Carleton University
Mechanical and Aerospace Engineering

MAAE2400 Thermodynamics and Heat Transfer
Laboratory Instructions

Last Revised: September 2016

Laboratory Experiments

1 Ford Six Cylinder Gasoline Engine

2 Ford Turbocharged Diesel Engine

3 Perkins Marine Diesel Engine

4 Saturated Water

5 Carrier Air Conditioning System

6 Heat Transfer Experiment

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Requirements at the beginning of each laboratory period

1. Printed lab instructions
2. Log book (loose-leaf paper is NOT acceptable)
    - Can be purchased at the bookstore (Unicenter)
    - A single log book should contain all four experiments
    - Completed pre-lab including data tables
3. Thermodynamics textbook
    - Fundamentals of Engineering Thermodynamics, Moran and Shapiro

- Hand calculator

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1.0 Laboratory Objectives

The objectives of the laboratory sessions are as follows:

- Give physical reality to the abstract concept of the thermodynamic "system" or "control volume", which is used in the analysis of energy-conversion systems.
- Introduce the methods of carrying out performance tests and to give the student the opportunity to examine and assess the relationship between actual performance and that predicted by simplified thermodynamic models.
- Give the student practice in the clear recording, assessment and reporting of test data.
- Familiarize the student with practical engineering instrumentation and equipment.
- Develop familiarity with experimental work on relatively complex engineering equipment.

It will be seen that the laboratory work is complementary to the lectures. It is not intended to illustrate principles so much as to develop familiarity and skill with experimental methods in thermodynamics and heat transfer, and to give students exposure to substantial and complex equipment.

The sign-up sheets posted in the laboratory (2230 ME) show which experiments each student is to perform. Each group is to perform 4 laboratory exercises. The overall rotation of experiments is intended to give each group exposure to a variety of exercises and measuring techniques used in the laboratory.

The results of all experimental work are to be recorded in a log book. Log books are commonly used by engineers in industry and requirements are often stringent. The MAAE 2400 log book should be of the hard-cover bound type; loose-leaf paper is NOT acceptable. All data reduction, analyses and graphs are to be bound in the log book; graphs can be pasted to pages in the book, but must be produced by hand. This log will represent the effort expended by the student, and its completeness and organization will have a major effect on the laboratory mark awarded.

The following section includes further information concerning the format of data sheets, graphs, and the log book.

2.0 Experimental Log Book

The objective in keeping a log book of engineering activity, whether experimental, analytical or managerial, is to record for future reference what was done, how it was done, and, usually, the consequences; note that the 'future' may be only a few weeks, as in this course, or several years away in professional activities or research work. Such a record can form the basis of a report, or merely act as a guide for future action in similar situations. The log book may become a "design manual" or it may even become evidence in a law suit. It is therefore important to keep records that are clear and accurate, and preferably of such a professional quality that one needs not be embarrassed if they are made public.

In this laboratory, the log book should contain the following information in the entry for each experiment:

1. Title of experiment, student's name and number, date performed, and group members and their duties.

2. A schematic sketch of the test set up, showing the layout, methods for measuring important quantities, and location of instrument sensors in the set-up. Circuit diagrams of special sub-systems such as coolant circuits are also required.

3. Outline of test procedure or a complete reference to the procedure in the MAAE 2400 Lab Instructions manual. A complete reference includes lab manual name, experiment name and page number, publisher and revision date, as well as an outline of deviations from the procedure suggested, together with the reasons for changing the procedure (if applicable). Any unexpected results or occurrences which might have an influence on the analysis of the test and its results should be recorded.

4. Data sheets.

5. Data reduction equations including working formulae required to convert raw data directly to desired performance figures, and calculation of performance or final results using data and the relevant formulae. A tabular form is recommended where several data sets are to be analyzed, as in an engine test. All units are to be specified, and conventional units are to be used so that comparison with published data can be made. The number of significant figures in the answers must be justified by the accuracy of the data. For example, more than three significant figures are seldom warranted in engine test work.

6. Graphs of performance, where appropriate, are required to be produced by hand. Comparison with theoretical performance is also useful.

7. Comments on accuracy, likely sources of error, unexpected results, or departures from the behaviour one would expect on the basis of lecture or text material, and one’s explanation of the probable causes of such departures.

8. Recommendations for improvements in the test set-up, the method of instrumentation, the test procedure, or the laboratory experience as a whole.

The log book must be kept up to date; that is, the entries (items 1-8) for any particular experiment must be completed and submitted before the end of the laboratory session during which the experiment was conducted. Normally, the log book will be marked and returned to the student on the day of the student’s next problem analysis session.

It should be remembered that the log book grade will reflect how easy it is to read it and to understand what was done, seen and measured. Tabulated or plotted results are much easier to follow than long rambling calculations. Conciseness and clarity is very important.

2.1 Data Sheets

In order to prepare a data sheet properly, it is necessary to plan the test, decide what is going to be controlled (the independent variables) and what is going to be measured. Since some desired quantities cannot be measured directly, the experimenter must determine what can be measured, from which the desired quantity can be deduced.

Normally the data sheet is a table, with the independent variables listed first, followed by the dependent variables, and finally the "monitoring" quantities which indicate the "health" of the equipment. If space permits, additional columns for calculated quantities (for example, power, SFC in engine testing) should be inserted. Each column or row of the data sheet should be clearly labelled and the units of all quantities should be indicated. The data sheet should be neat in appearance.

Procedure to be followed when drawing up data sheets

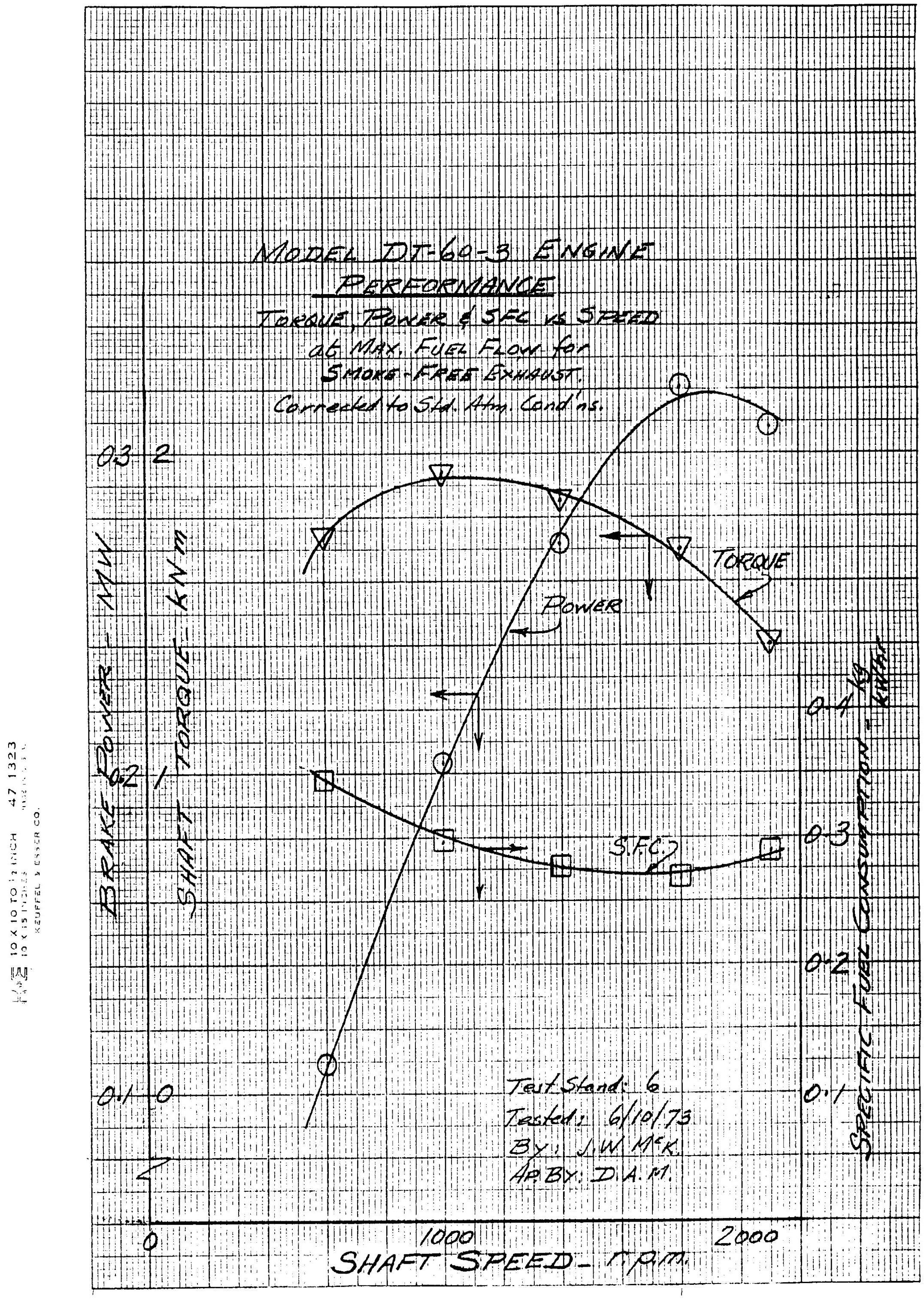
1. All measurements taken during a performance test should be recorded in each student's log book. The data may be recorded in one student's book and then transcribed to the other students' books at the end of the laboratory session.
2. Readings should be recorded as taken, with the time of the test, and the monitoring-instrument readings as well as those of the performance instruments should be included.
3. Columns should be included for calculated performance parameters such as torque, power and SFC (when applicable) on the data sheet, and these should be worked out as the test proceeds. A rough plot of the calculated performance should be maintained so that dubious readings can be repeated immediately.
4. A laboratory instructor should be asked to examine and initial the data sheet, including one full set of sample calculations, before leaving the laboratory.

2.2 Performance Graphs

Performance graphs should be drawn and lettered in pencil. Scales should be chosen with care. If they are too expanded, experimental uncertainties are magnified and the trend of the data is obscured. If too contracted, no trend appears, and significant features are lost. The smallest division should be about equal to the uncertainty of the quantity. The scale must also be easily readable. This means that one NEVER uses a subdivision of 3 or 7 to the inch or cm; 5 or 10 units per division is the most convenient scale.

Data points are to be indicated by a point surrounded by a distinctive symbol such as a circle, square or triangle. Axes should be labelled with a descriptive name; the symbol representing it may be used in addition. Units must be given where applicable.

A sample graph is shown on the next page. The curves must be drawn so that they are consistent with each other. This means, for example, that power and torque curves, plotted against shaft speed, cannot be drawn independently; once a curve for one has been drawn, the location of the other is specified.


MODEL DT-60-3 ENGINE
PERFORMANCE
TORQUE, POWER & SFC vs SPEED
at Max. Fuel Flow for
Smoke-Free Exhaust.
Corrected to Std. Atm. Cond'ns.
BRAKE POWER - MW
SHAFT TORQUE - kNm
SPECIFIC FUEL CONSUMPTION - kg/kWhr
0.3
2
0.2
1
0.1
0
0.4
0.3
0.2
0.1
TORQUE
POWER
S.F.C.
Test Stand: 6
Tested: 6/10/73
By: J.W. McK.
Ap. By: D.A.M.
0
1000
2000
SHAFT SPEED - r.p.m.
10 X 10 TO 1/2 INCH 47 1323
KEUFFEL & ESSER CO.

