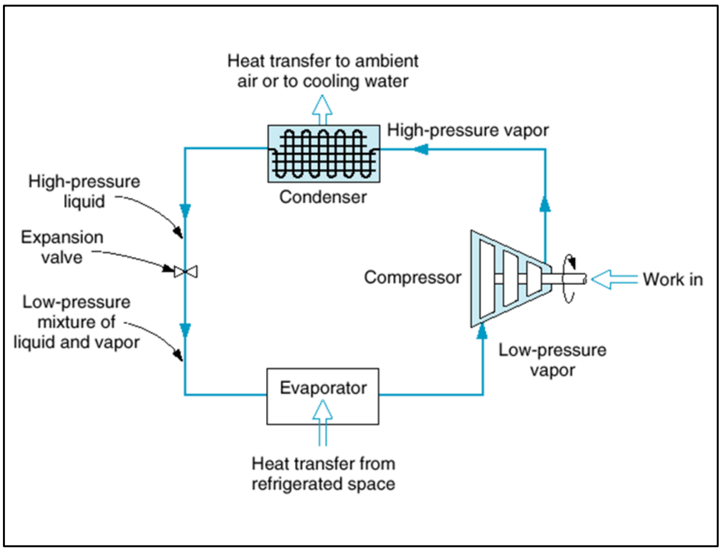


Fig. 1: Basic Vapor Compression Cycle

The Hilton Refrigeration Unit R-714 is a vapor compression cycle unit utilizing a small work input to transfer heat from electric heater source evaporator to a water cooled condenser. All relevant temperatures, pressures and power inputs are measured enabling the complete cycle to be investigated both diagrammatically and numerically.

1- Ideal Vapor-Compression Cycle

The vapor compression cycle has four components: evaporator, compressor, condenser, and expansion (or throttle) valve. In an ideal vapor-compression cycle, the refrigerant enters the compressor as a saturated vapor and is cooled to the saturated liquid state in the condenser. It is then throttled to the evaporator pressure and vaporizes as it absorbs heat from the refrigerated space. The ideal vapor compression cycle consists of four processes. (See Figure 2)

Process	**Description**
1-2	Isentropic compression
2-3	Constant pressure heat rejection in the condenser
3-4	Throttling in an expansion valve
4-1	Constant pressure heat addition in the evaporator

Component	Process	First Law Result
Compressor	s = Const.	$\dot{W}_{in} = \dot{m}(h_2 - h_1)$
Condenser	P = Const.	$\dot{Q}_H = \dot{m}(h_2 - h_3)$
Throttle Valve	Δs > 0	$h_4 = h_3 \qquad \dot{W}_{net} = 0 \qquad \dot{Q}_{net} = 0$
Evaporator	P = Const.	$\dot{Q}_L = \dot{m}(h_1 - h_4)$

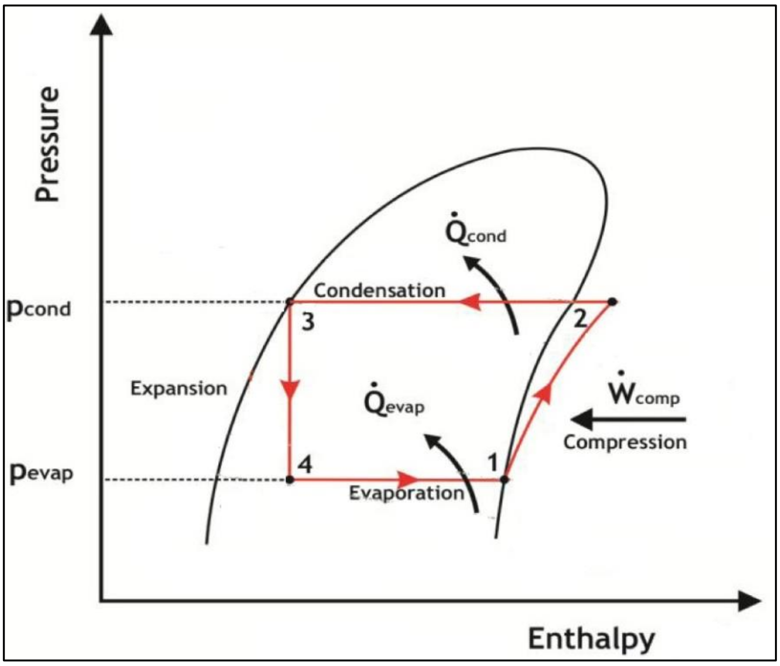


Fig. 2: The P-h Diagram of Ideal Vapor-Compression Cycle

2- Actual Vapor-Compression Cycle

An actual vapor-compression cycle differs from the ideal one in several ways, owing mostly to the irreversibilities that occur in various components, mainly due to fluid friction (causes pressure drops) and heat transfer to or from the surroundings. The COP decreases as a result of irreversibilities. DIFFERENCES: Non-isentropic compression, superheated vapor at evaporator exit Subcooled liquid at condenser exit, Pressure drops in condenser and evaporator. (See Figure 3)

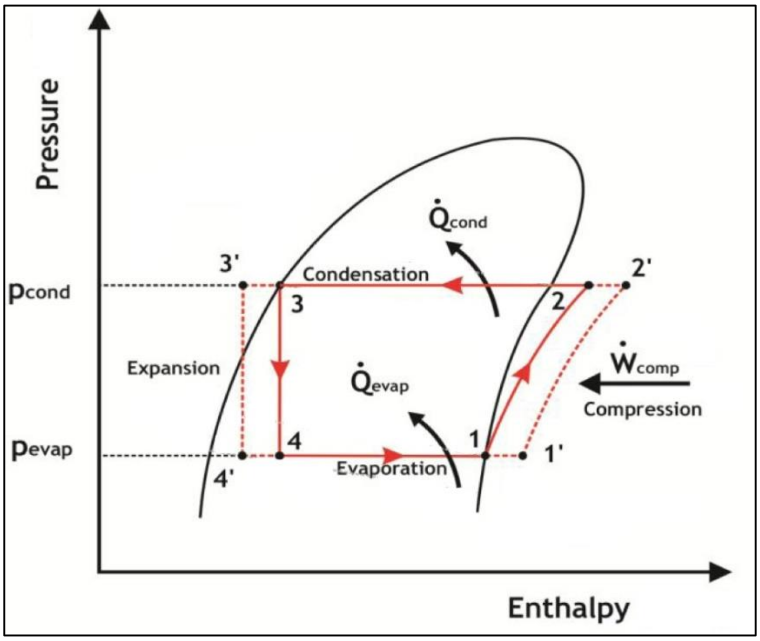
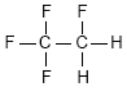


Fig. 3: The P-h Diagram of Actual Vapor-Compression Cycle

3. APPARATUS

This experiment will be conducted on the Hilton Computer-Linked Refrigeration Laboratory Unit No. RC 714. This unit operates on R 134 a Tetrafluoroethane (CF3 CH2F). A fully instrumented refrigerant ***R134a** vapor compression refrigerator with belt driven compressor, electrically heated evaporator, thermostatic expansion valve and water cooled condenser. Operating parameters can be varied by adjustment of condenser cooling water flow and electrically heated evaporator supply voltage. Components have a low thermal mass resulting in immediate response to control variations and rapid stabilization. Instrumentation includes all relevant temperatures, condenser pressure, evaporator pressure, refrigerant and cooling water flow rates, evaporator and motor power, motor torque and compressor speed. (See Figure 4 & 5)

Fig. 4: Refrigeration Laboratory Unit No. RC 714 - General View

* The chemical properties of **HFC-134a** are listed below:
Chemical Name: Tetrafluoroethane
Molecular Formula: CH_2FCF_3
Molecular Weight: 102.0
Chemical Structure: 
Boiling Point: at 1 atm (101.3 kPa or 1.013 bar): –26.1°C

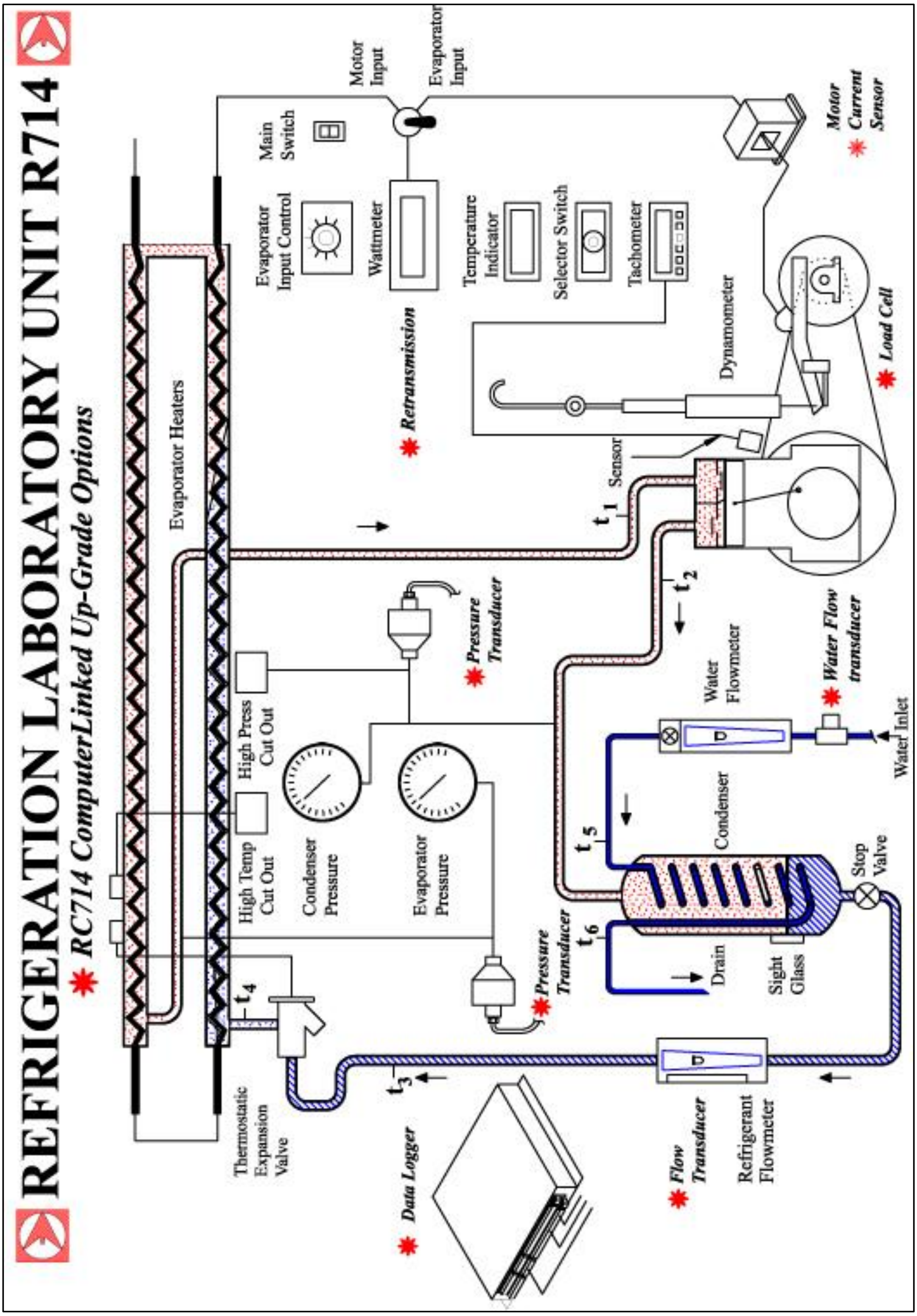


Fig. 5: Refrigeration Laboratory Unit No. RC 714 - Schematic Layout

4. PROCEDURE

1. Turn on the water supply to the RC 714 unit and open the water control valve several turns to allow a moderate flow rate of water through the condenser coil.
2. Switch ON the main switch located at the side of control panel.
3. For the spring scale, level the arm to the pointer. Record the initial value of it.
4. Turning the water control valve on the flow meter to get the desire flow rate.
5. Switch ON the compressor.
6. Adjust the heat power regulator to get to desired condenser pressure.
7. The spring scale now will move down and not level to the pointer. Loose the knob and pull the holder to adjust back to previous position.
8. Let the machine to run about 10 minutes.
9. Wait until readings reach steady state (After 10 minutes), then start recording data and records down all readings.
10. Reduce the evaporator input control to zero and after one minute switch off at main switch and turn off the cooling water.

