Complete this worksheet after you have modified your course, delivered it, and assessed it. Attach a syllabus/course outline, Activity Sheets for new activities, summary of your assessment, and essential copies of teaching materials to help the mentor team evaluate your achievement of workshop goals.

Course Name: Thermodynamics 2 Laboratory

Instructor Name: Amanda D. Smith

List learning goals for your course, lesson, or activity that highlight new sustainability elements.

1. Become acquainted with the physical equipment and instrumentation, its operation, usefulness and limitations.
2. Set specific test objectives and plan the test accordingly.
3. Obtain data with an appreciation of its corresponding uncertainty.
4. Calculate system performance and operating characteristics.
5. Present significant results and trends in a neat, understandable and logical manner.
6. Interpret and critically evaluate the final results using a sound technical argument.
7. Relate experiments in the lab with real world applications.
8. Be able to identify impacts of thermodynamic systems to the surrounding environment.
9. Recognize laws and regulations that related to thermodynamic systems and their environmental impacts.
10. Cally think about potential solutions to reduce negative impacts.

Explain the new sustainability element(s) you incorporated into your course and how they related to the learning goals above (at course, lesson, or activity level). Describe how you see these elements relating to sustainability.

The new elements along with the existing elements in the laboratory objectives incorporate system thinking. The original laboratory experiments tended to focus more on the technical aspect of Thermodynamics. The new elements were designed to bring more critical thinking about the results and relate them to real world applications/problems.
Provide a concise listing of sustainability lessons and activities and show their location in the course schedule. For selected new activities attach a completed Activity Sheet.

The Thermodynamics 2 Laboratory was different from a regular course. Students learned materials from the class lecture. During the lab sessions, students performed experiments that related to the class. The sustainability lessons in the lab were incorporated into the lab reports, where students expected to apply class materials and critical thinking to complete the reports. There were 4 lab experiments throughout the semester. The following activities were added to the lab reports.

Lab 1: Spark Ignition Internal Combustion Engine

- What would you recommend in order to improve the efficiency of the engine? For example, how would turbo-charging, inner cooling, split-fire spark plugs, and other hardware alterations change the efficiency of the engine?
- Describe the importance of combustion engines in your day-to-day life. What are their drawbacks? List at least 2 benefits and 2 drawbacks. What would you suggest to mitigate the drawbacks?
- We understand that combustion engines tend to release greenhouse gases like CO₂ into the environment. Based on your understanding, draw a diagram of carbon lifecycle. What are some other alternative solutions for reducing greenhouse gases emission from combustion engines? List at least 2 alternative solutions.

Lab 2: Vapor Compression Refrigeration Cycle

- What are your suggestions to improve the COPR of the system? List at least two suggestions and explain how each of them works
- What are some popular refrigerants that used in refrigeration systems? What are their environmental impacts? List at least two refrigerants and two environmental impacts.

Lab 3: Cooling Tower

- Discuss environmental impacts of cooling towers and possible solutions to reduce the environmental impact. List at least two impacts and two solutions.

Lab 4: Propane Burner

- Besides the combustion products that we measured in the experiment, what are some other emission products from combustion systems? List at least 3 products. What are their potential environmental impacts from combustion products and how to improve the situation?
What motivated you to change your course?

The lab discussions were changed to help students understand the results in more meaningful ways. Furthermore, they can relate the lab lessons to real world applications and relevant environmental issues. As a result, students were able to appreciate the cause and effect of Thermodynamics systems.
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The students particularly enjoyed the new experience with less computational work, while they were able to do research to answer sustainable questions. Some of the students commented that they had learned to think outside of the box. Moreover, the sustainable questions on the lab allowed them to connect the math to real world applications.
ME EN 3600-002 to -010
Thermodynamics II Lab
Department of Mechanical Engineering
University of Utah
Fall 2016

INSTRUCTOR
Amanda Smith, Assistant Professor of Mechanical Engineering
See Section 1 syllabus.