2.3 Log Book Marking Scheme

The log books are marked out of 10, and the 10 points are broken down as follows:

1. Lab title, experiment number, date, group number, member names, ID numbers, group member duties along with a reference to the procedure, and an explanation of any deviations if applicable, Pre-lab completeness (**1 mark**)

2. Clear and well-labelled schematic drawing that is <u>either hand drawn or photocopied from the lab manual</u> and <u>attached</u> in the log book (**1 mark**)

3. Data tables (**1 mark**)

4. Calculations, graphs and results **(3 marks)**

5. Analysis **(1 mark)**
   An analysis is expected to answer two questions:
   a. Do the results make sense? (0.5 marks)
      A first demonstration should compare results to the theory seen in class. In these cases, measured/calculated performances should follow the laws of thermodynamic: for example, efficiencies exceeding 100% should be identified by the students as experiences where something obviously went wrong.
      A second demonstration could compare performances to those expected from similar equipment. Since these labs do not test innovative equipment supposed to outperform existing ones, properly measured/calculated performances should fall into this range.
   b. What are the sources of error? (0.5 marks)
      Sources of error generally are: instruments' precision, procedural, uncontrolled changes to the environment, and mistakes. Instruments precision may include the sensors, electronics/readers, and graphs used. Procedural uncertainty stem from the lab description/methodology: waiting time between measurements, equations used, etc. Changes to the environment include temperature and humidity variations. Mistakes are mostly human: reading, calculation, graphing, etc. You should not list mistakes as experimental errors. Mistakes should have already been identified and eliminated during the preparation of the report.

6. Conclusions **(1 mark)**
   Conclusions should provide a link between the varied parameters and the performance of the setup. The main incentive to perform an experiment is to determine the effect of a parameter on performance, so the conclusions should discuss this.

7. Recommendations **(1 mark)**
   Recommendations should fall in two categories:
   a. To improve setup performance (0.5 marks)
      If you were to acquire such a setup, what would you do in order to maximise its performance? This section should be influenced by the conclusions.
   b. To improve the lab (0.5 marks)
      If you were to redo this lab, what changes would you make (instruments, setup, and procedure). These changes could: improve the precision of the results, extend the range of validity of the conclusions, or ameliorate the learning process. This section should be influenced by the identified sources of error.

8. Neatness (**1 mark)**

   TOTAL: 10 marks

IMPORTANT NOTES:

1. Students must submit their log book prior to the end of the lab session. Late submissions will not be accepted.

2. Each group member must submit a log book.

3. Individual group members who are late for the lab session will be penalized (-2 marks/10). *If a student arrives too late for a lab session, he/she will be asked to repeat the lab.*

4. Incomplete write-ups will not be accepted, and students will be required to repeat the lab.

EXPERIMENT 1

Fixed Throttle Performance Test of a Six Cylinder Automotive Gasoline Engine (Ford Engine)

1. Introduction

The purpose of this experiment is to measure the torque, power, specific fuel consumption (SFC), and thermal efficiency (η) of a typical automotive engine at two fixed throttle settings.

4. Torque: load on the engine [N·m or lbf·ft]
5. Power: rate of work done or energy transferred [W or hp]
    - Power input determined by fuel consumption
    - Power output = torque x engine speed
6. SFC: rate of fuel consumption divided by power output of the engine
7. Thermal efficiency: power output / power input

Gasoline engines are spark-ignition internal combustion engines, which use gasoline (petrol) fuel. Gasoline engines differ from diesel engines in that they use spark plugs to ignite the air-fuel mixture in the cylinder. Diesel engines, on the other hand, utilize the heat of compression (compressed air) to ignite the injected fuel [1]. The thermodynamic cycle of a gasoline engine is referred to as the Otto cycle, named after the German engineer Nikolaus August Otto [2]:

0-1: Intake of the air-fuel mixture

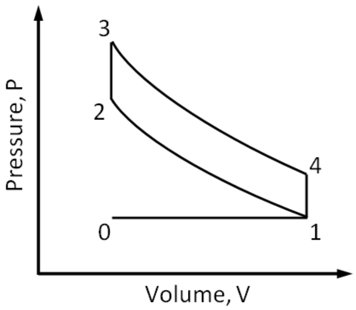
1-2: Compression of the air-fuel mixture

2-3: Combustion after ignition by a spark plug

3-4: Expansion due to combustion

4-1: Exhaust after opening of exit valve

1-0: Push-out of the combustion products



The premixing of air and fuel allows gasoline engines to operate at higher speeds (higher rpm) than diesel engines. As a result, gasoline engines typically outperform diesel engines over a wider range of operating conditions. Diesel engines, on the other hand, can operate at much higher compression ratios (gasoline engines are susceptible to premature ignition at higher pressure ratios), and so they may be more efficient than gasoline engines for higher power outputs. Compression ratios of gasoline engines range from 9:1 to 12:1. Compression ratios of diesel engines range from 15:1 to 22:1. Students can refer to experiments 3 and 4 for more information regarding diesel engines.

The engine drives a dynamometer which is bolted to the engine block. This dynamometer is a water brake with a swinging stator; the restraining force and hence the torque, is provided by a hydraulic load cell and the load cell pressure is read on a remotely-mounted gauge. The load is varied by changing the water flow rate through the dynamometer. The engine speed is measured by a remotely mounted tachometer driven by a flexible cable. Fuel flow rate is measured by a rotameter-type flowmeter, which consists of a ball in a tapered-bore tube. Instruments showing engine coolant temperature, oil temperature and oil pressure are also mounted on the console, so that the engine operating conditions can be monitored. If any of these instruments exceed their ranges (identified by red pointers), immediately bring the engine to idle and ask for assistance from the T.A. or Lab Technician.

A secondary objective of this experiment is it to analyze engine emissions at start-up, during warm-up and at stead-state operation. Exhaust gas analyzers are used to determine the concentration of the combustion by-products: carbon monoxide (CO), unburnt hydrocarbons (UHC) and nitrogen oxides (NOx).

2. Instructions

The hand-written data sheets should resemble the following, as well as include a second table for emission readings:

Table 1: Experimental Data

Test No.	Load Scale Reading	Engine Speed (rpm)	Fuel Flow Reading (s)	Oil Pressure (psi)	Oil Temp (°F)	Water Temp (°F)
1 (idle)	0.5	1700				
2	3	4000				
3		3600				
4		3200				
5		2800				
6		2600				
7 (idle)	0.5	1700				
8	5	4000				
9		3600				
10		3200				
11		2800				
12		2600				
13 (idle)	0.5	1700				

***** Always increase RPM (engine speed) prior to increasing load (torque). *****
***** Use the OUTER scale on torque gauge. *****

1) Have an instructor initial the data sheet.
2) Allow the engine to warm up under a light load (1700 rpm and 0.5 on the OUTER scale of the torque gauge) before proceeding with the test. Record a set of data at this condition: engine idling point.
3) Record engine emissions: CO, UHC and CO_2.
4) Set the throttle at about 3/8 throttle. To do this, set the engine speed to 4000 rpm and increase the load to 3 on the torque gauge (OUTER scale).
5) Do NOT adjust the engine speed until step (9).
6) Record a set of data: engine speed, load scale reading, fuel flow reading, oil pressure, oil temperature and water temperature. Call the laboratory demonstrator if these instruments indicate an engine malfunction.
7) Increase the load gradually until the engine speed falls to 3600 rpm and record a second set of data.
8) Repeat this process for the following engine speeds: 3200, 2800 and 2600 rpm.
9) Simultaneously reduce the load to 0.5 and reduce the engine speed to 1700 rpm. Allow the engine to idle at this condition for 5 minutes. Check your data to make sure that there are no outliers.
10) Record engine emissions: CO, UHC and CO_2.
11) Set the throttle at about 5/8 throttle. To do this, set the engine speed to 4000 rpm and increase the load to 5 on the torque gauge (OUTER scale).
12) Repeat steps (6) – (10).
13) Do NOT shut down the engine. Have the instructor check and initial the data sheet. Clean up and leave the equipment in good order.

3. Presentation of Results

1) Calculate torque (T), power output of the engine (P_{out}), fuel mass flow rate ($\dot{m}_f$) and specific fuel consumption (SFC) for all data points. The specific gravity (S.G.) of gasoline fuel is 0.68.
2) Calculate the thermal efficiency (η_{th}) of the engine at the point of best SFC for each throttle setting (not idle conditions). The lower heating value of the gasoline fuel may be taken as 19,000 Btu/lbm (44 MJ/kg). The lower heating value is the maximum amount of heat (energy) that can be generated by combusting a unit mass of fuel (combustion products at 150 ºC).
3) On a graph with engine speed as abscissa, plot the torque, power and SFC for each throttle setting; pass reasonably smooth curves through the data. Title the graph and label the axes and the curves. (see the graph on page 4 of this lab manual as an example).
4) Discuss the performance graphs, torque, power output, SFC and thermal efficiency.
5) Discuss engine control issues at different engine speeds.
6) Briefly discuss the suitability of this type of engine as a motor vehicle power plant in the light of your results. Are its characteristics such that stable operation is obtained at all engine speeds?
7) Discuss any changes in engine emissions between start-up and stead-state operation.

4. References

[1] Moran, M.J. & Shapiro, H.N. (2007) "Fundamentals of Engineering Thermodynamics", 6th Edition, Wiley.

[2] Müller, I. & Müller, W.H. (2009) "Fundamentals of Thermodynamics and Applications with Historical Annotations", Springer.

5. Other Sources

- Obert, "Internal Combustion Engines" (TJ 785-02)
- Schmidt, "The Internal Combustion Engine" (TJ 785S3)
- Ricardo and Hempson, "The High Speed Internal Combustion Engine" (TJ 785R52)

Important Equations:

$$T\ [lb_f \cdot ft] = 5.252\ \times scale\ reading$$

$$P_{out}\ [hp] = scale\ reading\ \times \frac{engine\ speed\ [rpm]}{1000}$$

$$SFC\left[\frac{lb_m}{hp \cdot hr}\right] = \frac{\dot{m}_f\left[\frac{lb_m}{hr}\right]}{P_{out}\ [hp]}$$

$$\eta_{th}[\%] = \frac{P_{out}\ (at\ best\ SFC)}{LHV\ \times \dot{m}_f}$$

EXPERIMENT 2

Fixed Throttle Performance Test of a Four Cylinder Automotive Honda Gasoline Engine

1. Introduction

The purpose of this experiment is to measure the torque, power, specific fuel consumption (SFC), and thermal efficiency (η) of a typical automotive engine.