*** At least perform two runs for different evaporator load**

5. OBSERVATIONS

Table 1: DATA OBSERVED

Test: Constant Condenser Pressure		Atmospheric Pressure: _______ *Kpa*				
SERIES	**No.**	**Parameter**	**1**	**2**	**3**	**UNITS**
Refrigerant HFC134a	1	Condenser Pressure, Pc (abs.)*				kpa
	2	Evaporator Pressure, Pe (abs.)*				kpa
	3	Compressor Suction Temp. (t_1)				°C
	4	Compressor Delivery Temp. (t_2)				°C
	5	Refrigerant Leaving the Cond. (t_3)				°C
	6	Evaporator Inlet Temp. (t_4)				°C
	7	R134a flow rate, $\dot{m}_r$				g/s
Water Condenser Cooling	8	Cooling water inlet Temp. (t_5)				°C
	9	Cooling water outlet Temp. (t_6)				°C
	10	Water flow rate, $\dot{m}_w$	**30**	**20**	**10**	g/s
	11	Evaporator Heat Input, $\dot{Q}\,e$				Watt
	12	Motor Input, $\dot{Q}\,m$				Watt
	13	Spring Balance Force (F)				N
	14	Compressor Speed (n_c)				rpm
	15	Motor Speed (n_m= 1.98 x n_c)				rpm

*Note: pressures must be converted to absolute values in order to locate the states on p-h diagram [Pabs. = Pgage+Patm] & [1 bar ≅100 kPa]

6. DATA ANALYSIS

1- Compressor

$\boldsymbol{Compressor\ Shaft\ Power = P_s = T \times \omega = F \times r \times \frac{2\pi \times n_C \times 1.98}{60}}$	(1)

$\boldsymbol{Compressor\ Friction\ Power = \ P_f = F_f \times r \times \frac{2\pi \times n_C \times 1.98}{60}}$	(2)

$\boldsymbol{Compressor\ Indicated\ Power = P_i = P_s - P_f}$	(3)

Where F: Force measured by the local cell.

F_f: Typical compressor friction force = 5 N, this is the spring balance load determined by running the compressor with suction valve closed.

r: Torque arm radius = 0.165 m

n_C: Compressor rpm.

$\boldsymbol{Compressor\ Power\ input\ from\ enthalpy\ change\ rate}$ $\boldsymbol{P_h = \dot{m}_r \times (h_2 - h_1)}$	(4)

$\boldsymbol{Heat\ losses\ from\ the\ compressor}$ $\boldsymbol{\dot{Q}_{rad+conv} = P_s - \dot{m}_R \times (h_2 - h_1)}$	(5)

2- Evaporator

$\boldsymbol{Evaporator\ Load\ from\ electric\ measurement}$ $\boldsymbol{\dot{Q}\ e,1 =}$ *Obtained from digital wattmeter*	(6)

$\boldsymbol{Evaporator\ load\ from\ enthalpy\ change\ rate}$ $\boldsymbol{\dot{Q}\ e,2 = \dot{m}_r \times (h_1 - h_4)}$	(7)

3- Condenser

$\boldsymbol{Condenser\ load\ from\ heat\ transfer\ to\ cooling\ water}$ $\boldsymbol{\dot{Q}\ c,1 = \dot{m}_w \times C_{pw}(t_6 - t_5)}$	(8)

$\boldsymbol{Condenser\ load\ from\ enthalpy\ change\ rate\ \ \dot{Q}\ c,2 = \dot{m}_r \times (h_2 - h_3)}$	(9)

4- Coefficient of performance

$\boldsymbol{COP_{R,act} = \frac{\dot{Q}_L}{W_{com}} = \frac{\dot{m}_r \times (h_1 - h_1)}{\dot{m}_r \times (h_2 - h_1)}}$	(10)

Determine location of state points:

No.1 is located by intersection of Pe Bar abs. and t_1°C (in superheated region)

No.2 is located by intersection of Pc Bar abs. and t_2 °C (in superheated region)

No.3 is located by intersection of Pc Bar abs. and t_3 °C (in subcooled region)

No.4 is located by dropping a vertical line from point 3 to the intersection with the Pe line, assumed adiabatic process.

Note that pressure drops in both the evaporator and condenser are assumed to be negligible and Pe and Pc are horizontal lines of constant pressure. (See Figure 6)

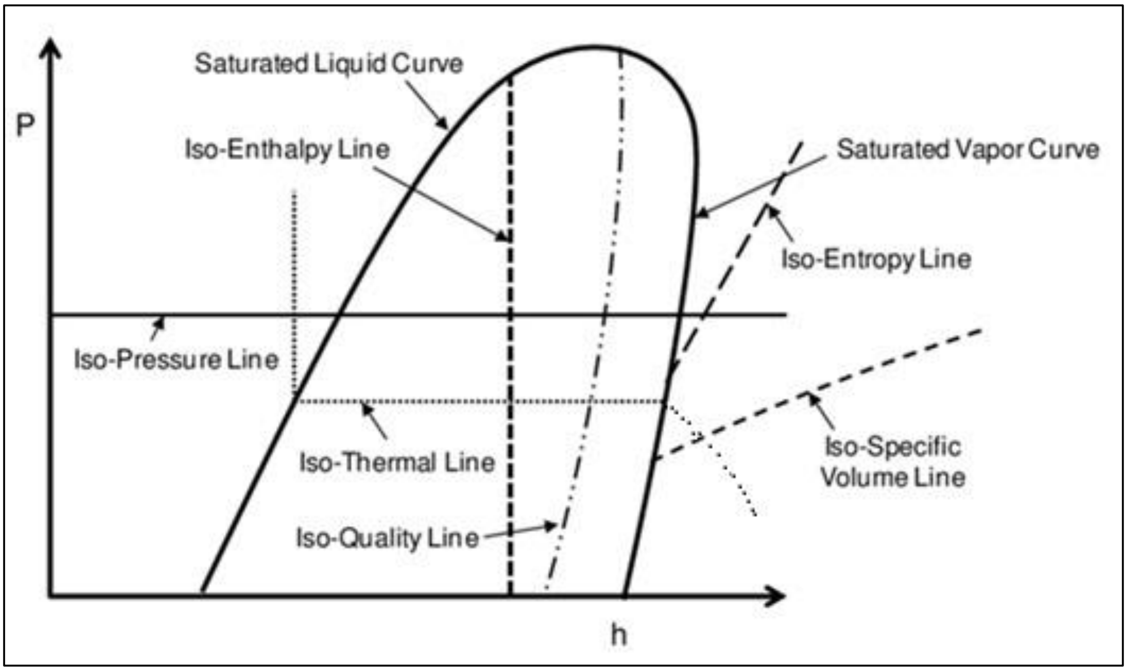


Fig. 6: Pressure - Enthalpy Diagram (Basics)

7. RESULTS & DISCUSSION

Table 2: SUMMARY OF RESULTS

No.	Compressor					Evaporator		Condenser		COP
parameters	P_s	P_f	P_i	P_h	$\dot{Q}_{rad+conv}$	$\dot{Q}\ e,1$	$\dot{Q}\ e,2$	$\dot{Q}\ c,1$	$\dot{Q}\ c,2$	$COP_{R,act}$
1										
2										
3										

1. Sketch the refrigeration cycle on the p-h diagram of R-134a with actual property values at all points.
2. Find h1, h2, h3, and h4. [You may find h3, and then set h4=h3]
3. All the results were recorded and tabulated under the results table.
   a) By using p-h diagram.
   b) By using ″Direct Measurements″.
4. Calculate the percentage difference between the two values found.
5. Discuss the results obtained and comment on discrepancies.
6. Do you think the cycle COP will increase or decrease with the evaporator temperature T_E increase?

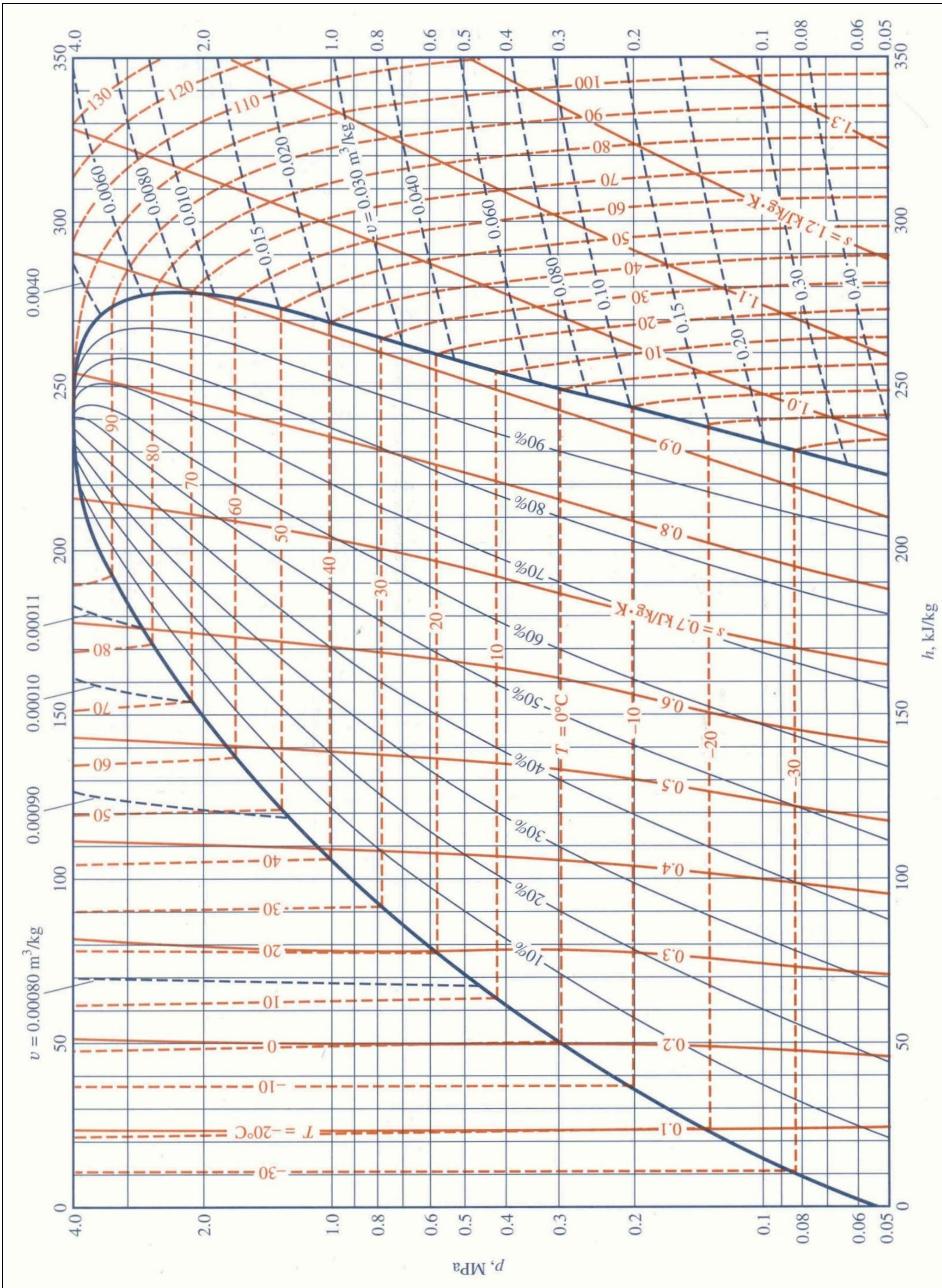


Chart A·11 R134a *ph* diagram. (*Source:* Based on *Thermodynamic Properties of HFC-134a (1,1,1, 2-tetrafluoroethane)*, DuPont Company, Wilmington, Delaware, 1993, with permission.)