TEACHING ASSISTANTS

<table>
<thead>
<tr>
<th>Name</th>
<th>Phone</th>
<th>Email</th>
<th>Office Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rich Didier</td>
<td>1-4650</td>
<td><a href="mailto:Rich.didier@utah.edu">Rich.didier@utah.edu</a></td>
<td>MEK 2121</td>
</tr>
<tr>
<td>Zahra Fallahi</td>
<td>1-4650</td>
<td><a href="mailto:Zahra.fallahi@utah.edu">Zahra.fallahi@utah.edu</a></td>
<td>MEK 2121</td>
</tr>
<tr>
<td>Sina Hamian</td>
<td></td>
<td><a href="mailto:Sina.hamian@utah.edu">Sina.hamian@utah.edu</a></td>
<td>MEB 1361</td>
</tr>
<tr>
<td>Vahid Hatami</td>
<td>1-4589</td>
<td><a href="mailto:Vahid.hatami@utah.edu">Vahid.hatami@utah.edu</a></td>
<td>MEB 1371</td>
</tr>
<tr>
<td>Thomas Tran</td>
<td>1-4650</td>
<td><a href="mailto:Thomas.tran@utah.edu">Thomas.tran@utah.edu</a></td>
<td>MEK 2121</td>
</tr>
</tbody>
</table>

OBJECTIVE
The main objective of the laboratory is to reinforce the concepts addressed in the lectures. Particular emphasis is placed on experimental studies and connections with real-world systems. The laboratory experience consists of 4 experiments, 1 safety briefing/computer tutorial, 4 help sessions, and 3 review sessions.

COREQUISITES
ME EN 3600 – Thermodynamics II (section 001)

LAB LOCATION
MEB 1156

TIMES

<table>
<thead>
<tr>
<th>Section</th>
<th>Day</th>
<th>Time</th>
<th>Lab Instructor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Tu</td>
<td>02:00PM-05:00PM</td>
<td>Vahid Hatami</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
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<td>Vahid Hatami</td>
</tr>
<tr>
<td>4</td>
<td>W</td>
<td>03:00PM-06:00PM</td>
<td>Rich Didier</td>
</tr>
<tr>
<td>5</td>
<td>W</td>
<td>06:00PM-09:00PM</td>
<td>Rich Didier</td>
</tr>
<tr>
<td>6</td>
<td>Th</td>
<td>07:30AM-10:30AM</td>
<td>Thomas Tran</td>
</tr>
<tr>
<td>7</td>
<td>Th</td>
<td>10:45AM-01:45PM</td>
<td>Sina Hamian</td>
</tr>
<tr>
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<td>Sina Hamian</td>
</tr>
<tr>
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<td>F</td>
<td>10:45AM-01:45PM</td>
<td>Zahra Fallahi</td>
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<tr>
<td>10</td>
<td>F</td>
<td>02:00PM-05:00PM</td>
<td>Zahra Fallahi</td>
</tr>
</tbody>
</table>

MEETING TIMES
Meet in MEB 1156 at the beginning of your scheduled 3-hour lab period, except when notified otherwise by your TA. See schedule for dates when new labs will be introduced. Meeting times, formats, and locations will be discussed in further detail at the first lab meeting.

SCHEDULE
The weekly lab schedule is found in the right-hand column of the first sheet on the course schedule: [http://bit.ly/3600f16](http://bit.ly/3600f16)

TEXT

LAB GRADING
There will be a total of 4 lab reports, each worth 100 points. The lab reports are worth
15% of the final course grade for ME 3600 (3.75% for each of the 4 labs). You must pass with 70% or greater to consider the lab section of the course “passed.”

GROUPS

All lab exercises are to be conducted in groups of 4 to 7. Groups will be formed by the TAs and should remain intact for the duration of the course. Data are to be shared by all of the group members; however, each student must submit a report based on their individual data reduction and analysis.

CLASS POLICIES

It is each student's decision whether to attend the lab lectures and to conduct the labs. However, if you are submitting a lab report for grading, you will receive a deduction for missing the intro to the lab or the data acquisition section. Absence from a lab session will result in a 20% penalty on the lab report; lateness will result in a 10% penalty per day. If you are absent, it is your responsibility to get the lesson information or the data from your group members. Students are responsible for all material covered in laboratory presentations, with or without an excused absence.