- Torque: load on the engine [N·m <u>or</u> lbf·ft]
- Power: rate of work done or energy transferred [W <u>or</u> hp]
  - Power input determined by fuel consumption
  - Power output = torque x engine speed
- SFC: rate of fuel consumption divided by power output of the engine
- Thermal efficiency: power output / power input

Gasoline engines are spark-ignition internal combustion engines, which use gasoline (petrol) fuel. Gasoline engines differ from diesel engines in that they use spark plugs to ignite the air-fuel mixture in the cylinder. Diesel engines, on the other hand, utilize the heat of compression (compressed air) to ignite the injected fuel [1]. The thermodynamic cycle of a gasoline engine is referred to as the Otto cycle, named after the German engineer Nikolaus August Otto [2]. The Otto cycle consists of the following processes:

0-1: Intake of the air-fuel mixture

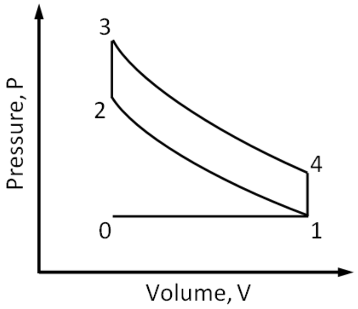
1-2: Compression of the air-fuel mixture

2-3: Combustion after ignition by a spark plug

3-4: Expansion due to combustion

4-1: Exhaust after opening of exit valve

1-0: Push-out of the combustion products



The premixing of air and fuel allows gasoline engines to operate at higher speeds (higher rpm) than diesel engines. As a result, gasoline engines typically outperform diesel engines over a wider range of operating conditions. Diesel engines, on the other hand, can operate at much higher compression ratios (gasoline engines are susceptible to premature ignition at higher pressure ratios), and so they may be more efficient than gasoline engines for higher power outputs. Compression ratios of gasoline engines range from 9:1 to 12:1. Compression ratios of diesel engines range from 15:1 to 22:1.

The engine drives a dynamometer which is bolted to the engine block. This dynamometer is a water brake with a swinging stator; the restraining force and hence the torque, is provided by a hydraulic load cell and the load cell pressure is read on a remotely-mounted gauge. The load is varied by changing the water flow rate through the dynamometer. The engine speed is measured by a remotely mounted tachometer driven by a flexible cable. Fuel flow rate is measured by a rotameter-type flowmeter, which consists of a ball in a tapered-bore tube. Instruments showing engine coolant temperature, oil temperature and oil pressure are also mounted on the console, so that the engine operating conditions can be monitored. If any of these instruments exceed their ranges (identified by red pointers), immediately bring the engine to idle and ask for assistance from the Teaching Assistant (TA) or Lab Technician.

2. Instructions

The hand-written data sheets should resemble the following.

Table 1: Experimental Data

Test No.	Load Scale Reading	Engine Speed (rpm)	Fuel Flow Reading (mm)	Oil Pressure (psi)	Oil Temp (°F)	Water Temp (°F)
1 (idle)	0.5	1700				
2	2	3500				
3		3200				
4		2800				
5		2500				
6		2200				
7 (idle)	0.5	1700				

***** Always increase RPM (engine speed) prior to increasing load (torque). *****
***** Use the OUTER scale on torque gauge. *****

1) Have an instructor initial the data sheet.
2) Allow the engine to warm up under a light load (1700 rpm and 0.5 on the OUTER scale of the torque gauge) before proceeding with the test. Record a set of data at this condition: engine idling point.
3) Set the engine speed to 3500 rpm. Once reached at 3500 rpm, do NOT adjust the engine speed anymore for the rest of the test. Increase the load to 2 on the torque gauge (OUTER scale).
4) Record a set of data: engine speed, load scale reading, fuel flow reading, oil pressure, oil temperature and water temperature. Call the laboratory demonstrator if these instruments indicate an engine malfunction.
5) Increase the load gradually until the engine speed falls to 3200 rpm and record a second set of data.
6) Repeat this process for the following engine speeds: 2800, 2500 and 2200 rpm.
7) Simultaneously reduce the load to 0.5 and reduce the engine speed to 1700 rpm. Check your data to make sure that there are no outliers.
8) Do NOT shut down the engine. Have the instructor check and initial the data sheet. Clean up and leave the equipment in good order.

3. Presentation of Results

1) Calculate torque (T), power output of the engine (P_{out}), fuel mass flow rate ($\dot{m}_f$) and specific fuel consumption (SFC) for all data points. The specific gravity (S.G.) of gasoline fuel is 0.68.
2) Calculate the thermal efficiency (η_{th}) of the engine at the point of best *SFC* for each throttle setting (not idle conditions). The lower heating value (*LHV*) of the gasoline fuel may be taken as 19,000 Btu/lbm (44 MJ/kg). *LHV* is the maximum amount of heat (energy) that can be generated by combusting a unit mass of fuel (combustion products at 150 ^{o}C).
3) On a graph with engine speed as abscissa, plot the torque, power and *SFC* for each throttle setting; pass reasonably smooth curves through the data. Title the graph and label the axes and the curves. (See the sample graph under "2.0 Experimental Log Book" section of this lab manual as an example).
4) Discuss the performance graphs, torque, power output, *SFC* and thermal efficiency.
5) Discuss engine control issues at different engine speeds.
6) Briefly discuss if this type of engine would be a good choice as an automotive engine in the light of your results. Hint: Did you obtain a stable operation at all engine speeds?

4. References

[1] Moran, M.J. & Shapiro, H.N. "Fundamentals of Engineering Thermodynamics", Wiley.
[2] Müller, I. & Müller, W.H. (2009) "Fundamentals of Thermodynamics and Applications with Historical Annotations", Springer.

5. Other Sources

1. Obert, "Internal Combustion Engines" (CU Library call number: TJ 785-02)
2. Schmidt, "The Internal Combustion Engine" (CU Library call number: TJ 785S3)
3. Ricardo and Hempson, "The High Speed Internal Combustion Engine" (CU Library call number: TJ 785R52)

Important Equations:

$$T\left[lb_f \cdot ft\right] = 5.25 \times scale\ reading$$

$$P_{out}\ [hp] = scale\ reading \times \frac{engine\ speed\ [rpm]}{1000}$$

$$\dot{V}_f = 1 \times 10^{-12}t^6 - 1 \times 10^{-9}t^5 + 5 \times 10^{-7}t^4 - 8 \times 10^{-5}t^3 + 0.006t^2 + 1.0133t - 2.5137$$

Where $\dot{V}_f$ is the fuel volumetric flowrate in cm^3/min and t is the Fuel Flow Reading in mm.

$$SFC\left[\frac{lb_m}{hp \cdot hr}\right] = \frac{\dot{m}_f\left[\frac{lb_m}{hr}\right]}{P_{out}\ [hp]}$$

$$\eta_{th}[\%] = \frac{P_{out}\ (at\ best\ SFC)}{LHV\ \times \dot{m}_f}$$

EXPERIMENT 3

Constant-Speed Performance Test of a Marine Diesel Engine (Perkins Engine)

1. Introduction

The purpose of this experiment is to measure the torque, power, specific fuel consumption (SFC), and thermal efficiency (η) of a small diesel engine at <u>two constant-speed settings</u>.

12. Torque: load on the engine [N·m <u>or</u> lbf·ft]
13. Power: rate of work done or energy transferred [W <u>or</u> hp]
    - Power input determined by fuel consumption
    - Power output = torque x engine speed
14. SFC: rate of fuel consumption divided by power output of the engine
15. Thermal efficiency: power output / power input

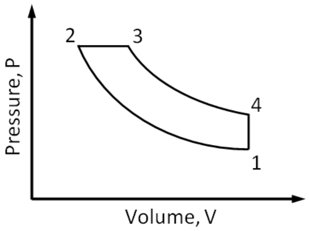
The compression-ignition or Diesel engine is made in a wide range of sizes, from about 10 hp (7.5 kW) up to 50,000 hp (37 MW). The Perkins Marine Diesel in the laboratory is a high speed, 4-stroke cycle, unsupercharged engine rated at 45 hp at 3600 rpm. Diesel engines differ from gasoline engines in that they use the heat of compression to ignite the injected fuel. Gasoline engines, on the other hand, use spark plugs to ignite the compressed air-fuel mixture (see experiments 1 and 2 for more detail regarding gasoline engines). The diesel cycle, named after the European inventor Rudolf Christian Karl Diesel, is shown next [1,2]:

1-2: Isentropic air compression

2-3: Reversible constant-pressure heating

3-4: Isentropic expansion

4-1: Reversible constant-volume cooling



The premixing of air and fuel allows gasoline engines to operate at higher speeds (higher rpm) than diesel engines. As a result, gasoline engines typically outperform diesel engines over a wider range of operating conditions. Diesel engines, on the other hand, can operate at much higher compression ratios (gasoline engines are susceptible to premature ignition at higher pressure ratios), and so they may be more efficient than gasoline engines for higher power outputs. Compression ratios of gasoline engines range from 9:1 to 12:1. Compression ratios of diesel engines range from 15:1 to 22:1.

The load on the engine (engine torque) is provided by a Stuska water brake dynamometer. The dynamometer has a swinging stator which is restrained from turning by a hydraulic load cell. The cell pressure is indicated on a remote gauge appropriately calibrated to read torque directly. The load is varied by changing the water flow rate through the dynamometer. Speed is also remotely indicated by a flexible cable-driven tachometer. Fuel flow rate is measured by a rotameter type flowmeter. Typical engine instruments, oil and water temperature and oil pressure, are also located on the console. The engine has an "all-speed" governor, so that the throttle lever resets the governor, which in turn meters fuel to the engine to keep it at approximately constant speed. However, due to "governor droop" the speed varies slightly with load, and small throttle readjustments are required to maintain constant speed at all loads.

2. Test Instructions

The hand-written data sheets should resemble the following, as well as include a second table for emission readings:

Table 1: Experimental Data

Test No.	Load Scale Reading	Engine Speed (rpm)	Fuel Flow Reading (mm)	Oil Pressure (psi)	Oil Temp (°F)	Water Temp (°F)
1 (idle)	0.5	1300				
2	0.5	2200				
3	2	2200				
4	4	2200				
5	6	2200				
6	8	2200				
7 (idle)	0.5	1300				
8	0.5	3200				
9	2	3200				
10	4	3200				
11	6	3200				
12	8	3200				
13 (idle)	0.5	1300				

***** Always increase RPM (engine speed) prior to increasing load (torque). *****
***** Use the INNER scale on torque gauge. *****

1) Have an instructor initial the data sheet.
2) Allow the engine to warm up under a light load (1300 rpm and 0.5 on the INNER scale of the torque gauge) before proceeding with the test. Record a set of data at this condition, including CO, UHC, CO_2 and NOx: engine idling point.
3) Increase the engine speed to 2200 rpm. Set the torque to approximately 0.5. Check the engine health monitoring gauges, torque and fuel flow rate during this process. <u>Call the laboratory demonstrator if these instruments indicate an engine malfunction.</u>
4) Record a set of data: engine speed, load scale reading, fuel flow reading, oil pressure, oil temperature and water temperature.
5) Increase the load gradually to 2. Maintain an engine speed of 2200 rpm (<u>you may need to make small adjustments due to governor droop</u>), and record a set of data. Repeat this process for the following loads: 4, 6 and 8.
6) Reduce the load to 0.5 and reduce the engine speed to 1300 rpm. Allow the engine to idle at this condition for 5 minutes. Record data at this condition, including emission readings again. Check your data to make sure that there are no outliers.
7) Increase the engine speed to 3200 rpm. Set the torque to approximately 0.5. Check the engine health monitoring gauges, torque and fuel flow rate during this process.
8) Repeat steps (4) – (6).
9) Do NOT shut down the engine. Have the instructor check and initial the data sheet and the rough performance graph. Clean up and leave the equipment in good order.