NOTE: This page is intentionally left blank to identify your important notes

Experiment 7
SINGLE STAGE AIR COMPRESSOR

1. OBJECTIVE

- To determine the compressor performance parameters and efficiencies.

2. INTRODUCTION & THEORETICAL BACKGROUND

Compressors use mechanical work to take gas at low pressure and raise it to a higher pressure. A reciprocating compressor consists of a piston and cylinder. The basic arrangement is shown in figure 1.

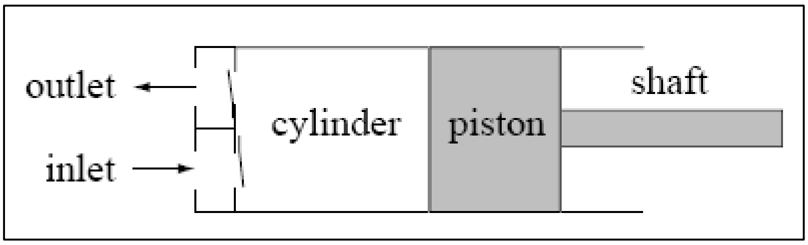


Fig. 1: Basic Reciprocating Compressor

Compressors are classified depending on the mechanical means used to produce compression of the fluid; the main types of compressors are: -

Positive Displacement Type

- Reciprocating Compressors

- Rotary Screw Compressors

Dynamic Type

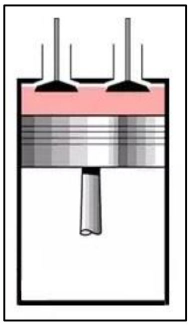
- Centrifugal Compressors

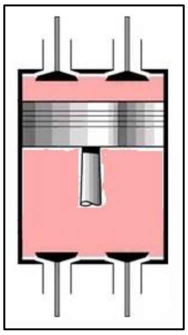
- Axial-flow Compressors
- Scroll Compressors

The main advantages of the reciprocating compressor are that it can achieve high pressure (but at comparatively low mass flow rates).

1- Single-acting vs. Double-acting Compressors

A single-acting compressor (Figure 2-A) has inlet and discharge valves on one side of the cylinder, and so only one side of the piston is active. A double-acting compressor (Figure 2-B) has inlet and discharge valves on both sides of the cylinder. This gives two compression cycles for every turn of the crankshaft. As the piston goes in a given direction, air is compressed on one side and the suction is created on the other one. During the return stroke, the same thing occurs with the sides reversed. (See Figure 2)



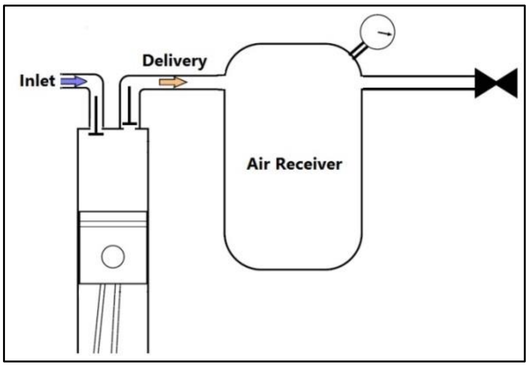


(A) (B)

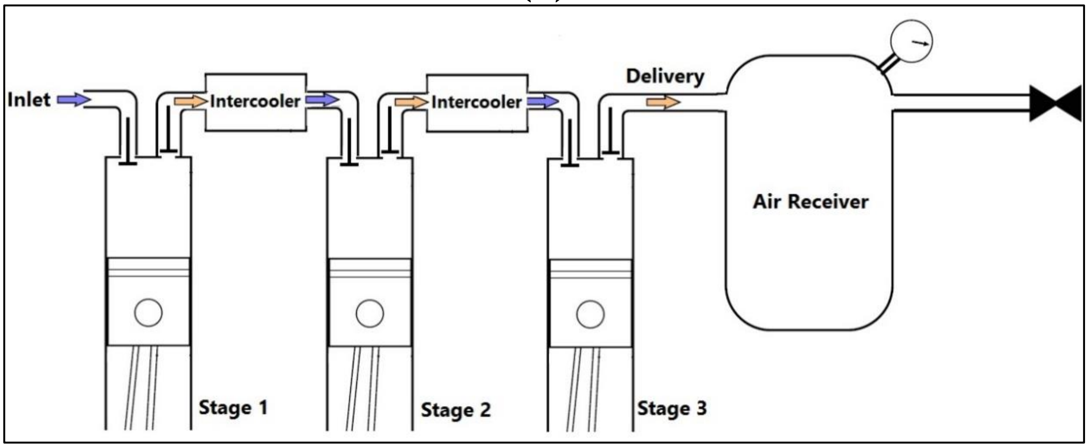
Fig. 2: Single-acting vs. Double-acting Compressors

2- Single stage vs. Multi stage Compressors

In a single stage compressor (Figure 3-A), the air is drawn into a cylinder and compressed to a certain pressure and then sent to the storage tank. In Multi stage compressor (Figure 3-B) and to avoid unacceptable reductions in compressor capacity (RPM and volumetric efficiency) and to minimize power input with high compression ratios, the first step is the same except that the air is not directed to the storage tank, the air is sent via an intercooler tube and compressed a second time and finally it is sent to the storage tank. (See Figure 3)



(A)



(B)

Fig. 3: Single Stage vs. Multi Stage Compressors

1- Basic theory of air compressor

When the piston moves from BDC to TDC air gets compressed, as a result, pressure increases and therefore volume decreases. The work done to compress the air converted to heat energy in the air so that, the air temperature is increased.

Isothermal Compression

During compression, if all the heat generated is taken by cylinder wall then it is called **Isothermal compression**. Here, further temperature rise is avoided and the compression is taking place at constant temperature. The relationship between the pressure and volume would follow Boyles law (PV= C).

Adiabatic Compression

During compression, if there is no heat transfer from the compressed air, then all the work done during compression would appear as stored heat energy. This is known as the **Adiabatic compression** and the relationship between pressure and volume would be $PV^k = C$, (**k** = 1.4 for air).

Polytropic Compression

The actual compression process in an air compression is between the isothermal and the adiabatic and is referred to as **Polytropic compression**. And the relationship between pressure and volume is $PV^n = C$, where n is a value of about 1.25-1.35. (See Figure 4)

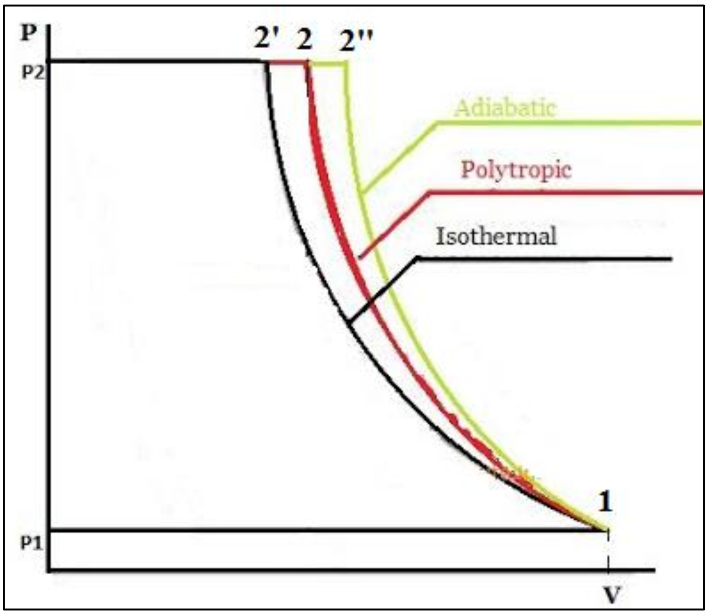


Fig. 4: Compression Types

2- PV Diagram with Explanation

@ Point (3): The piston is at TDC & the cylinder volume is smallest, (Clearance Volume - V_C), with a pressure P_2, and temperature T_2.

(3 → 4): Expansion: The piston is start moving down from TDC, (Air is expand polytropcally ($PV^n = C$), pressure & temperature of air decreases, and volume increases, with suction valve still closed.

@ Point (4): The suction valve open and air starts to enter the cylinder.

(4 → 1): Intake (Suction): Air is drawn into the cylinder from the atmosphere at constant pressure P_1.

@ Point (1): The piston is at BDC & the cylinder volume is greatest, (Swept Volume –Vs), with a pressure P_1, and temperature T_1.

(1 → 2): Compression: The piston is start moving up from BDC (Air is compressed polytropcally ($PV^n = C$), pressure & temperature of air increases, and volume decreases, with the delivery valve still closed.

@ Point (2): Air is completely compressed with pressure = P_2, volume = Vc, and temperature = T_2, the delivery valve open and air starts to leave the cylinder.