If you wish to move to a different lab section, your request will be considered on a space-available basis, if your request is received before Friday, August 26, 2016. Send your request to Thomas Tran with your name, unid, currently enrolled section, and requested section(s) by emailing thomas.tran@utah.edu.

If you wish to re-use a (passing) lab grade from a previous offering of the course at the University of Utah, you must contact your professor and have them send me your lab grade by Friday, August 26, 2016. If I was not the professor, I need to receive an email directly from them at: amanda.d.smith@utah.edu.

The lab reports submitted for grading should represent only your work.

Attendance is necessary for:

- Lab 0, Experiments for Labs 1-4

Attendance is strongly recommended, but not required, for:

- Help sessions for Labs 1-4
- Review sessions for Tests 1-2 and Final Exam (You may attend another section for review sessions if it is not overcrowded; write to thomas.tran@utah.edu to check enrollment for the section you wish to attend.

Attendance is not necessary for:

- Any week marked “No meeting”

Academic honesty will be enforced according to university policy 6-400 (see Section 1 syllabus). You may receive help in completing from your TA at a help session, but not from other students.

The parts of your lab report which MAY look identical to those of other students are:

- Original data sheet
- Memo heading
The parts of your lab report which may NOT look identical to those of any other student, past/present/future, are:

- Everything else (including but not limited to, computer code and text)

Submitting work copied from others is academic misconduct. Plagiarism of ideas or work will be considered academic misconduct. All academic misconduct will result in, at a minimum, a score of “0” on the lab report in question for all participants.

**ORDER OF LABS**

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<th>Title</th>
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<tr>
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<tr>
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<td>Spark Ignition Engine</td>
</tr>
<tr>
<td>2</td>
<td>Refrigeration</td>
</tr>
<tr>
<td>3</td>
<td>Cooling Tower</td>
</tr>
<tr>
<td>4</td>
<td>Gas Burner</td>
</tr>
</tbody>
</table>

**SPECIFIC OBJECTIVES**

1) Become acquainted with the physical equipment and instrumentation, its operation, usefulness and limitations.
2) Set specific test objectives and plan the test accordingly.
3) Obtain valid data with an appreciation of its corresponding uncertainty.
4) Calculate some performance and operating characteristics.
5) Present significant results and trends in a neat, understandable and logical manner.
6) Interpret and critically evaluate the final results using a sound technical argument.

**REPORT GUIDELINES**

A written report is due two weeks after the data acquisition associated with the exercise, as listed in the Lab Schedule.

**Written (hard copy) FULL report**

The report (hard copy) should be delivered to your TA by the time your lab starts on the week marked “Report Submitted.” You may also turn in your lab report early during your TA’s office hours, or hand deliver the report to your TA at a time and place that is mutually agreed upon.

[Note: You only need to turn in the hard copy of your code. A previous version of this syllabus was out-of-date. See grading sheet in the student manual for requirements on each specific lab.]

In the event that unavoidable conditions prevent a student from complying with the submission date and time of a report, consultation and approval must be made with the instructor or TA a minimum of two days prior to the report deadline. Reports submitted after the due date and time will be viewed as late and the late penalty will be assessed (20% for each 24-hour period of lateness). Reports submitted more than 4 business days late will therefore receive a grade of 0. Late reports are officially turned in when they are hand delivered to your TA or the instructor.
If extenuating circumstances prevent you from reaching campus, an electronic submission of the entire report (.pdf file) may be used to time-stamp the report; however, your hard copy still must be submitted by hand to your lab TA. One numeric grade will be assigned for each written report based on technical content, readability, presentation, and format. Grade sheets will be provided with each lab handout and should be included with the lab report submitted for grading. A generic grade sheet that indicates the typical distribution of points is attached to this report; however the specific numbers can vary from experiment to experiment based on what is emphasized.