3. Presentation of Data

1) Calculate torque (T), power output of the engine (P_{out}), fuel mass flow rate ($\dot{m}_f$) and specific fuel consumption (SFC) for all data points. The specific gravity (S.G.) of diesel fuel is 0.84.
2) Calculate the thermal efficiency (η_{th}) of the engine at the point of best SFC for each engine speed. The lower heating value of the diesel fuel may be taken as 18,600 Btu/lbm (43.2 MJ/kg). The lower heating value is the maximum amount of heat (energy) that can be generated by combusting a unit mass of fuel (combustion products at 150 ºC).
3) Calculate the cost of electrical power generated at best SFC for each engine speed (lookup the current cost of diesel fuel in $/litre).
4) On a graph having brake power as the abscissa, plot the specific fuel consumption (SFC) data for the two speeds, and pass reasonably smooth curves through the data. Title the graph and label the axes and the curves. (see the graph on page 4 of this lab manual as an example)
5) Discuss the performance graphs, torque, power output, SFC, thermal efficiency and cost.
6) Discuss engine control issues at different engine speeds.
7) Briefly discuss the suitability of this type of engine as a constant-speed prime mover (e.g. to drive an electrical generator) in the light of the characteristics you have measured.
8) Discuss any changes in engine emissions between start-up and stead-state operation.

4. References

[3] Moran, M.J. & Shapiro, H.N. (2007) "Fundamentals of Engineering Thermodynamics", 6th Edition, Wiley.
[4] Moon, J.F. (1974) "Rudolf Diesel and the Diesel Engine", Priority Press, London.

5. Other Sources

- Armstrong and Hartman, "The Diesel Engine" (TJ 795 A73).
- Williams, "The Modern Diesel," Butterworths, 1972 (TJ 795 AlM6).

Important Equations:

$$T\ [lb_f \cdot ft] = 5.252\ \times scale\ reading$$

$$P_{out}\ [hp] = scale\ reading\ \times \frac{engine\ speed\ [rpm]}{1000}$$

$$SFC\left[\frac{lb_m}{hp \cdot hr}\right] = \frac{\dot{m}_f\left[\frac{lb_m}{hr}\right]}{P_{out}\ [hp]}$$

$$\eta_{th}[\%] = \frac{P_{out}\ (at\ best\ SFC)}{LHV\ \times \dot{m}_f}$$

$$Cost\ \left[\frac{cents}{kW \cdot hr}\right] = \frac{ents}{L} \times \frac{SFC}{\rho_{fuel}}$$

Be careful with the units in the cost calculation, you may need to apply conversion factors for:

$L \leftrightarrow m^3$

$lb_m \leftrightarrow kg$

$hp \leftrightarrow kW$

EXPERIMENT 4
Measuring Properties of Saturated Water

1. Introduction

The Armfield TH3 Saturation Pressure apparatus is a bench-top device designed to introduce students to the characteristics of saturated water. The apparatus is illustrated in Figure 1.

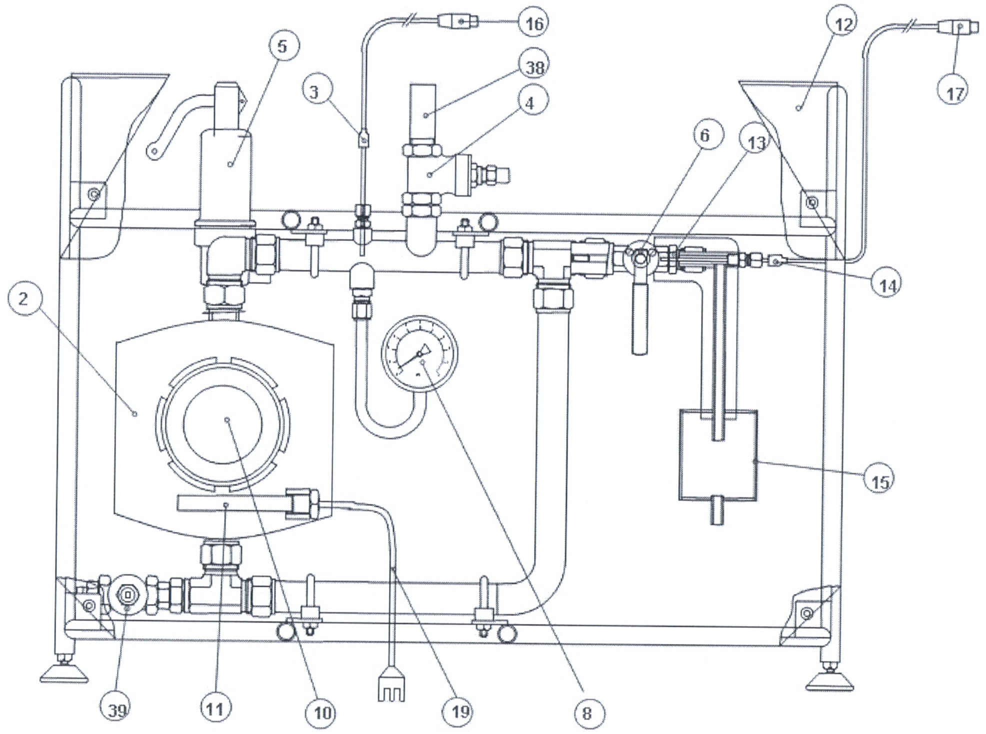
The equipment consists of a pipe loop in rectangular form. A boiler (indicated by 2 in the figure) is located in one of the vertical limbs of this pipe loop. This boiler heats water to its boiling point using a pair of electric resistance heaters (11) that are located near the bottom of the boiler. A sight glass (10) is situated at the front of the boiler to allow the operator to observe the behaviour of the water within the boiler.

Once the water has been heated to its boiling point, the boiler contains a mixture of liquid and vapour; its state is located within the vapour dome. Saturated steam rises in the boiler and exits through the pipe located at the top of the boiler; its state is located on the saturated vapour line. The water then flows around the rectangular loop in a clockwise direction.

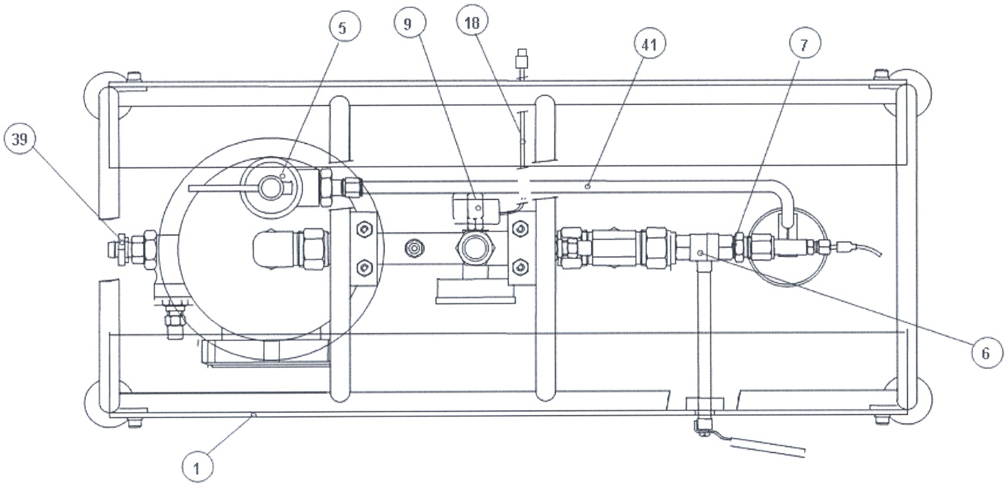
Because the water's temperature is higher than the room air temperature, heat will be transferred from the water to its surroundings as it flows around the loop. As a result of this heat transfer, some of the saturated steam will condense as it travels around the pipe loop, returning the state to within the vapour dome. The amount of liquid in the mixture will increase the further the water flows from the boiler, reaching a maximum where the pipe loop reenters the boiler to complete the cycle.

As the pressure drop due to friction within the pipe loop is very low, the entire loop can be considered to be operating at the same pressure.

The top horizontal limb of the pipe loop contains electronic temperature (3) and pressure (9) sensors to measure the properties of the water at this location.



(a) Side view



(b) Top view

Figure 1: TH3 Saturation Pressure apparatus

As explained above, the state of the water will lie within the vapour dome at this location due to heat transfer from the working fluid to the surroundings. This location is labelled state point 1. A Bourdon gauge is also located at this point to give the operator quick, albeit approximate, indication of the pressure.

Only two properties can be measured with this apparatus: pressure and temperature. However, pressure and temperature are not independent at state point 1 because this point lies within the vapour dome. Consequently, the state cannot be fixed (i.e. quality determined) at this location using only these two properties. But the apparatus includes a throttling calorimeter (7) that can be used—along with the 1st law of thermodynamics—to determine the quality of the water at state point 1.

When the isolation valve (6) is opened, some of the water is bled from the loop and allowed to pass into the throttling calorimeter. The bled water passes along a labyrinth (13) where it expands to atmospheric pressure. During this expansion process, the water leaves the vapour dome and passes into the superheated region. A second temperature sensor (14) is located within the calorimeter to measure the temperature of this superheated steam, which is at atmospheric pressure. Since pressure and temperature are independent within the superheated region, this temperature reading and the atmospheric pressure serve to fix the state of water at this location. This location is labelled state point 2.

As the superheated steam expressed from the throttling calorimeter cools, it condenses and is collected by a container (15) located below the calorimeter, and is then removed from the apparatus through a plastic tube.

2. Objectives

The objectives of this experiment are as follows:

- To observe the physical behaviour of water during the transition between liquid and vapour phases and at the onset of boiling.
- To understand the relationship between pressure and temperature of saturated water.
- To understand how the quality of a mixture can be determined using a throttling calorimeter.

3. Preparation prior to lab

The following tasks must be performed before you come to the lab:

1. Review Section 6 and Figure 1.

2. Prepare the following data sheet in your logbook for recording water properties and your observations of the appearance of the water within the boiler during the heating-up phase of the experiment.

Elapsed time (min)	$R_{m1}(Ohms)$	$P_{g,1}$ (kPa)	Appearance of water
5			
10			
15			
...			

3. Prepare the following data sheet in your logbook for recording water properties during the cooling-down phase of the experiment.