(2 → 3): Delivery: Compressed air is delivered out of the cylinder to the receiver at constant pressure P_2. (See Figure 5)

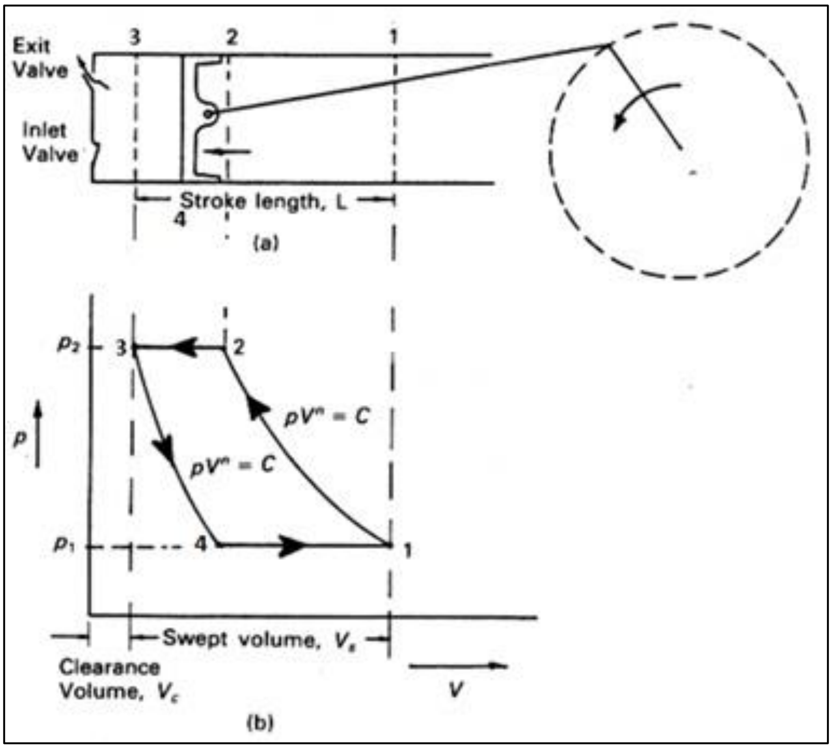


Fig. 5: PV Diagram with Explanation

3. APPARATUS

It is a single stage double cylinder compressor, with a provision for indicator diagrams. The compressor is driven by an electric motor / dynamometer. The speed is recorded by signals from a magnetic transducer whose output is fed to a digital tachometer which shows the RPM time and total revolutions. The compressed air-is stored in a receiver and a throttling valve permits the air pressure to be controlled. (See Figure 6 & 7)

Fig. 6: Single Stage Air Compressor - General View

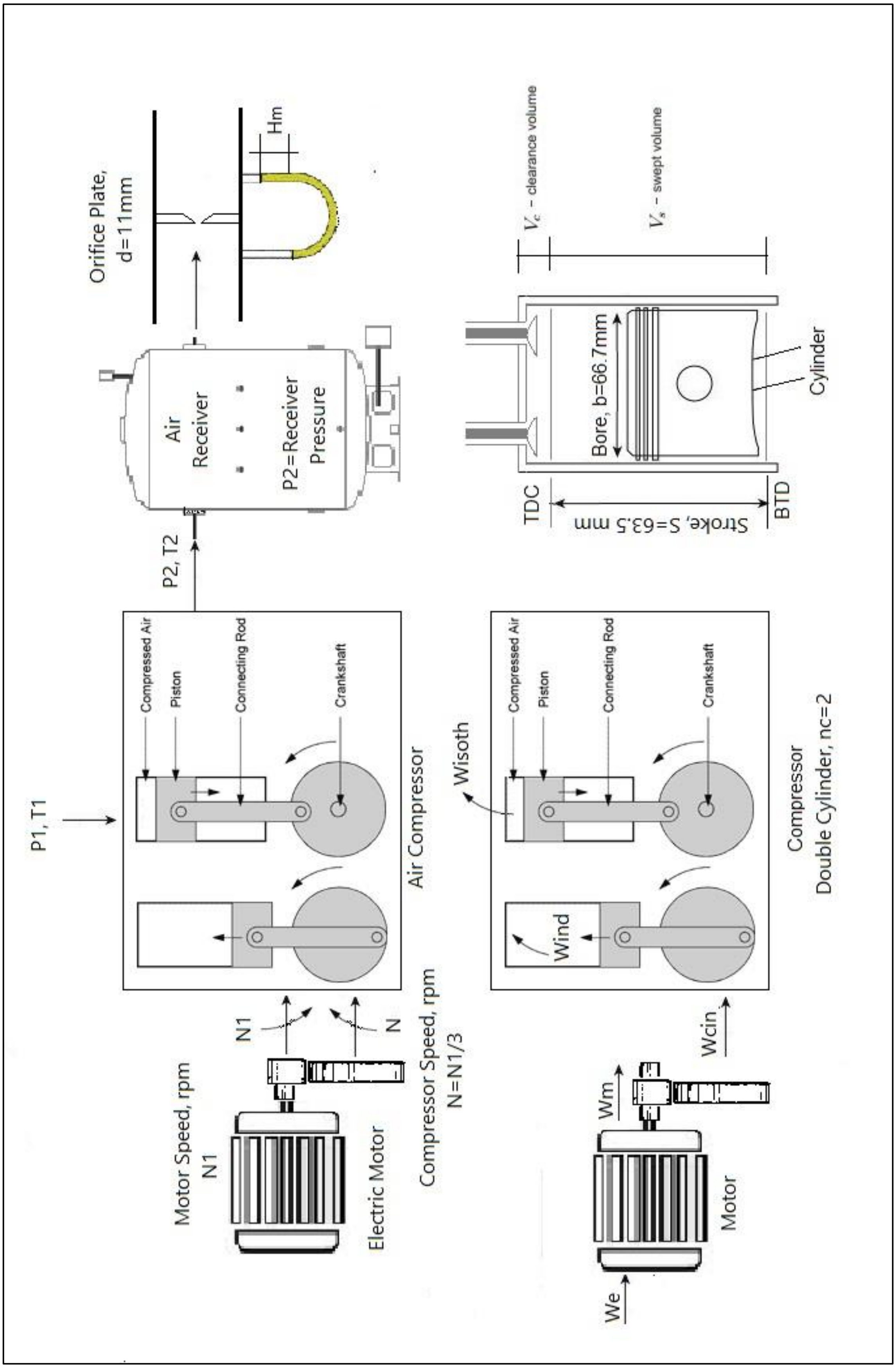


Fig. 7: Single Stage Air Compressor - Schematic Layout

4. PROCEDURE

1. Before starting, record the inlet air temperature and the barometer pressure.
2. Turn on the main switch
3. Revolve the speed wheel gradually to speed of about 530 rpm.
4. Wait receiver to approaches the desired pressure.
5. Open the throttling valve gradually; the manometer reading should indicate the pressure head.
6. By opening the throttling valve, check that manometer reading is not lower than 5 mm pressure head, for the condition of calculating air flow rate.
7. Set compressor speed and air receiver pressure to the desired values and run for 30 minutes to attain steady state which will be maintained by small adjustments of the throttling valve.
8. After changing any variable run the machine for 20 minutes before taking readings.
9. Take indicator diagram during each test.
10. Repeat for other values of compressor speed and air receiver pressure.
11. At the end of the test, revolve speed wheel gradually to return speed to the zero speed.

5. OBSERVATIONS

Table 1: TECHNICAL DATA

NO.	Item	Value	Unit
1	Number of Cylinders, n_C	2	
2	Bore, b	66.7	mm
3	Stroke, S	63.5	mm
4	Diameter of the Orifice, d	11	mm
5	Spring Calibration, SPC	20	kpa/mm
6	Torque Arm Radius, Tar	220	mm
7	Speed Ratio, motor/compressor,	3:1	

Table 2: DATA OBSERVED

NO.	Measured Parameter	Value	Unit
1	Barometric Pressure, P_1		kpa
2	Ambient Temperature,T1		℃
3	Motor Speed, N1		rpm
4	Motor Voltage, V		V
5	Motor Current, I		A
6	Dynamometer Force, F		N
7	Manometer Reading, H_m		mm H_2O
8	Compressor Air Inlet Temperature, T_1		℃
9	Compressor Air Outlet Temperature, T_2		℃
10	Air Receiver Temperature, T_5		℃
11	Air Nozzle Temperature, T_6		℃
12	Air Receiver Gauge Pressure, P_2		kpa
13	Diagram Area, A		mm^2
14	Diagram Length, L		mm

6. DATA ANALYSIS

1- Work Calculations

1 – Motor input – electrical power, (Watt)

$W_E = V \times I$	(1)

V = motor voltage, 220 Volt

I = motor current, in (Ampere)

2 – Motor output – Mechanical power, (Watt)

$W_m = \dfrac{F \times N1}{K}$	(2)

F = motor force, in (N)

N1 = motor speed, in (rpm)

K = constant = 43.41

3 – Compressor input power, in (Watt)

$W_{Cin} = 0.98 \times W_m$	(3)

Where 0.98 is the efficiency of the belt drive

The mean effective pressure developed inside the compressor, in Kpa

From indicated P – V diagram

$\bar{P}_m = \dfrac{diagram\ area}{diagram\ length} \times spring\ calibration = \dfrac{A(mm^2)}{L(mm)} \times 20kpa/mm$	(4)

Where the diagram area is obtained by using a blanimeter device

4 – Indicated power developed inside the compressor (Watt)

$W_{ind} = \left(\dfrac{\pi}{4} b^2 \times S\right) \times n_C \times \bar{P}_m \times \dfrac{N_1}{3} \times \dfrac{1}{60}$	(5)

$V_S = \left(\dfrac{\pi}{4} b^2 \times S\right) = Swept\ volume, in\ (m^3/rev)$

b = bore diameter, in (m)

S = stroke length, in (m)

n_C = number of cylinders

5 – The Isothermal power developed outside the compressor

$W_{isoth} = \dot{m}_a\, R\, T_1\, ln\left(\dfrac{P_2}{P_1}\right) \quad (Watt)$	(6)

$\dot{m}_a$ = mass flow rate of air in kg/s

R = Air gas constant = 287 J/kg. K

P_1 = Atmospheric Pressure , in kpa

P_2 = Receiver Pressure , in kpa, absolute value

T_1 = Air inlet temperature, in K

6- Mass flow of air measured with help of orifice plate in Kg/s

$\dot{m}_a = 0.002012\, d^2 \sqrt{\frac{H_m P_1}{T_1}}$	(7)

$\mathrm{d} =$ orifice diameter, in cm

$\mathrm{H_m} =$ Pressure difference a cross the orifice plate in cm H_2O (manometer reading)

$\mathrm{P_1} =$ Atmospheric pressure, in kpa

$\mathrm{T_1} =$ Atmospheric temperature, in K

$\mathrm{N_1} =$ Motor speed, in (rpm)

2- Efficiency Calculations

1 – Motor Efficiency

$\eta_{motor} = \frac{W_m}{W_E}$	(8)

2 – Mechanical Efficiency

$\eta_{mech} = \frac{W_{isoth}}{W_{Cin}}$	(9)

3 – Isothermal Efficiency

$\eta_{iso} = \frac{W_{isoth}}{W_{ind}}$	(10)

4 – Volumetric Efficiency

$\eta_V = \frac{\dot{m}_a}{\rho_a \times V_s \times n_C \times \frac{N_1}{3} \times \frac{1}{60}}$	(11)

$Where: \rho_a = density\ of\ air, in\ (kg/m^3)\ , and \quad \rho_a = \frac{P_a}{R \times T_a}$

$In\ this\ relation\ the\ pressure\ is\ in\ Pa, \quad T_a\ in\ K \quad and \quad \mathrm{R = 287\ J/kg.K}$

$V_s = \left(\frac{\pi}{4} b^2 \times S\right) = swept\ volume, in\ (m^3/rev)$

5 – Overall Efficiency

$\eta_o = \frac{W_{isoth}}{W_E}$	(12)

7. RESULTS & DISCUSSION

Table 2: SUMMARY OF RESULTS

NO.	Performance	Value	Unit
Motor			
1	Motor input electrical power – W_E		kW
2	Motor output Mechanical power – W_m		kW
3	Motor Efficiency – η_{motor}		%
Compressor			
4	Compressor input power – W_{Cin}		kW
5	Indicated power developed inside the comp. –W_{ind}		kW
6	Isothermal power developed outside the comp. –W_{isoth}		kW
7	Mechanical Efficiency – η_{mech}		%
8	Isothermal Efficiency – η_{iso}		%
9	Volumetric Efficiency – η_V		%
Complete Cycle			
10	Overall Efficiency – η_o		%
Flow Rate			
11	Mass Flow Rate of Air – $\dot{m}_a$		kg/s

1. All the results were recorded and tabulated under the results table.
2. Discuss any discrepancy and the possible causes of errors of the experiment.
3. Write your own opinions about the results. What might be? Discuss about whether the results are acceptable or not?