**REPORT FORMAT**

Written reports will be in the form of technical memos that are intended to be short, concise, and to-the-point. Lengthy reports are not necessary. Conciseness is a means of achieving readability. The report objective is to concisely communicate all of the needed information about an experiment, in the appropriate format. Neatness of presentation should also be considered.

Reports should follow the standard Department of Mechanical Engineering memo format. The reports should be neatly typed, submitted on 8-1/2 x 11 in standard paper and single-spaced. Use a third person, passive style since it is the more formal accepted standard for engineering reports and papers (i.e., avoid the use of “I” and “we”). Attachments should include all reported data in the form of tables and figures, the raw data sheet(s), computer codes, and sample calculations. Major section titles should be in bold font on the left side of the page. Graphs and tables should be labeled and numbered as Figures and Tables with appropriate descriptive titles. Graphics in landscape format should be oriented with the top of the figure or table toward the inside of the memo. The sections of the written report include the following:

**Memo Headings** Headings include To, From, Date, Subject, CC, and Attachments. You should initial next to your name to indicate that you approve of the report’s contents.

**Introduction** Explain the purpose and objectives of the laboratory exercise. The purpose is a one-sentence description that answers the question about why the lab was conducted.

**Results** Present the significant results in tabular and graphical form (when possible) in a manner that clearly demonstrates the effect of a control variable on a resulting performance characteristic of interest. Discuss the measured data and how the results were generated. Tables and graphs should be computer generated and placed in the Attachments. All computer-based data reduction and analysis should be conducted with Matlab or EES. These are the only software packages for which support will be provided. Data reduction utilizing spreadsheet software will not be supported. All data should be presented in SI units, unless specific units are requested.

**Tabular Form** Tables should contain the control variables (and units) at the head of succeeding horizontal rows. Each vertical column should list important measured and calculated data for a single set of control variables.

**Graphical Form** Neatness cannot be overemphasized. The set of curves should constitute a complete, independent report of significant test results containing all essential information such as a descriptive title, completely labeled axes (including variable names and units), and a legend to describe each data set. Plot the independent variable as an abscissa, indicating the name of the quantity (with its units in parenthesis) and the scale number. Note that data should be presented in nondimensional form if possible. Plotted points representing original data should be indicated by small distinctive geometric symbols (include a legend for symbols). All curves should be "faired" (do not connect each data point). Each curve should be clearly identified. If there is more than one dependent variable, an attempt should be made to show both dependent variables on the same graph.

**Discussion** Critically analyze the results and trends as reported in the Results section. Utilize the depth of your understanding of the phenomena on the performance characteristics being studied and their dependence on the control variable(s). How you handle this critical part of the report will heavily determine your grade. If your data set does not come out as expected, use your discussion section to address it. Unique, “real” lab experiments often do not come out as planned. Remember that your understanding of the principles and your hands on experience are the real purpose of the lab. Make sure all questions that are included in the lab handout are answered in this section.
Conclusions and Recommendations The conclusions should relate the results to the original objectives and elaborate on the practical implications. Restate the objectives and indicate whether or not these were satisfied. Recommendations should be given for possible improvements to the experiment and/or for additional studies that could be performed to increase the understanding of the phenomena studied.

Participation Description Describe in one sentence to one paragraph your participation in the lab. How did you prepare for the lab and what did you do during the data acquisition period? Coordinate with your group members to rotate jobs such as setup, instrument reading, and data recording during the four different experiments. Be considerate of other group members who have not yet had the opportunity to participate in the hands-on work. (Please do use the first person for this section).

Attachments Attach all figures and tables, original data sheets (original handwritten data sheet or a copy of the original), computer codes, and sample calculations. These should be limited to material that supports the discussion and results presented earlier. All material in the Attachments should be referenced in the main text.

Reduced Data These data should be in the form of tables and figures, all of which should be referenced and discussed in the report main body.

Raw Data Sheet(s) Include the data sheet(s) used to record the original raw data taken in the lab. These data are the origination of the chain of evidence that results in the reported findings. Transcription errors can occur in data input to a data reduction program, but these errors may be recognized easily by referring to the original data.