Nominal pressure (bar)	$R_{m1}(Ohms)$	$P_{g,1}$ (kPa)	$R_{m2}(Ohms)$
7			
4			

4. Prepare a hand-drawn P-T diagram (phase diagram) for water in your logbook (use a full page). The diagram should span a temperature range of 80 to 210°C and the pressure axis should be in units of kPa. This diagram must be drawn to scale. Label the axes, indicate the units, and apply a title to the diagram.

   Use data from Table A-2 of Moran et al. (2014) to plot the pressure and temperature of saturated water from 90 to 200°C, at 10°C increments. Draw a line through these points to indicate the saturated liquid-vapour line. You may wish to consult Section 3.2 of Moran et al. (2014) for guidance on phase diagrams.

5. Prepare a hand-drawn T-v diagram for water in your logbook (use a full page). This diagram need not be drawn to scale. Clearly indicate the vapour dome and draw isobars at 7 bar and 1 bar. Label the axes, include appropriate units, and apply a title to the diagram. On the temperature axis,

mark the location of the saturation temperature corresponding to each isobar. You may wish to consult 3.2 of Moran et al. (2014) for guidance on T-v diagrams.

6. Draw a schematic of the throttling calorimeter in your logbook, that is the process from state 1 to state 2. Illustrate the system boundary with a dashed line. The flow of fluid streams entering and exiting the system should be clearly indicated, as should any energy transfers across the system boundary by work or heat transfer.

7. Write a 1st law energy balance for the throttling calorimeter that is consistent with your schematic. Each mass flow across the system boundary should be considered. Ensure that the sign of each term agrees with the directions indicated on your schematic. Cancel any unnecessary terms from the energy balance; explicitly list and justify all assumptions. You may wish to consult Section 4.10 of Moran et al. (2014) for guidance.

4. Instructions for running the experiment

1. Review Section 6 and Figure 1, and familiarize yourself with the equipment before turning the system on.

2. Have a teaching assistant check and initialize the schematic, 1st law energy balance, data sheets, and the P-T and T-v diagrams you prepared in your logbook.

3. Record the atmospheric pressure (P_{atm}) using the mercury barometer located within the laboratory. Convert this reading taken in mm or inches of mercury to kPa.

4. Switch on the heater and turn the heater power control to maximum. Start recording time from the moment the heater is switched on.

5. At the start of the experiment the liquid water within the boiler will be in a subcooled liquid state. The heaters will slowly warm the subcooled liquid to the boiling point; this process will take approximately 20 minutes. During this process, continuously observe the appearance of the water within the boiler by looking through the sight glass. Pay particular attention to

movement at the surface of the liquid, evidence of evaporation at the surface of the liquid, formation of bubbles at the heater elements, condensation of bubbles on the sight glass or within the liquid, and movement of bubbles to the surface of the liquid.

6. Five minutes after the heater is turned on, record the resistance of the temperature sensor (R_{m1}) and the gauge pressure ($P_{g,1}$) at state point 1 using the first data sheet you prepared prior to the lab. Also, record your observations on the appearance of the water (refer to Step 5).
7. Repeat Step 6 every 5 minutes until the maximum working pressure of 7 bar has been reached.
8. Monitor the pressure within the pipe loop using the Bourdon pressure gauge. Switch the heater power to minimum and open the throttling calorimeter isolation valve to bleed off a sample of water once the maximum working pressure of 7 bar (gauge) has been achieved. Once the resistance of the temperature sensor at state point 2 (R_{m2}) stabilizes, record this value using the second data sheet you prepared prior to the lab. Also record the resistance of the temperature sensor (R_{m1}) and the gauge pressure ($P_{g,1}$) at state point 1 using this sheet.
9. The pressure in the loop will continue to drop as water is bled through the throttling calorimeter. Repeat the measurements of $P_{g,1}$, R_{m1}, and R_{m2} when the Bourdon gauge indicates a nominal gauge pressure of 4 bar.
10. Once the Bourdon gauge indicates that the gauge pressure has been reduced to approximately 1.5 bar, close the calorimeter isolation valve and turn off the heater. Have a teaching assistant check your results and have them shut the system down for you.

5. Data analysis and presentation of results

1. Describe the behaviour observed as the water was heated. Was there a sudden change in behaviour, or were the transitions gradual? At what pressure and temperature did these changes occur? Did the bubbles that were formed on the heating elements collapse before reaching the surface? Explain why.

2. For each row of your first data sheet determine the temperature (T_1) and absolute pressure (P_1) at state point 1 using the procedures described in Section 6.

3. Plot each pair of T_1 and P_1 determined in Step 2 on the P-T diagram (phase diagram) you prepared prior to the lab.

   State point 1 is located within the vapour dome, as explained in Section 1. Consequently, all of your data points should lie on the saturated liquid-vapour line of your P-T diagram. Observe any differences in your logbook and provide an explanation if this is not the case.

4. Determine the temperature (T_1) and absolute pressure (P_1) at state point 1 and the temperature at state point 2 (T_2) using the procedures described in Section 6 for the first row of your second data sheet (ie that corresponding to a nominal gauge pressure of 7 bar). As explained in Section 1, state point 2 is at atmospheric pressure. Locate state points 1 and 2 on the T-v diagram your prepared prior to the lab.

5. Determine the enthalpy at state 2 (h_2) using data from Table A-4 of Moran et al. (2014). Interpolate as necessary.

6. Determine the enthalpy of saturated liquid ($h_{f,1}$) and of saturated vapour ($h_{v,1}$) corresponding to the pressure measured at state point 1 (P_1) using data from Table A-3 of Moran et al. (2014). Interpolate as necessary.

7. Write an expression for determining the enthalpy at state point 1 (h_1) using the unknown quality (x_1) and the values of $h_{f,1}$ and $h_{v,1}$ determined in Step 6.

8. Substitute the properties determined in Steps 5 through 7 into the 1st law energy balance of the throttling calorimeter your prepared prior to the lab. Rearrange as necessary to solve for x_1.

9. Repeat Steps 4 through 8 for the second row of your second data sheet (ie that corresponding to a nominal gauge pressure of 4 bar). Contrast the values of x_1 determined at these two pressures.

6. Operational notes and instrumentation

1. The heater on/off switch is located at the bottom left of the electrical console as is the heater power control dial. Turn this dial all the way to the right for maximum power, and all the way to the left for minimum power.

2. The temperature sensors at state points 1 and 2 are platinum resistance thermometers (PRT). The resistance of a PRT changes with its temperature. A bridge circuit is used to determine the resistance of the PRT by using a small current source and by measuring the voltage across the bridge. Tabulated calibration tables are then used to relate the PRT's resistance to its temperature.

   The resistances of the two PRTs can be read on the electrical console's digital display by toggling the dial to the appropriate channel: R_{m1} for state point 1, and R_{m2} for state point 2. Conversion of these measured resistances to temperatures is a two-step process. Firstly, determine the "corrected" resistance from the measured resistance (R_{m1} or R_{m2}) using the table in Appendix A. Interpolate between the rows of data as necessary.

   Secondly, determine the temperature corresponding to the corrected resistance using the table in Appendix B. Interpolate between the rows of data as necessary.

3. The pressure sensor at state 1 uses a semiconductor to sense the deflection of a diaphragm. The deflection of this diaphragm is proportional to the gauge pressure of the working fluid (in this case water) pressing against it. A conditioning circuit is used to convert the semiconductor's signal to the corresponding pressure in kN/m^2 (equivalent to kPa), which is displayed directly on the electrical console's digital display by toggling the dial to the appropriate channel.

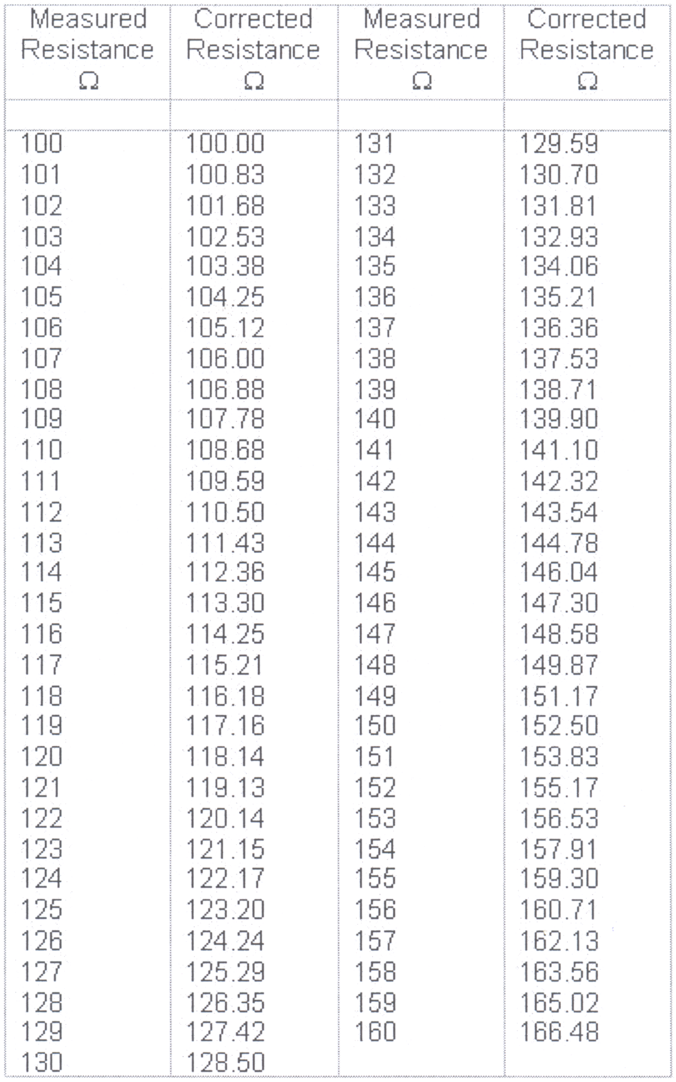
   The total pressure of the water can be determined by adding the atmospheric pressure to the gauge pressure read from the digital display:

   $$P_1 = P_{g,1} + P_{atm}$$

References

Moran, M. J., Shapiro, H. N., Boettner, D. D., and Bailey, M. B. 2014. *Fundamentals of Engineering Thermodynamics*. John Wiley & Sons, Inc., 8th edition.