NOTE: This page is intentionally left blank to identify your important notes

Experiment 8

AIR AND WATER HEAT PUMP

(UNIT – R832)

1. OBJECTIVE

- Enhance students' knowledge on the concept of how heat can move from a region of low temperature to that of a higher one due to work done.
- Draw the actual vapor compression cycle on the P-h diagram and compare it with the ideal cycle.
- Determine the coefficient of performance of heat pump.
- Compare the coefficient of performance of both the air and water evaporator.

2. INTRODUCTION & THEORETICAL BACKGROUND

Heat pump finds applications in countless industrial, commercial and domestic situations and activities throughout the world. The major uses of heat pumps are in the form of air conditioners. Other applications are home heating in cooler climates, pool heaters and so on. A heat pump is a device which allows transport of heat from lower temperature level to a higher one (in a direction that is opposite of spontaneous flow), by using external energy (European Renewable Energy Council, 2008).

The air and water heat pump being used in this experiment relies on the vapor compression cycle which needs a small work input to transfer heat from either air source evaporator or water source evaporator to a water cooled condenser.

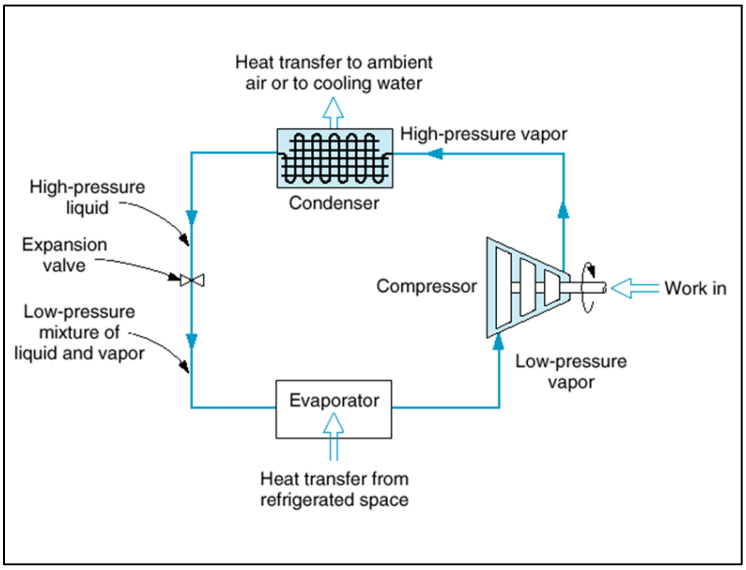


Fig. 1: Basic Vapor Compression Cycle

The Hilton Air and Water Heat Pump R-832 is a vapor compression cycle unit utilizing a small work input to transfer heat from either an air evaporator or water evaporator source to a water cooled condenser. All relevant temperatures, pressures and power inputs are measured enabling the complete cycle to be investigated both diagrammatically and numerically.

1- Ideal Vapor-Compression Cycle

The vapor compression cycle has four components: evaporator, compressor, condenser, and expansion (or throttle) valve. In an ideal vapor-compression cycle, the refrigerant enters the compressor as a saturated vapor and is cooled to the saturated liquid state in the condenser. It is then throttled to the evaporator pressure and vaporizes as it absorbs heat from the refrigerated space. The ideal vapor compression cycle consists of four processes. (See Figure 2)

Process	**Description**
1-2	Isentropic compression
2-3	Constant pressure heat rejection in the condenser
3-4	Throttling in an expansion valve
4-1	Constant pressure heat addition in the evaporator

Component	Process	First Law Result
Compressor	s = Const.	$\dot{W}_{in} = \dot{m}(h_2 - h_1)$
Condenser	P = Const.	$\dot{Q}_H = \dot{m}(h_2 - h_3)$
Throttle Valve	Δs > 0	$h_4 = h_3 \quad \dot{W}_{net} = 0 \quad \dot{Q}_{net} = 0$
Evaporator	P = Const.	$\dot{Q}_L = \dot{m}(h_1 - h_4)$

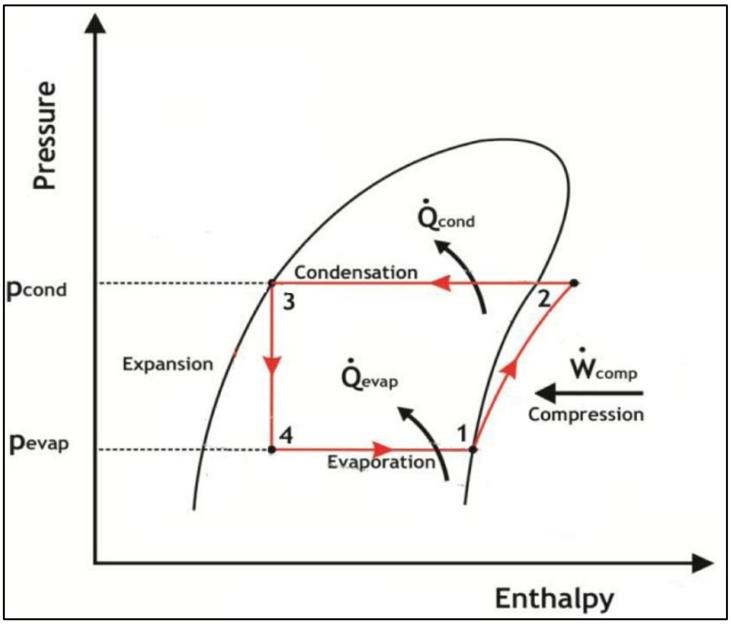


Fig. 2: The P-h Diagram of Ideal Vapor-Compression Cycle

2- Actual Vapor-Compression Cycle

An actual vapor-compression refrigeration cycle differs from the ideal one in several ways, owing mostly to the irreversibility's that occur in various components, mainly due to fluid friction (causes pressure drops) and heat transfer to or from the surroundings. The COP decreases as a result of irreversibility's. DIFFERENCES: Non-isentropic compression, superheated vapor at evaporator exit Subcooled liquid at condenser exit, Pressure drops in condenser and evaporator. (See Figure 3)

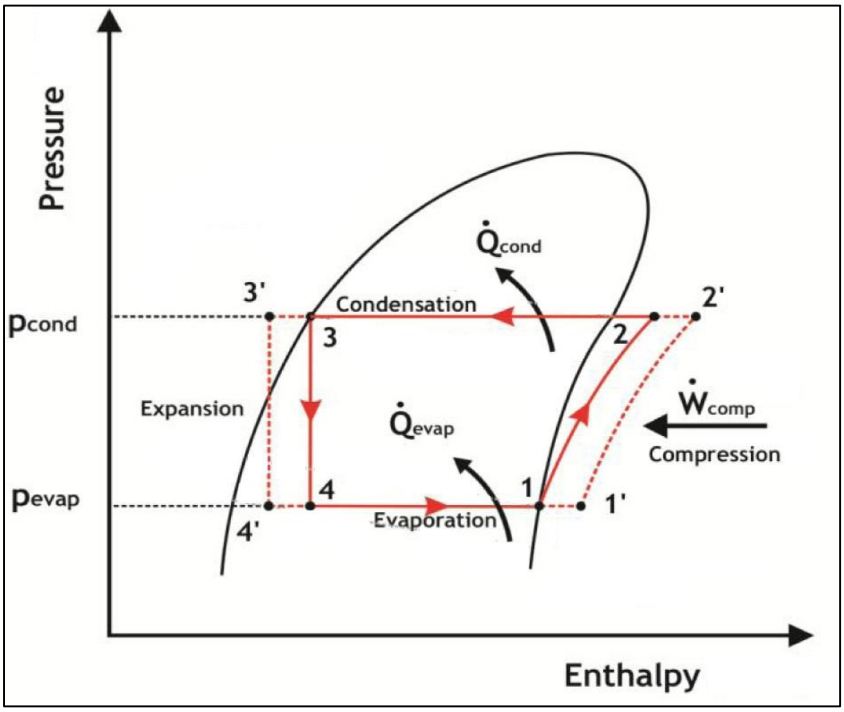


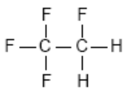
Fig. 3: The P-h Diagram of Actual Vapor-Compression Cycle

3. APPARATUS

This experiment will be conducted on the Hilton Computer-Linked Air and Water Heat Pump Unit R832, see figure 3 and 4. The unit was provided with a fully instrumented vapor compression heat pump operating on ***R134a** with an aluminum finned air source evaporator, high efficiency plate type condenser and similar water source evaporator. The evaporator source may be selected using a simple switch. Instrumentation allows investigation of heat transfers at each component of the refrigeration cycle. Instrumentation includes digital temperature indicator, condenser and evaporator pressure gauges, refrigerant flowmeter and compressor power meter. Water flow rate may be measured and controlled by variable area flowmeters on both the evaporator and condenser, thereby varying both evaporating pressure and condensing pressure. Safety devices include condenser high pressure switch and compressor thermal overload switch, residual current circuit breaker and a combined double pole main switch and overload cut out. (See figure 1 & 2)

Fig. 1: Air and Water Heat Pump (Unit R832) - General View

* The chemical properties of **HFC-134a** are listed below:
Chemical Name: Tetrafluoroethane
Molecular Formula: CH_2FCF_3
Molecular Weight: 102.0



Chemical Structure:
Boiling Point: at 1 atm (101.3 kPa or 1.013 bar): –26.1°C

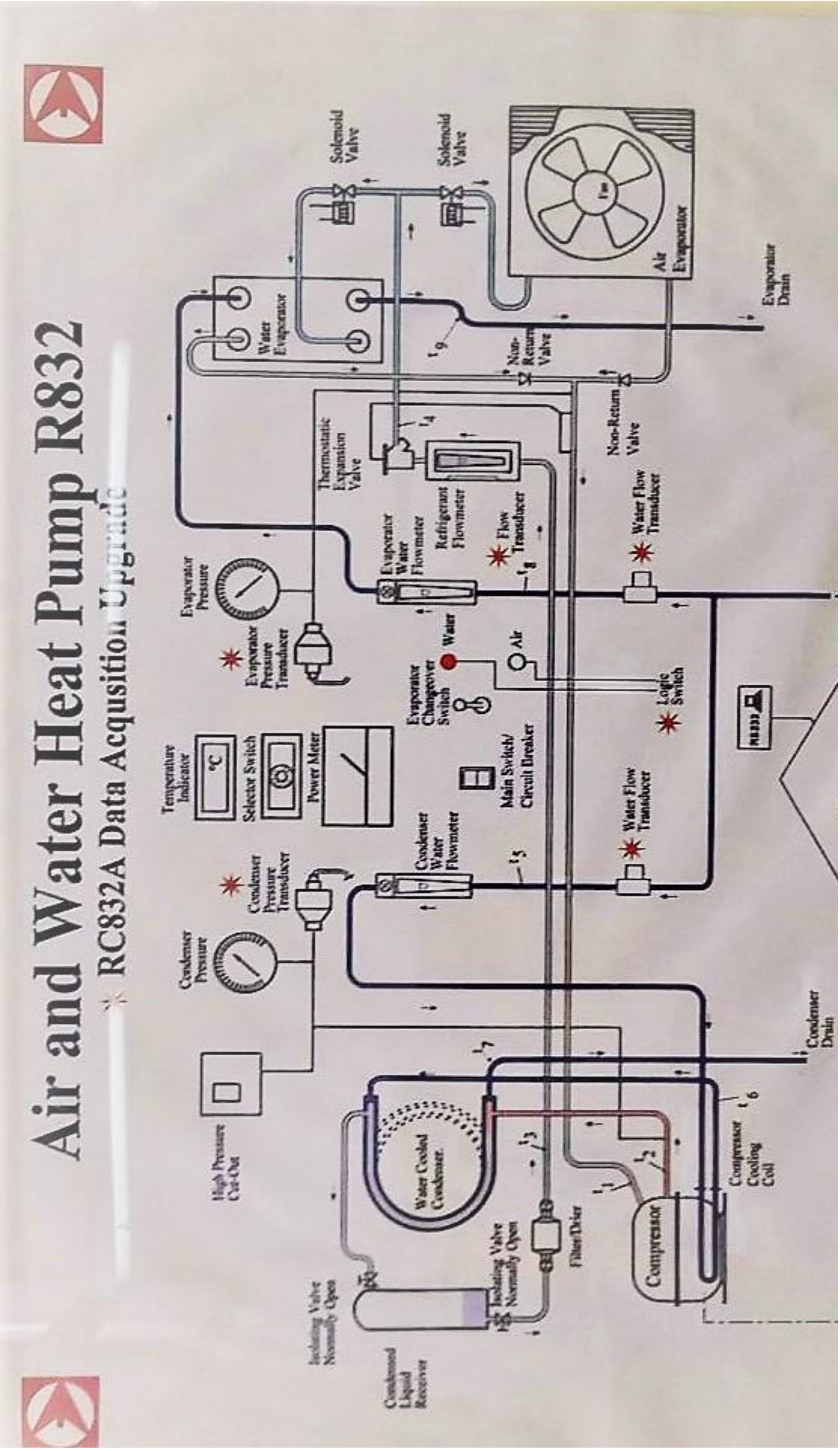


Fig. 2: Air and Water Heat Pump (Unit R832) - Schematic Diagram

4. PROCEDURE

1. Turn on the water supply to the unit and then turn on the main switch.
2. Select the water evaporator by pressing the evaporator change over switch down.
3. Set the condenser gauge pressure to between 700 and 1100 kpa by adjustment of the condenser cooling water flow rate.
4. Allow the unit time for all of the system parameters to reach a stable condition and fill up the observation sheet.
5. Repeat the above procedures for water evaporator by switching the changeover switch up condition and fill up the observation sheet.
6. Set the condenser cooling water flow rate to approximately 50 % of full flow and evaporator water flow as set by instructor.

5. OBSERVATIONS

Table 1: DATA OBSERVED

Heat Source: Water Evaporator **Atmospheric Pressure: ________ *kpa***

SERIES	No.	Parameter	1	2	3	UNITS
Refrigerant HFC134a	1	Condenser Pressure, Pc (Abs.)*				kpa
	2	Evaporator Pressure, Pe (Abs.)*				kpa
	3	Compressor Suction Temp. (t_1)				℃
	4	Compressor Delivery Temp. (t_2)				℃
	5	Refrigerant Leaving the Cond. (t_3)				℃
	6	Evaporator Inlet Temp. (t_4)				℃
	7	R134a flow rate, $\dot{m}_r$				g/s
Water Compressor Cooling	8	Cooling water inlet Temp. (t_5)				℃
	9	Cooling water outlet Temp. (t_6)				℃
	10	Water flow rate, $\dot{m}_w$				g/s
Water Condenser Cooling	11	Cooling water inlet Temp. (t_6)				
	12	Cooling water outlet Temp. (t_7)				
	13	Water flow rate, $\dot{m}_w$				g/s
Water Source Evaporator	14	Water inlet Temp. (t_8)				
	15	Water inlet Temp. (t_9)				
	16	Water flow rate, $\dot{m}_w$				g/s

6. DATA ANALYSIS

The heat delivered to cooling water from compressor

$$\dot{Q}_{cmp} = \dot{m}_w \times Cp_w \times (T_6 - T_5) \tag{1}$$

The heat delivered to cooling water from condenser

$$\dot{Q}_{cond} = \dot{m}_w \times Cp_w \times (T_7 - T_6) \tag{2}$$

The total heat delivered to cooling water from compressor & condenser

$$\dot{Q}_T = \dot{Q}_{cmp} + \dot{Q}_{cond} \tag{3}$$

The COP if the heat delivered to condenser is considered

$$COP_{HP} = \frac{Rate\ of\ Heat\ Delivered}{Compressor\ Electrical\ Power\ Input} = \frac{\dot{Q}_{cond}}{W} \tag{4}$$

The COP if the total heat delivered is considered

$$COP_{HP} = \frac{Rate\ of\ Heat\ Delivered}{Compressor\ Electrical\ Power\ Input} = \frac{\dot{Q}_T}{W} = \frac{\dot{Q}_{cond} + \dot{Q}_{cmp}}{W} \tag{5}$$

The COP using p-h diagram and rate of enthalpy change

$$COP_{HP} = \frac{Q_H}{W} = \frac{\dot{m}_r \times (h_2 - h_3)}{\dot{m}_r \times (h_2 - h_1)} = \frac{(h_2 - h_3)}{(h_2 - h_1)} \tag{6}$$

Determine location of state points:

No.1 is located by intersection of Pe Bar abs. and t_1°C (in superheated region)

No.2 is located by intersection of Pc Bar abs. and t_2 °C (in superheated region)

No.3 is located by intersection of Pc Bar abs. and t_3 °C (in subcooled region)

No.4 is located by dropping a vertical line from point 3 to the intersection with the Pe line, assumed adiabatic process.

Note that pressure drops in both the evaporator and condenser are assumed to be negligible and Pe and Pc are horizontal lines of constant pressure. (See Figure 6)

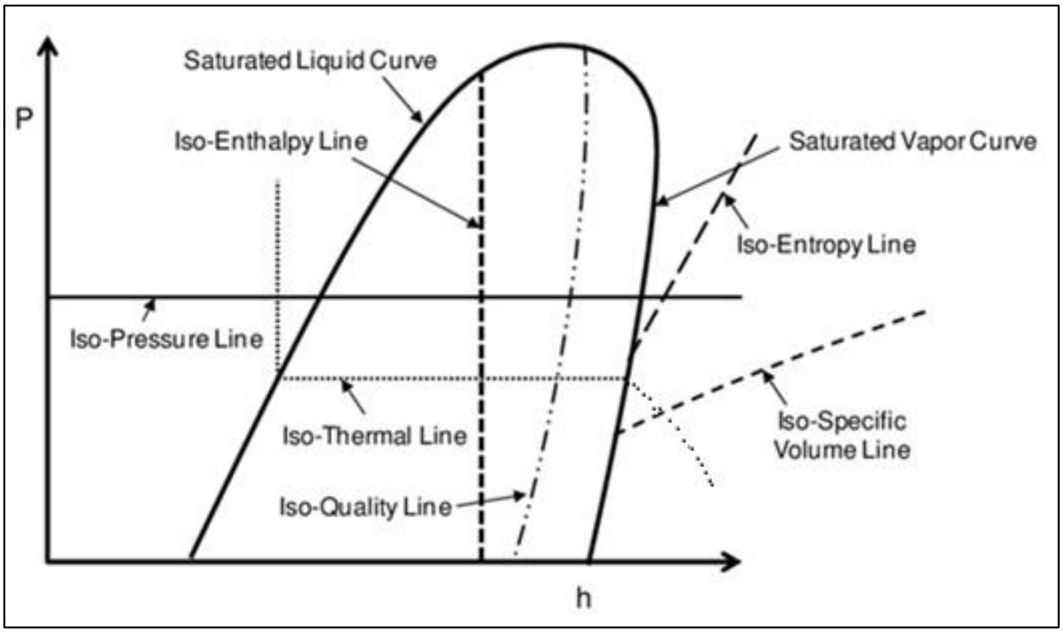


Fig. 6: Pressure - Enthalpy Diagram (Basics)

7. RESULTS & DISCUSSION

Table 2: SUMMARY OF RESULTS

	$\dot{Q}_{cmp}$ Watt	$\dot{Q}_{cond}$ Watt	$\dot{Q}_T$ Watt	COP_{HP} Considering Condenser Heat	COP_{HP} Considering Total Heat	COP_{HP} Using p-h Diagram
1						
2						

1. Sketch the refrigeration cycle on the p-h diagram of R-134a with actual property values at all points.
2. Find h1, h2, h3, and h4. [You may find h3, and then set h4 = h3]
3. All the results were recorded and tabulated under the results table.
   - By using p-h diagram.
   - By using ″Direct Measurements″.
4. Calculate the percentage difference between the two values found.
5. Discuss the results obtained and comment on discrepancies.
6. Do you think the cycle COP will increase or decrease with the evaporator temperature T_E increase?