Appendix A PRT resistance bridge correction



Measured Resistance Ω	Corrected Resistance Ω	Measured Resistance Ω	Corrected Resistance Ω
100	100.00	131	129.59
101	100.83	132	130.70
102	101.68	133	131.81
103	102.53	134	132.93
104	103.38	135	134.06
105	104.25	136	135.21
106	105.12	137	136.36
107	106.00	138	137.53
108	106.88	139	138.71
109	107.78	140	139.90
110	108.68	141	141.10
111	109.59	142	142.32
112	110.50	143	143.54
113	111.43	144	144.78
114	112.36	145	146.04
115	113.30	146	147.30
116	114.25	147	148.58
117	115.21	148	149.87
118	116.18	149	151.17
119	117.16	150	152.50
120	118.14	151	153.83
121	119.13	152	155.17
122	120.14	153	156.53
123	121.15	154	157.91
124	122.17	155	159.30
125	123.20	156	160.71
126	124.24	157	162.13
127	125.29	158	163.56
128	126.35	159	165.02
129	127.42	160	166.48
130	128.50		

Appendix B PRT resistance to temperature calibration

Corrected Resistance	Temperature	
Ω	°C	K
100.00	0	273.15
100.78	2	275.15
101.56	4	277.15
102.34	6	279.15
103.12	8	281.15
103.90	10	283.15
104.68	12	285.15
105.46	14	287.15
106.24	16	289.15
107.02	18	291.15
107.79	20	293.15
108.57	22	295.15
109.35	24	297.15
110.12	26	299.15
110.90	28	301.15
111.67	30	303.15
112.45	32	305.15
113.22	34	307.15
113.99	36	309.15
114.90	38	311.15
115.54	40	313.15
116.31	42	315.15
117.08	44	317.15
117.85	46	319.15
118.62	48	321.15

Corrected Resistance	Temperature	
Ω	°C	K
119.40	50	323.15
120.16	52	325.15
120.93	54	327.15
121.70	56	329.15
122.47	58	331.15
123.24	60	333.15
124.01	62	335.15
124.77	64	337.15
125.54	66	339.15
126.31	68	341.15
127.07	70	343.15
127.84	72	345.15
128.60	74	347.15
129.37	76	349.15
130.13	78	351.15
130.89	80	353.15
131.86	82	355.15
132.42	84	357.15
133.18	86	359.15
133.94	88	361.15
134.70	90	363.15
135.46	92	365.15
136.22	94	367.15
136.98	96	369.15
137.74	98	371.15

Corrected Resistance	Temperature	
Ω	°C	K
138.50	100	373.15
139.26	102	375.15
140.02	104	377.15
140.77	106	379.15
141.53	108	381.15
142.29	110	383.15
143.04	112	385.15
143.80	114	387.15
144.55	116	389.15
145.31	118	391.15
146.06	120	393.15
146.81	122	395.15
147.57	124	397.15
148.32	126	399.15
149.07	128	401.15
149.82	130	403.15
150.57	132	405.15
151.33	134	407.15
152.08	136	409.15
152.83	138	411.15
153.58	140	413.15
154.32	142	415.15
155.07	144	417.15
155.82	146	419.15
156.57	148	421.15

Corrected Resistance	Temperature	
Ω	°C	K
157.31	150	423.15
158.06	152	425.15
158.81	154	427.15
159.55	156	429.15
160.30	158	431.15
161.04	160	433.15
161.79	162	435.15
162.53	164	437.15
163.27	166	439.15
164.02	168	441.15
164.76	170	443.15
165.50	172	445.15
166.24	174	447.15
166.98	176	449.15
167.72	178	451.15
168.46	180	453.15
169.20	182	455.15
169.94	184	457.15
170.68	186	459.15
171.42	188	461.15
172.16	190	463.15
172.90	192	465.15
173.63	194	467.15
174.37	196	469.15
175.10	198	471.15
175.84	200	473.15

EXPERIMENT 5
Carrier Air Conditioning System

1. Introduction

The Carrier air conditioner is a typical system used for the air conditioning (cooling) of homes. It consists of two units: an “indoor” unit and an “outdoor” unit. The “indoor” unit (i.e., the unit that would be located indoors in a standard installation) consists of an evaporator coil and an evaporator fan. This is mounted on the wall in this experiment. The compressor, the condenser coil, and the condenser fan make up the “outdoor” unit. This is mounted on the floor in this experiment. The “indoor” unit is commonly referred to as the evaporator unit, while the “outdoor” unit is commonly referred to as the condenser unit.

Figure 1 shows a schematic of the Carrier air conditioning system and instrumentation as installed in Room ME 2230. The system operates as a vapour-compression refrigeration cycle with R22 as the refrigerant. The cooling effect for air conditioning is obtained by drawing warm room air (T_5 in the schematic) over the evaporator coil, and by circulating low temperature refrigerant through the coil ($T_{3'}$). Heat is transferred from the air to the refrigerant during this process. As a result, the air is cooled to T_6 and distributed back to the room, while the refrigerant expands and undergoes a change in phase from state $3'$ to state 4.

After exiting the evaporator, the refrigerant passes through the compressor, which raises the refrigerant’s pressure and temperature (state 2). At this point the refrigerant is hotter than the surrounding air. The refrigerant then flows through the coil of the condenser. The condenser’s fan causes room air to flow over the condenser coil (in an actual installation this unit would be located outdoors, so outdoor air would flow over the coil). This causes a heat transfer from the refrigerant to the air. As a result, the temperature of the refrigerant is lowered to its saturation temperature and then undergoes a change in phase, ending the process at state 3.

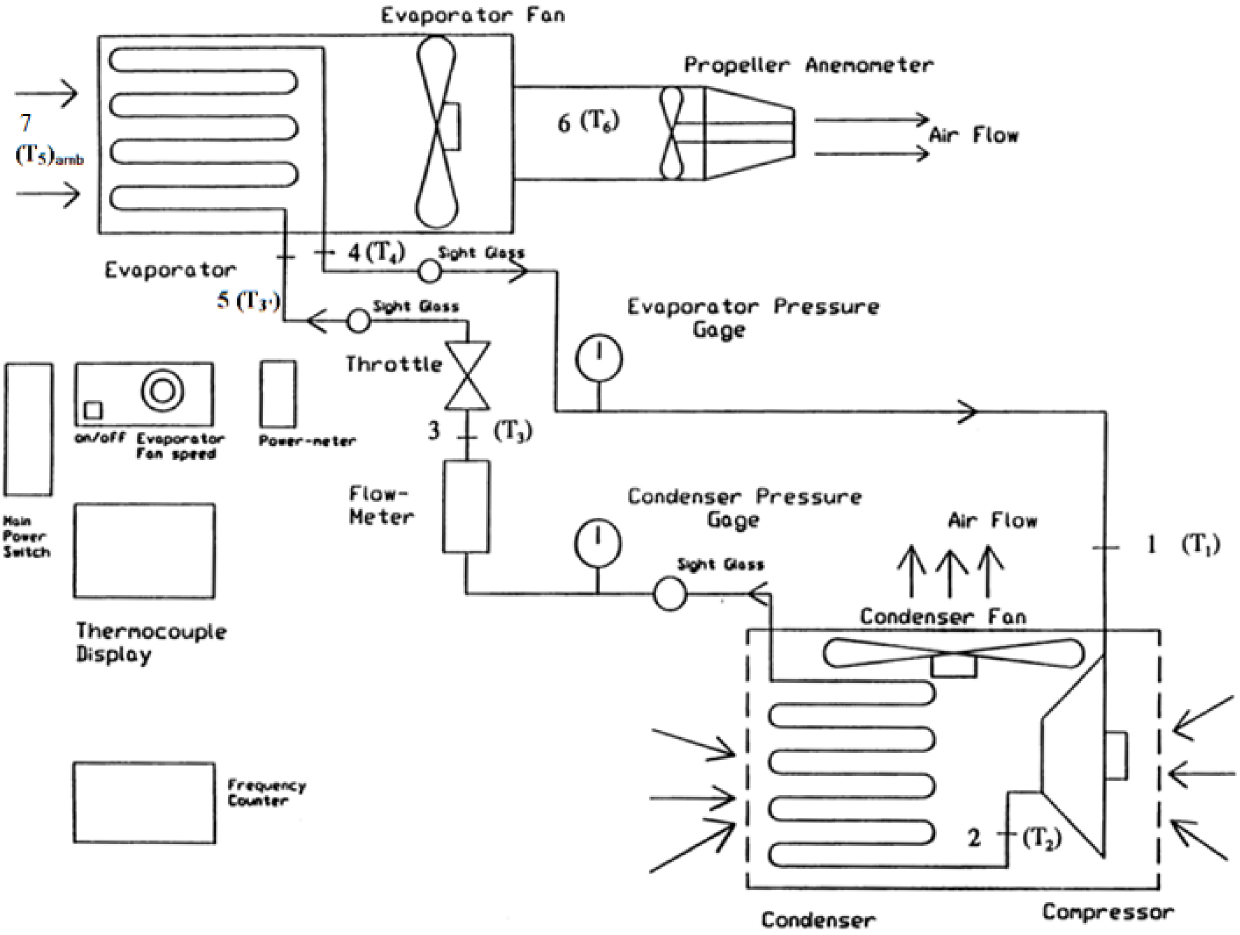


Figure 1: Carrier air conditioning system and instrumentation (The measurement points and state points are indicated, e.g. measurement point 7 on the thermocouple meter corresponds to state point 5 (T_5).)

The refrigerant then flows through the throttling valve, which expands the fluid to a lower pressure and temperature, and causes a partial phase change from state 3 to $3'$. It is the cold temperature of the refrigerant at state $3'$ that makes the refrigeration effect possible. This cold refrigerant then enters the evaporator coil to repeat the cycle.

This experiment focuses upon the processes occurring within the evaporator unit. The cycle's throttling valve will also be considered. The functioning of the cycle's compression and condensing processes will not be explored in this experiment, but will be treated in the lecture portion of the course.

2. Objective

The objective of this experiment is to obtain performance data for the air conditioning system and to use these data to perform a 1st law energy balance on the evaporator unit. The performance data will also be used to fix the state of the refrigerant at various points in the cycle.

3. Preparation prior to lab

The following tasks must be performed before you come to the lab:

1. Review Sections 6 and 7 and Figure 1.
2. Prepare the following data sheet in your logbook for recording properties, operational states, and the state of the refrigerant (vapour, liquid, mixture of vapour and liquid), as observed through the sight glasses:

	value	**units**
T_1		
T_2		
T_3		
$T_{3'}$		
T_4		
T_5		
T_6		
P_{evap}		
P_{cond}		
$\dot{\omega}$		
$\dot{V}_{H_2O}$		
Fan speed setting		
State of refrigerant upstream of compressor		
State of refrigerant upstream of refrigerant flow meter		
State of refrigerant upstream of evaporator		

3. Prepare a hand-drawn T-v diagram for the refrigerant in your logbook (use a full page). This diagram need not be drawn to scale. Clearly indicate the vapour dome and draw isobars that represent the absolute pressure of the refrigerant in the evaporator (P_{evap}) and in the condenser (P_{cond}). Label the axes, include appropriate units, and apply a title to the diagram. On the temperature axis, mark the location of the saturation temperature corresponding to each isobar; however, do not indicate the value of these temperatures as they can only be determined once the experiment is run. You may wish to consult Moran et al. (2014, Section 3.2) for guidance on T-v diagrams.

4. Include Figure 1 in your logbook as the schematic for the experiment. Circle and label each of the following on the schematic: the evaporator unit, the condenser unit, the throttling valve, and the complete refrigeration cycle.

5. Draw a schematic of the evaporator on a separate page in your logbook and illustrate the system boundary with a dashed line. The control volume should be drawn to include the fan. The flows of all fluid streams entering and exiting the control volume should be clearly indicated. Indicate any energy transfers by work between the system and surroundings. Also indicate a heat transfer between the system and surroundings ($\dot{Q}_{surroundings}$), clearly indicating with an arrow your prediction for the direction of this heat trans-

fer. On the schematic add a brief explanation for why you predict the heat to be transferred in this direction.