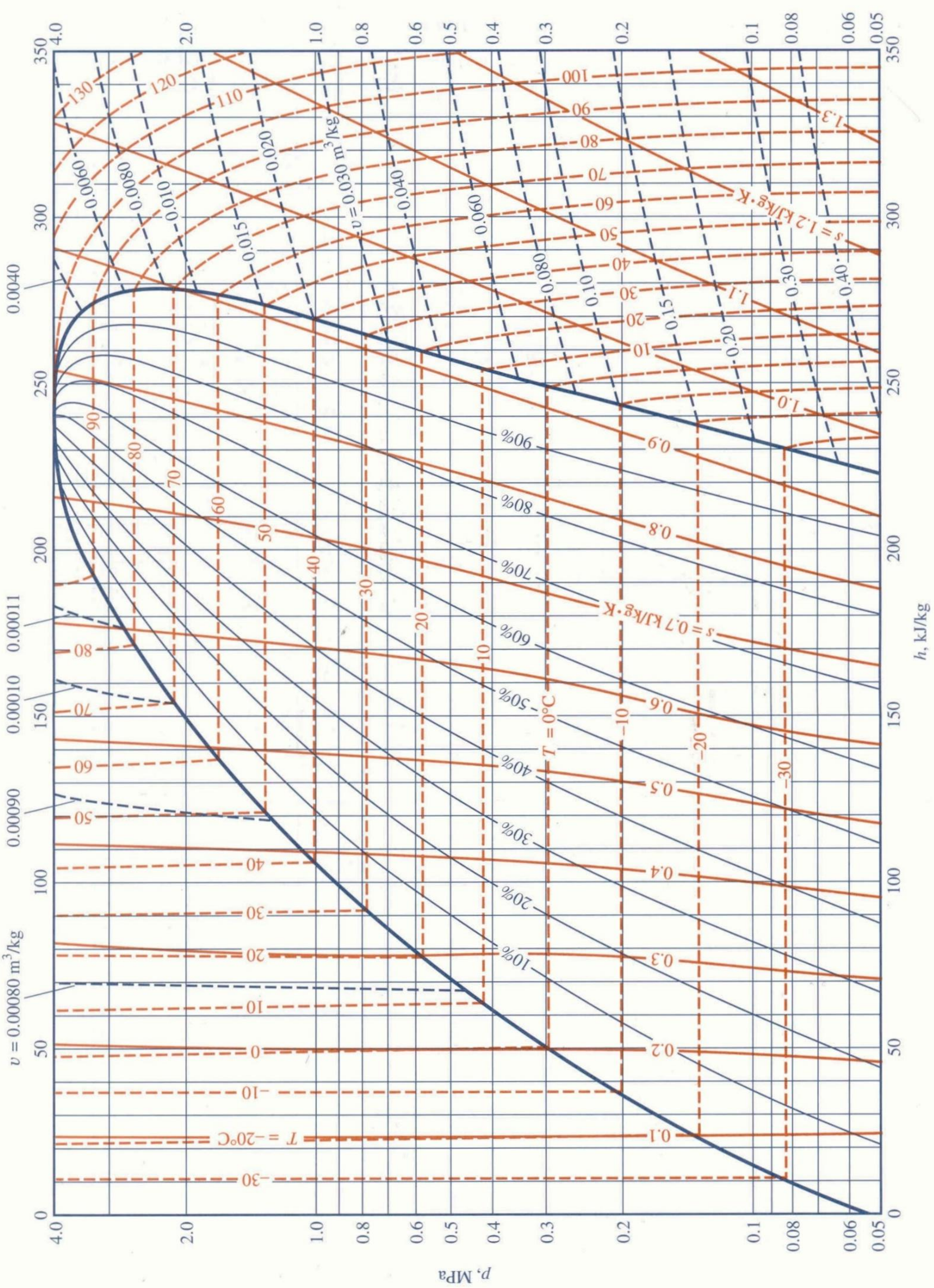


Chart A·11 R134a *ph* diagram. (*Source:* Based on *Thermodynamic Properties of HFC-134a (1,1,1,2-tetrafluoroethane)*, DuPont Company, Wilmington, Delaware, 1993, with permission.)

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Experiment 9
THERMAL POWER PLANT

1. OBJECTIVE

- To study and observe the performance of a small model thermal power plant in operation consisting of a pump, boiler, turbine, and condenser.
- To evaluate the first law efficiency of each component and the whole cycle.

2. INTRODUCTION &THEORETICAL BACKGROUND

A steam power plant mainly comprises of a **boiler**, **condenser**, **pump** and a **turbine** that is connected to a generator to produce electricity. It uses water as a working fluid. For electricity to be produced the turbine is rotated by high pressure and high temperature steam producing mechanical power that rotates the motor in the generator, thus converting the mechanical power into electricity. To ensure continuous production of steam and thus electricity, steam goes through a number of processes described below; this cycle is known as the Rankine cycle. (See figure 1)

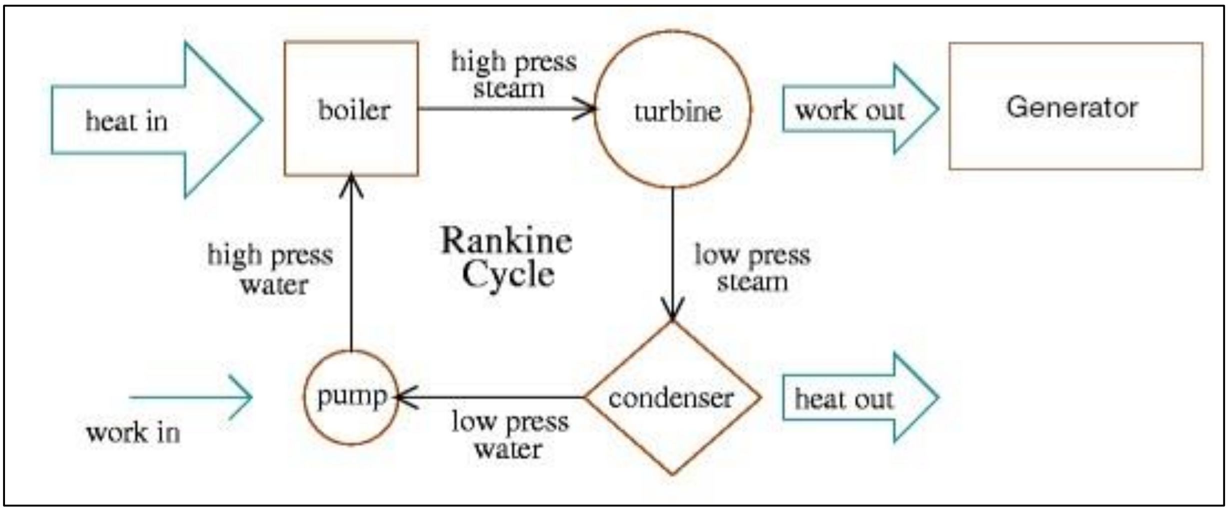


Fig. 1: Basic Ideal Rankine cycle

1- The ideal Rankine cycle

The ideal Rankine cycle does not involve any internal irreversibility's and consists of the four processes.

Process (1-2): Isentropic compression in the pump.

Water enters the pump at state 1 as saturated liquid and is compressed isentropically to operating pressure of the boiler. The water temperature increases somewhat during this isentropic compression process due to slight decrease in the specific volume of water.

Process (2-3): Constant pressure heat addition in the boiler.

Water enters the boiler as a compressed liquid at state 2 and leaves as a superheated vapor at state 3. Heat is transferred to the water essentially at constant pressure.

Process (3-4): Isentropic expansion in the turbine.

The superheated vapor at state 3 enters the turbine, where it expands isentropically and produces work by rotating the shaft connected to an electric generator. The pressure and the temperature of the steam are drop during this process to the values at state 4, where steam enters the condenser.

Process (4-1): Constant pressure heat rejection in the condenser.

At this state, the steam is usually a saturated liquid-vapor mixture with a high quality. Steam is condensed at constant pressure in the condenser by rejecting heat to the cooling tower. Steam leaves the condenser as saturated liquid and enters the pump, completing the cycle. (See figure 2)

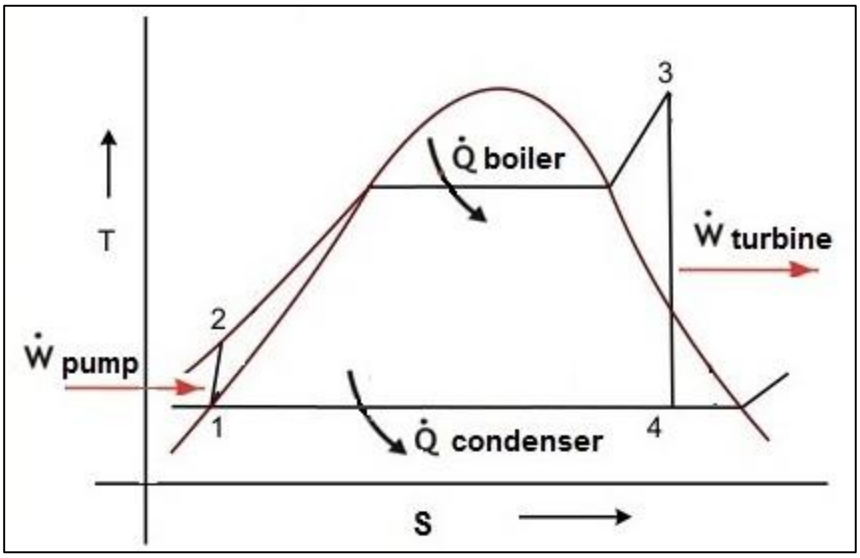


Fig. 2: The T-S Diagram of Ideal Rankine cycle

2- The Actual Rankine cycle

The actual vapor power cycle differs from the ideal Rankine cycle, as a result of irreversibilites in various components. *Fluid friction* and *heat loss* to the surroundings are the two common sources of irreversibilites.

Fluid friction causes pressure drop in the boiler, the condenser, turbine, and the piping between various components.

Heat loss from the steam to the surrounding as the steam flows through various components.

In actual practice, the pump and the turbine cannot be operated under isentropic condition because of irreversibilities. Therefore process (1-2) and (3-4) are non-isentropic. (See Figure 3)

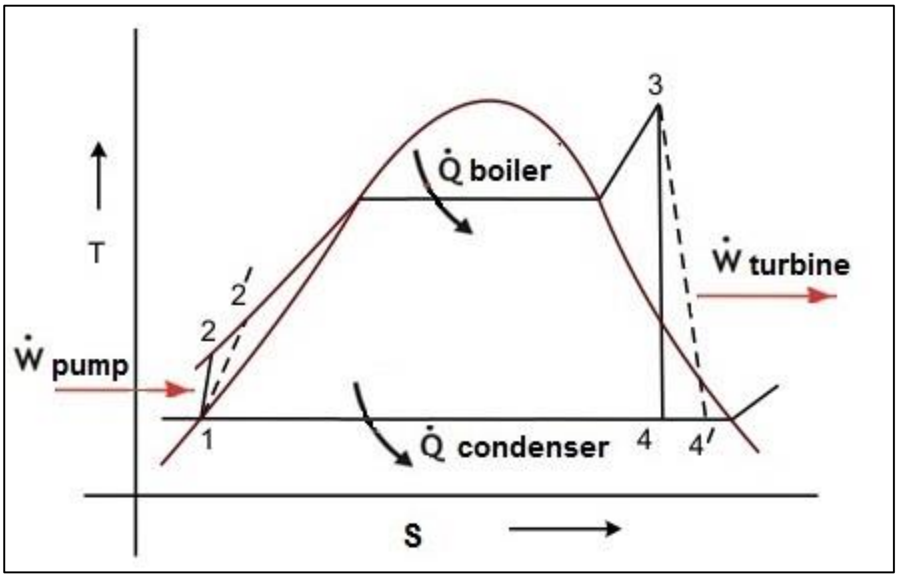


Fig. 3: T-S Diagram of Actual Rankine Cycle

3. APPARATUS

The steam power plant apparatus is consisting of:

Feed Pump: To force water into the boiler, by mechanical energy.

Boiler: To convert water to steam, there are two types:

- **A fire tube boiler**: In Fire-tube boilers hot flue gases pass through tubes and water surrounds them, like the one in our experiment.

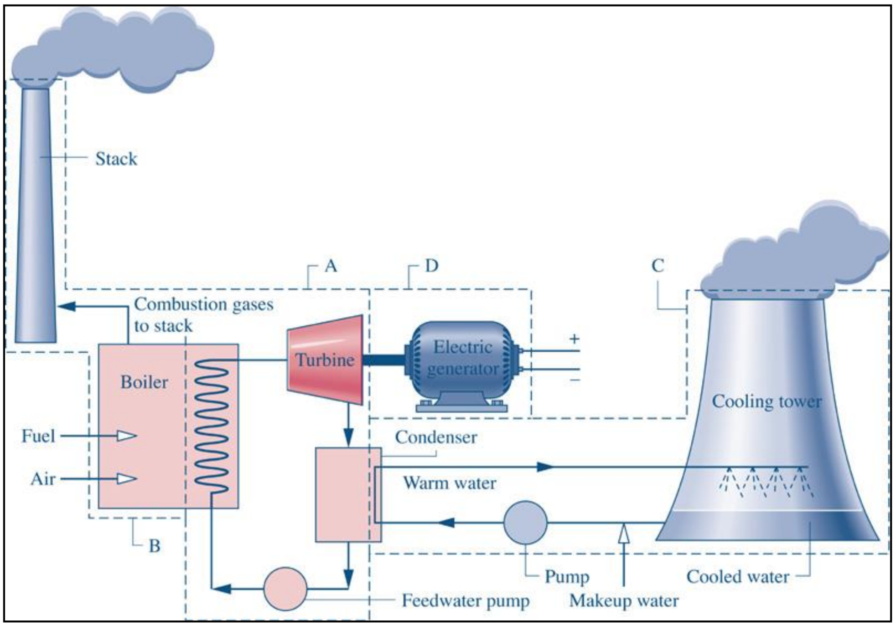
- A **water tube boiler**: In Water-tube boilers water passes through tubes and hot flue gasses surround them. There are many advantages of water tube boiler: Larger heating surface can be achieved, due to convectional flow, movement of water is much faster, and hence rate of heat transfer is high which results into higher efficiency, very high pressure can be obtained smoothly.

Steam Turbine: A Steam Turbine is a mechanical device that extracts thermal energy from pressurized steam and transforms it into mechanical work.

Condenser: The condenser brings the exit steam into contact with a usually cold in order to remove heat and condense it back to water known as condensate.

Cooling Tower: To decrease the temperature of the cooling water after condensing the steam in the condenser. The type used is cross flow tower, where the tower provides a horizontal air flow as the water falls down the tower in the form of small droplets. The fan centered at one side of unit draws air through the cells.

AC Electric Generator: a generator is a device that converts mechanical energy to electrical energy for use in an external circuit, where the source of mechanical energy is the steam turbine coupled to the generator. (See figure 4)



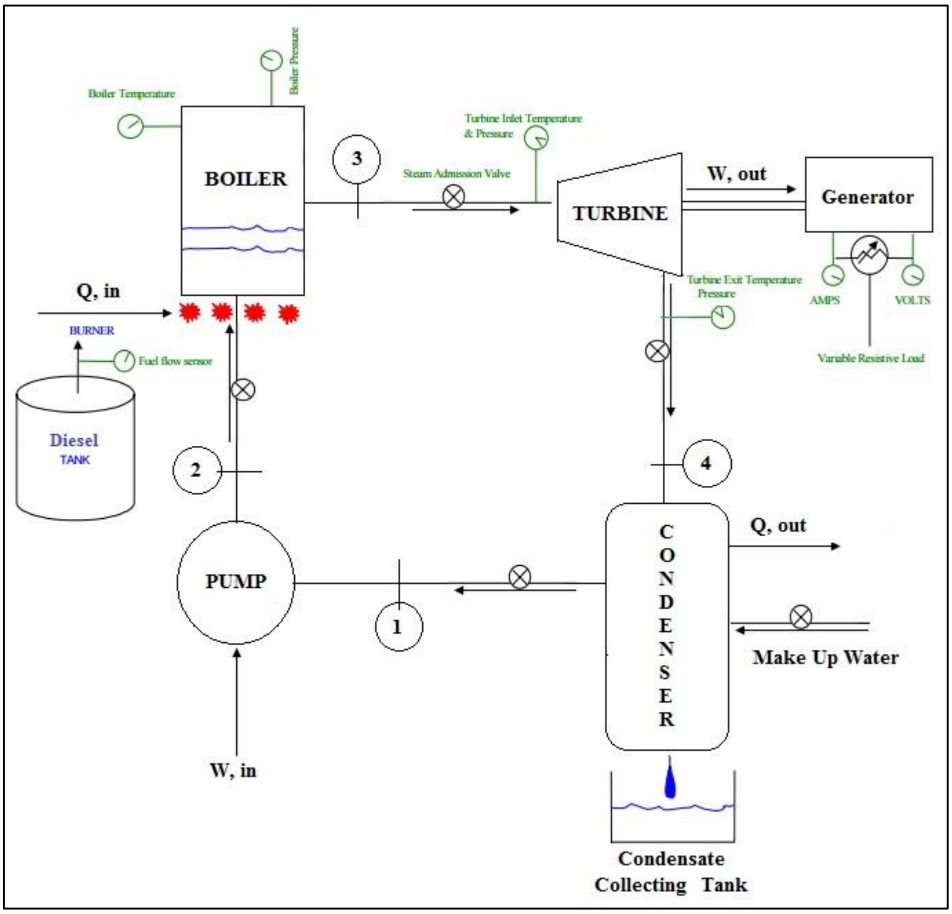


Fig. 4: Thermal Power Plant

4. PROCEDURE

1. Start the boiler and operate the burner.
2. One hour is necessary to obtain the normal operation conditions of the boiler.
3. Start the steam turbine.
4. A reasonable time should be allowed for warming the turbine before applying the load.
5. Start the circulation water pump.
6. Start the vacuum pump.
7. At the end of the experiment, close the Main Steam valve then turn off the light switches on the main switchboard. Leave the cooling water pump running for about an hour.

5. OBSERVATIONS

Table 1: DATA OBSERVED

Atmospheric Pressure: __________bar			
SERIES	**Item**	**Value**	**Unit**
Fuel (Diesel)	Consumed volume		ml
	Time taken		sec
	density	880	kg/m^3
	Calorific value	41400	kj/kg
Boiler Section	Feed water temperature		T1 / °C
	Exit steam temperature		T3 / °C
	Exit steam pressure (abs.)		P_2/kpa
	Mass flow rate of steam		kg/hr
Turbine Section	Steam inlet temperature		T3 / °C
	Steam exit temperature		T4' / °C
	Steam inlet pressure		P_2/kpa
Condenser Section	Condensate flow rate		m^3 / hr
	Condensate temperature		T5 / °C
	Condensate pressure(gauge)		P_2/kpa
	Cooling water inlet temperature		T_{wi} / °C
	Cooling water exit temperature		T_{wo} / °C
Generator Section	Generated Voltage		$Volt$
	Generated Current		$Ampere$
	Torque		$N.m$
	Speed		rpm

6. DATA ANALYSIS

1- Energy Analysis of the Actual Rankine Cycle

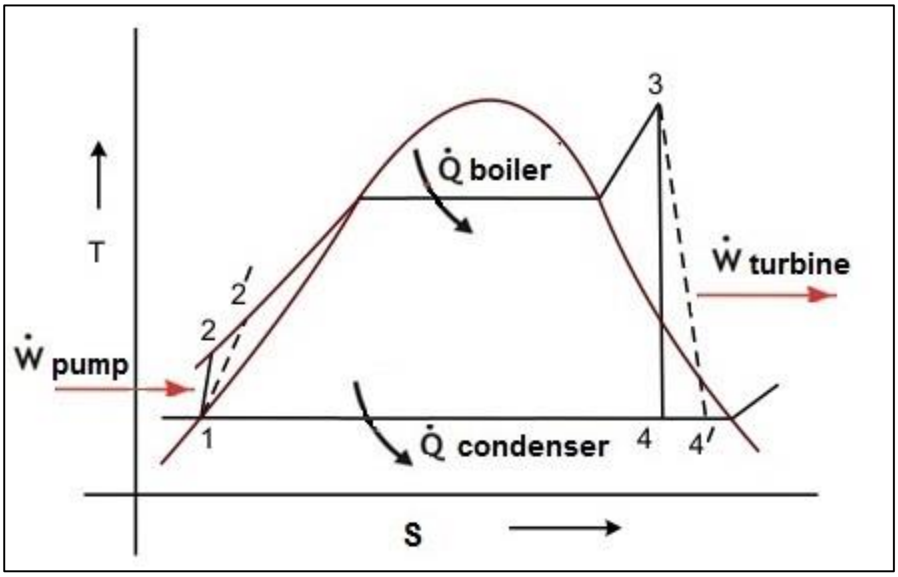


Fig. 6: T-S Diagram of Practical Rankine Cycle

The boiler efficiency is:

$\eta_b = \dfrac{\textit{Heat absorbed by water}}{\textit{Heat given by the consumed fuel}} = \dfrac{\dot{m}_s \times (h3 - h2)}{\dot{m}_f \times I.c.v}$	(1)

Where: $\dot{m}_s$: mass flow rate of steam measured by the flow meter

$\dot{m}_f$: mass flow rate of fuel to the burner $= \rho_f \times \dot{V}_f$

$\dot{V}_f = \dfrac{\textit{fuel volume collected}(m^3)}{\textit{elapsed time }(sec)}$	(2)

ρ_f: the density of fuel used – Diesel (880 kg/m^3)

h2 = enthalpy of water at inlet to boiler at the inlet temperature

h3 = enthalpy of steam at exit of the boiler at exit temperature and pressure

I. c. v: lower calorific value of fuel used – Diesel (41400 kj/kg)

The turbine efficiency is defined here as:

$\eta_t = \dfrac{(h3 - h4')}{(h3 - h4)}$	(3)

h4′ = Actual enthalpy of steam leaving the turbine

h4 = Enthalpy of steam at condenser pressure if the expansion was isentropic S3 = S4

To obtain h4 you should equate the heat rejected by steam in the condenser to the heat taken by the cooling water in the condenser, i.e.

$\dot{m}_s \times (h4' - h1) = \dot{m}_w \times Cp_w \times (Tw_o - Tw_i)$	(4)

$\dot{m}_w$ = The mass flow rate of cooling water through the condenser.

Cp_w = the specific heat of cooling water 4.186 $\mathrm{kj/kg.K}$

Tw_o and Tw_i = exit and inlet temperatures of cooling water respectively.

The Cycle or Thermal efficiency is defined as:

$$\eta_{th} = \frac{\text{Turbine work}}{\text{heat added in the boiler}} = \frac{(h3 - h4')}{(h3 - h2)} \qquad (5)$$

The mechanical efficiency of the turbine / generator is:

$$\eta_m = \frac{\frac{\tau \times \omega}{1000}}{\text{Turbine output}} = \frac{\frac{\tau \times \omega}{1000}}{\dot{m}_s\left((h3 - h4')\right)} \qquad (6)$$

Where: τ is the torque N. m, and ω is the rotational speed, rad/sec

The generator efficiency is:

$$\eta_G = \frac{\text{Power output}}{\text{Power input}} = \frac{(V \times I)}{(\tau \times \omega)} \qquad (7)$$

Where: V and I are the generator voltage and current respectively.

7. RESULTS & DISCUSSION

Table 2: SUMMARY OF RESULTS

No.	Item	Value %
1	Boiler efficiency	
2	Turbine efficiency	
3	Thermal efficiency	
4	Mechanical efficiency	
5	Generator efficiency	

1. Draw the associated Rankine- cycle for the thermal power plant on the T-S diagram showing all processes
2. Calculate the following efficiencies:
    a) Boiler efficiency
    b) Turbine efficiency
    c) Cycle efficiency
    d) Mechanical efficiency
    e) Generator efficiency
3. All the results were recorded and tabulated under the results table.
4. State three methods to improve the thermal efficiency of the cycle with briefly with neat sketch for each.

Note: to perform the required calculations each student must have his own steam tables.

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