6. Write a 1st law energy balance for the evaporator. Include all possible terms in this energy balance. Each mass flow across the system boundary should be considered. Furthermore, ensure that the sign of each term agrees with the directions indicated on your evaporator schematic (Step 5). Cancel any unnecessary terms from the energy balance; explicitly list and justify all assumptions. You may wish to consult Moran et al. (2014, Chapter 4).
7. Draw a schematic of the throttling valve on a separate page in your logbook and illustrate the system boundary with a dashed line. The flows of all fluid streams entering and exiting the control volume should be clearly indicated. Indicate any energy transfers by work and heat transfer between the system and surroundings.
8. Write a 1st law energy balance for the throttling valve. Include all possible terms in this energy balance. Ensure that the sign of each term agrees with the directions indicated on your throttling valve schematic (Step 7). Cancel any unnecessary terms from the energy balance; explicitly list and justify all assumptions. You may wish to consult Moran et al. (2014, Section 4.10).

4. Instructions for running the experiment

1. Review Sections 6 and 7 and Figure 1 and familiarize yourself with the equipment before turning the system on.
2. Have a laboratory instructor check and initialize the schematics, 1st law energy balances, and data sheet you prepared in your logbook.
3. Do the following to obtain a set of measurements:
   - (a) Turn the main power switch on.
   - (b) Turn the compressor on.
   - (c) Set the evaporator fan speed to LOW.
   - (d) After a few minutes of operation, gradually adjust the throttle to obtain a refrigerant flow meter reading of about 0.3 gallons/min.
   - (e) Turn the thermocouple meter on.

(f) Turn the frequency counter on.

(g) Allow the system to run for about 20 minutes in order for the measurements to stabilize. Do not attempt to use the data taken during this transient period. Monitor the various pressures and temperatures to determine the end of the transient period. In particular, the compressor exit temperature (T_2) requires a relatively longer period to stabilize. Ensure there is no liquid visible in the sight glass upstream of the compressor and that there is no vapour visible in the sight glass upstream of the refrigerant flow meter (refer to Section 6).

(h) Record the data on your data sheet.

4. After the appropriate data have been obtained, have a laboratory instructor check your results and have them shut the system down for you.

5. Data analysis and presentation of results

1. Determine P_{evap} and P_{cond} in MPa. Indicate these values on the isobars you drew on your P-v diagram.

2. Determine the saturation temperatures for P_{evap} and P_{cond} using Table A-8 of Moran et al. (2014). Indicate these saturation temperatures on the vertical axis of your P-v diagram.

3. Fix the state of the refrigerant at state points 1, 2, 3, and 4 (but not 3′) using the measured temperatures and by making the following assumptions:

$$P_1 = P_4 = P_{3'} = P_{evap}$$

$$P_2 = P_3 = P_{cond}$$

   Approximately locate these state points on your T-v diagram, clearly indicating whether each state point lies within the superheated, subcooled, or mixed region. Use your observations of the refrigerant state through the site glasses to confirm the placement of these state points on the T-v diagram.

4. Evaluate h_3, v_3, and h_4 using Tables A-7, A-8, and A-9 from Moran et al. (2014). Clearly list any assumptions taken and clearly show how data have been interpolated from the tables.

5. Determine the mass flow rate of the refrigerant ($\dot{m}_{R22}$). Refer to the description of the refrigerant flow meter in Section 7.

6. Fix the state of the refrigerant at state point 3′ by using $P_{3'}$ and by determining $h_{3'}$ using the 1st law energy balance for the throttling valve from Step 8 of Section 3.

7. Determine the enthalpy of saturated liquid and saturated vapour at $P_{3'}$ using Table A-8 from Moran et al. (2014). Then use these values and $h_{3'}$ to determine the quality at state point 3′ ($x_{3'}$). Approximately locate state point 3′ on your T-v diagram.

8. Determine the velocity of the air flow (V_{air}) through the propeller anemometer (refer to Section 7).

   Determine the specific volume (m^3/kg) of air at the anemometer's inlet (state point 6) by treating the air as an ideal gas,

   $$P_6 v_6 = \frac{RT_6}{M_{air}}$$

   Where R is the universal gas constant and M_{air} is the molar mass of air. Assume that P_6 is 101.325 kPa.

   Then determine the mass flow rate of air through the evaporator,

   $$\dot{m}_{air} = \frac{V_{air} \cdot A_{anemometer}}{v_6}$$

   Where $A_{anemometer}$ is the cross-sectional area of the anemometer (refer to Section 7).

9. Determine the enthalpy of the air entering (h_5) and exiting (h_6) the evaporator. The air can be treated as an ideal gas, so the data in Table A-22 of Moran et al. (2014) can be used. Clearly show how data have been interpolated from the table.

10. Using the mass flow rates and property data determined in the previous steps, evaluate each term of the evaporator energy balance developed in Step 6 of Section 3. Rearrange the energy balance to solve for the rate of heat transfer between the system and the surroundings ($\dot{Q}_{surroundings}$).

11. Comment on whether the direction of the derived $\dot{Q}_{surroundings}$ matches your prediction from Step 5 of Section 3.

    The magnitude of $\dot{Q}_{surroundings}$ should be less than 0.1 kW. If it is not, then provide some possible explanations for this discrepancy. What terms were neglected or eliminated from your energy balance that could be significant? There are measurement uncertainties associated with all instrumentation. Based upon your observations of the equipment and the magnitude of the terms in your energy balance, indicate the three most likely measurement errors that could cause a significant discrepancy in the derived $\dot{Q}_{surroundings}$.

6. Operational notes

1. The operating conditions may be varied by adjusting the air flow rate through the evaporator unit and/or by adjusting the refrigerant flow rate using the metering valve.

2. For any operating condition selected, ensure that the refrigerant at the compressor inlet is all vapour (i.e. dry saturated or superheated). This can be verified through the sight glass at measurement point 4 (Figure 1). If liquid is observed at this location, slightly reduce the flow rate of the refrigerant until the liquid disappears.

3. For any operating condition selected, ensure that saturated or subcooled liquid enters the refrigerant flow meter. This can be verified through the sight glass located upstream of measurement point 3. If vapour is observed at this location, slightly reduce the flow rate of the refrigerant until the vapour disappears.

4. To avoid excessive pressures and/or damage to the metering valve (throttle), a spacer is installed on the valve, preventing its complete closure.

5. If the compressor is turned off before completing the experiment, it should not be restarted until the condenser and evaporator pressures have equalized.

6. The system is automatically switched off in the event that: 1) the evaporator pressure drops below about 190 kPa(g) (28 psig); 2) the condenser pressure exceeds about 2760 kPa(g) (400 psig); or, 3) the refrigerant flow rate exceeds about 0.6 USGPM. In such an event, immediately turn off all

power switches. Do not restart the system until the condenser and evaporator pressures have equalized. Inform the laboratory instructor if the problem reoccurs.

7. System description and instrumentation

This section describes the components that comprise the experiment. Note that not all components are analyzed in the current laboratory experiment.

Evaporator

The evaporator coil consists of rifled copper tubing through which refrigerant flows. Louvered fins are attached to the copper tubing to provide greater surface area to improve heat transfer between the air and the refrigerant. The evaporator fan causes air to flow through the evaporator unit.

Heat is transferred from the relatively warm air to the colder refrigerant as the two streams flow independently through the evaporator. This causes a cooling of the air. Furthermore, water vapour may be condensed from the air. A drip pan at the base of the evaporator collects this condensed liquid water which then flows through tubing to a drain under the floor of the laboratory.

The speed of the evaporator fan can be controlled through a switch situated on the control panel. The electrical power draw of the fan at its three operational speeds is given in the following table.

fan speed	**electrical power draw (kW)**
LOW	0.26
MEDIUM	0.30
HIGH	0.36

Condenser

The condenser coil is made of copper tubing and aluminum fins. Air flows through the condenser unit at about 1900 cfm. The fan used to generate the air flow is driven at 1100 rev/min by a 1/2 hp motor.

Compressor

The compressor is of a hermetically-sealed scroll design and operates at 3450 rev/min. It is protected with internal temperature-sensitive and current-sensitive overload sensors.

Throttle

The throttle is an 8^o stem point, 0.125" orifice, stainless steel metering valve. A spacer placed in the valve prevents complete shut off.

Propeller anemometer

The Gill propeller anemometer is a low-threshold precision air velocity sensor employing a fast response carbon fibre thermoplastic propeller. The propeller diameter is 20 cm. The "pitch" (the distance the air stream is advanced for each full rotation) is 29.4 cm/rev, which is equivalent to 0.294 m/s per rev/s. Its accuracy is ± 0.3 m/s.

The rotational speed of the propeller is measured with a photo-chopper transducer. The frequency of the square-wave output signal of the photo-chopper is measured with a frequency counter. The reading on the frequency counter in Hz corresponds to the propeller rotational speed in rev/s.

Consequently, the velocity of the air stream through the propeller anemometer can be determined from the pitch and the measured rotational speed:

$$V_{air} = 0.294 \cdot \dot{\omega}$$

Where V_{air} is the air velocity (m/s) and $\dot{\omega}$ is the rotational speed (rev/s) measured with the frequency counter.

Refrigerant flow meter

The refrigerant flow rate is measured using a rotameter with an anodized aluminum float and a cylindrical control tube with V-groove. The body is nickel-plated brass. The meter's accuracy is $\pm$ 4% of the full scale.

The flow rate should be read off the top edge of the indicator. The indicator is actuated by a permanent magnet built into the float, allowing reading of the flow rate without requiring visibility of the float. This permits all metal construction of the rotameter, providing high pressure and shock resistance.

The readings on the water scale of the flow meter can be converted into the volumetric flow rate of refrigerant by using the following formula:

$$\dot{V}_{R22} = \left[(1.56 \cdot 10^3) \cdot v_{R22} - 0.556\right]^{\frac{1}{2}} \cdot \left[\dot{V}_{H_2O}\right] \cdot \left[6.31 \cdot 10^{-5}\right]$$

Where $\dot{V}_{R22}$ is refrigerant volumetric flow rate (m^3/s) and $\dot{V}_{H_2O}$ is the reading on the meter's water scale (USGPM). v_{R22} is the specific volume (m^3/kg) of the refrigerant at the flow meter's inlet (measurement point 3 in Figure 1).

The mass flow rate of refrigerant can be determined using the following formula:

$$\dot{m}_{R22} = \frac{\dot{V}_{R22}}{v_{R22}}$$

Where $\dot{m}_{R22}$ is the refrigerant mass flow rate (kg/s).

Compressor power meter

Measures the electric power consumed by the compressor. The meter is calibrated to display the power in kW when the display unit is set to the V-DC scale.

Pressure gauges

They measure the gauge pressure of the refrigerant (i.e., the ambient pressure must be added to the reading to determine the absolute pressure).

Thermocouples and thermocouple meter

J-type thermocouples are used to measure the refrigerant and air temperatures at the measurement points indicated in Figure 1. The thermocouple meter converts the thermocouple output (mV) into degree Celsius. Measurement number 5 on the temperature display measures the refrigerant temperature entering the evaporator ($T_{3'}$) while measurement number 7 on the temperature display measures the temperature of the air entering the evaporator (T_5).

Refrigerant filter/drier

A device for removing contaminants from the circulating refrigerant.

References

Moran, M. J., Shapiro, H. N., Boettner, D. D., and Bailey, M. B. 2014. *Fundamentals of Engineering Thermodynamics*. John Wiley & Sons, Inc., 8th edition.

EXPERIMENT 6

Conduction Heat Transfer Experiments

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1. Introduction

The purpose of this experiment, located in the Thermodynamics Laboratory (2230 Mackenzie Building) is to illustrate the conduction mode of heat transfer in solid media.

Conduction is the transfer of thermal energy through molecular interactions when the medium is exposed to a temperature gradient. According to Fourier's law of conduction (Note that this topic will be covered in more detail in the Heat Transfer section of the course), the rate of conductive heat transfer is proportional to the area across which heat is transferred and the temperature gradient:

$$\dot{Q} = -kA\frac{dT}{dx} \qquad (1)$$

where $\dot{Q}$: rate of heat transfer (W)
k: thermal conductivity (W/m·K)
A: area (m^2)

The negative sign indicates that heat flows in the opposite direction of the temperature gradient, namely from hot to cold. The constant of proportionality, k, is known as thermal conductivity, and expresses the ability of a substance to conduct heat. Values of k for several metals are listed in the following table.

Table 1: Thermal conductivity of selected metals.

Metal	***k*** **(W/m-K)**
Brass	110-128
Stainless steel	25
Aluminum	180
Copper	380

Further, if one assumes the temperature distribution to be linear and considering one-dimensional heat transfer, the Eq. (1) becomes:

$$\dot{Q} = -kA\frac{\Delta T}{\Delta x} \qquad (2)$$

If the temperature distribution of interest spans more than one material (i.e. a composite; see Figure 1), one may express the heat transfer as follows:

$$\frac{\dot{Q}}{A} = \frac{k_A \Delta T_A}{\Delta x_A} = \frac{k_B \Delta T_B}{\Delta x_B} = \frac{k_C \Delta T_C}{\Delta x_C} \tag{3}$$

where A, B, C: different materials

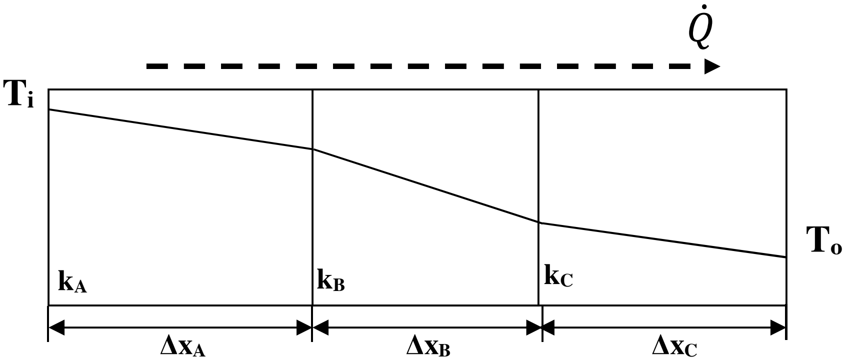

Figure 1: Example of a composite material

In other words, when thermal equilibrium is reached, the heat flux remains constant throughout the multiple layers of material due to conservation of energy. The temperature gradient, however, will differ depending on the value of the thermal conductivity, k. From equation (3), it follows that:

$$T_i - T_o = (\Delta T_A + \Delta T_B + \Delta T_C) = \frac{\dot{Q}}{A}\left(\frac{\Delta x_A}{k_A} + \frac{\Delta x_B}{k_B} + \frac{\Delta x_C}{k_C}\right) \tag{4}$$

One may therefore express $\dot{Q}$ using an overall heat transfer coefficient, U, and the overall temperature difference as follows:

$$\frac{\dot{Q}}{A} = U(T_i - T_o) \tag{5}$$

The overall heat transfer coefficient, U, provides an indication of the ability of the composite material to conduct heat. Its inverse, R, is known as the *thermal resistance* to heat flow.

$$R = \frac{1}{U} \tag{6}$$

2. Apparatus

Refer to Figure 2 for a schematic of the experimental apparatus.

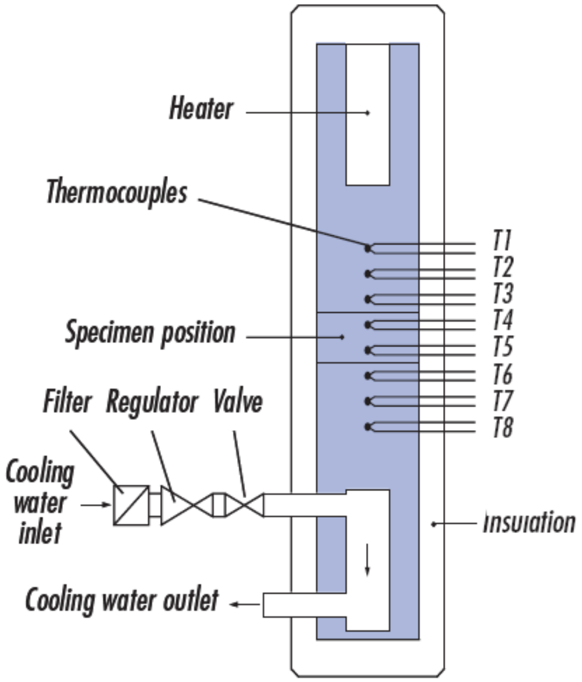

Figure 2: Linear heat conduction apparatus

The experimental apparatus, labelled HT11, consists of three insulated sections, each fitted with a metal cylinder. The top and bottom sections each contain a brass cylinder, whereas the intermediate section is reserved for the test specimen which can be removed. Brass and stainless steel test specimens are provided with the setup. Both metal cylinders have a circular cross section of diameter $D = 25$ mm.

An electric heater is located in the top section (hot section), and generates heat which is conducted through the metal cylinders. Conversely, the bottom section (cold section) is cooled by water. The flow rate of water may be varied by the operator using a knob on the pressure regulator.

Eight K-type thermocouples are located in the apparatus – three in the top section, two in the intermediate section, and three in the bottom section – to measure the temperature at different locations. The thermocouples are spaced 15 mm apart. Consequently, *T3* is 7.5 mm from the hot face of the test specimen, while *T6* is 7.5 mm from the cold face of the test specimen.

The voltage, current, water flow rate, and temperature readings are read off the main control panel when the appropriate knob is turned to the *V*, *I*, *Fw*, and *T1*-*T8* settings, respectively.

3. Procedure

Note: it may take a few minutes before temperatures stabilize for given power input and water cooling settings. During this period, students should continue to study the apparatus and this lab description to thoroughly understand the quantities to be measured, the sensor used for the measurements, the measurement procedure, and the subsequent data processing steps.

(a) Data sheets are given in Appendix A. Please attach these tables to your logbook.

Part I: Brass

(b) Apply conductive paste on both faces of the brass specimen as instructed by the T.A., and clamp it in place. Note that the conductive paste will enhance the thermal contact by filling the microscopic imperfections at the interface.

(c) Turn on the front panel switch and the cooling water. Verify that the water valve is open (parallel to tube). Using the knob on the pressure regulator, adjust the water flow rate to 1.5 L/min. The flow rate may be read on the front panel when the knob is set to *Fw*.

(d) Adjust the voltage to 9.0 V. The voltage is read on the front panel when the knob is set to *V*. Record the current (knob set at *I*). The voltage and current are required to determine the electric power input to the system ($\dot{Q}_{IN} = V \times I$), hence the rate of heat transfer through the test specimen. When temperatures have stabilized, record temperatures *T1* to *T8* by turning the knob to correspond to the appropriate thermocouple.

Part II: Stainless steel

(e) Apply conductive paste on both faces of the stainless steel specimen, and clamp it in place.

(f) Set the voltage at 9.0 V. Record the current *I*. When temperatures have stabilized, record temperatures *T1* to *T8*.

4. Data analysis and questions

Part I: Brass

(a) Plot a graph of temperature against longitudinal position along the bar (*T1* to *T8*).

(b) How does temperature vary with position? Is this consistent with Fourier's law of conduction?

(c) Calculate the average thermal conductivity k of brass $\dot{Q}$. How does the calculated value compare with the thermal conductivity listed in Table 1?

Part II: Stainless steel

(d) Plot a graph of temperature against longitudinal position along the bar.

(e) Why is the temperature gradient different in the stainless steel section compared to the brass sections?

(f) Determine the thermal conductivity (k) of stainless steel. How does it compare to the values listed in the table?

(g) Calculate the overall heat transfer coefficient (U) for the brass-steel-brass composite, as well as its thermal resistance (R). Can you name one common application for which the value of the thermal resistance is clearly advertised?

Part III: Additional questions

(h) Based on the test results, which of the two metals tested in this experiment is the best heat conductor?

(i) Do you expect the differences in the thermal conductivity of these two metals to follow the same trend as their relative conductivity of electricity?

(j) How do you expect the temperature to vary if conductive paste was only applied on the bottom face of the metal specimen, but not on the top face? Sketch the expected temperature distribution on a temperature vs. longitudinal position graph.

(k) Identify the sources of error that may have influenced the experimental results.

(a) Reference

Holman, J.P., *Heat Transfer*, 9th edition, McGraw-Hill Publishing Co

Appendix A - Experiment 9

$A = \pi D^2/4$ $D = 0.025$ m

Table 1: Data for conductive heat transfer for brass specimen.

Fw = 1.5 L/min		**Voltage (V) 9 V**
Current (A)		
Position (mm)	**Temperature (ºC)**	
0	T1	
15	T2	
30	T3	
45	T4	
60	T5	
75	T6	
90	T7	
105	T8	

Table 2: Data for conductive heat transfer for steel specimen.

Fw = 1.5L/min		**Voltage (V), 9 V**
		Current (A)
Position (mm)	**Temperature (ºC)**	**Steel**
0	T1	
15	T2	
30	T3	
37.5	interpolate	
67.5	interpolate	
75	T6	
90	T7	
105	T8	

Calculations

Table 3: Calculated results for conductive heat transfer for brass specimen.

Voltage (V)	**9 V**
$\dot{Q}_{IN}$ (W)	
ΔT_{13} (K)	
ΔT_{45}	
ΔT_{68}	
k_{13} (W/mK)	
k_{45}	
k_{68}	
k_{avg}	
k_{BRASS}	110 - 128

Table 4: Calculated results for conductive heat transfer for brass specimen.

	Steel
$\dot{Q}_{IN}$ (W)	
ΔT_{ext} (K)	
k_{calc}	

$U_{b\text{-}s\text{-}b}$ (W/m^{2}K)	
$R_{b\text{-}s\text{-}b}$ (m^{2}K/W)	