Sample Calculations Show a sample of how each different result was calculated from original data, noting applicable symbolic equations, numerical substitutions, unit checks and numerical answers. This section is required in order to demonstrate the process used to arrive at the final experimental outcomes. If your sample calculations do not lead to the numbers you provide in the rest of your report, you will not receive full credit.

Computer Code(s) Attach computer codes (fully commented) created in Matlab to reduce the raw data to the final reported form.

[Updated: 2016-09-26 (corrections on policies made on p. 3-4)]
<table>
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<th>Topic</th>
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<td><strong>Discussion</strong></td>
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<td>tables and graphs (appropriate labeling and numbering)</td>
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<tr>
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</table>
This is a sample lab report for ME EN 3600 – Thermodynamics II.

This memorandum provides details of Lab 1 - Pipe Pressure Drop and Shear Stress. A series of tests were conducted to measure the wall shear stress in a hydraulically smooth stainless steel pipe. The objective was to use the experimentally measured shear stress along the walls of the pipe to determine the friction factor for several different flow rates. The experimental data were compared with established data obtained from the Moody diagram to assess the accuracy of the measured friction losses in the pipe. A further objective of this test was to gain experience using pressure transducers and thermocouples to measure properties of the flow. This memo includes test results, a discussion of the findings, conclusions, and recommendations for improving the experiment.

Results
The results of the test are presented in Table 1. The raw data (mass flow rate $\dot{m}$, inlet temperature $T_1$, inlet pressure $P_1$, and outlet pressure $P_2$) have been used to produce the desired variables of density $\rho_1$, mean velocity $V$, wall shear stress $\tau_w$, Reynolds number $Re$, and friction factor $f$. (Since this is simply an example, only three data sets are shown). The effect of $Re$ on $f$ is shown graphically in Fig. 2.

Discussion
As shown in Table 1, the shear at the wall increases from a low of 8 N/m$^2$ at the lowest flow rate, to 15 N/m$^2$ at the highest flow rate of 0.20 kg/m$^3$. This is intuitively reasonable, as the boundary layer for flow in the pipe becomes thinner as the Reynolds number increases. A smaller boundary layer implies steeper velocity gradients near the wall, and thus high shear at the wall. (Recall that the shear at the wall is proportional to the velocity gradient there).

In Fig. 2, the friction factor is shown to decrease as the Reynolds number increases. The results are in excellent agreement with data obtained from the Moody diagram, which is also shown in Fig. 2. Minor discrepancies between the measured friction factor and the data from the Moody diagram may be due to several sources. These include variations in flow rate which could be up to 10% based on the accuracy of the flow meter, the assumption of constant density (air temperature was not measured at the location of the downstream pressure transducer so the assumption of constant density could not be explicitly tested) or measurement tolerances in the pressure transducers. Also note that the flow in the pipe is likely not fully developed at the location of the first pressure transducer, due to the closeness of the transducer to the stagnation...
chamber entrance (students: note that the entrance length could be determined to support this argument).

**Conclusion**
Overall, the test proved successful and provides evidence that other properties from unknown pipes (e.g., determining the roughness of a pipe from the measured friction factor) can be determined confidently. Friction factor was confirmed to decrease with Reynolds number for laminar flow and the shear stress was found to increase with mass flow rate. The experiment could be improved by 1) replacing the flow meter with one that has less uncertainty, 2) by installing additional thermocouples for air temperature measurement leading to improved density calculations, and 3) by increasing the tube entrance length to insure that the flow is fully developed in the region where measurements are made.

**Participation Description**
Before the lab, I prepared the table shown in Attachment 2. During the experiment, I confirmed the pipe diameter with calipers and wrote down the inlet and outlet pressures.
Table 1. Measured and computed data for pipe flow experiment

<table>
<thead>
<tr>
<th>Test</th>
<th>( m ) (kg/s)</th>
<th>( T_1 ) (°C)</th>
<th>( P_1 ) (kPa)</th>
<th>( \rho_1 ) (kg/m(^3))</th>
<th>( P_2 ) (kPa)</th>
<th>( V ) (m/s)</th>
<th>( \tau_w ) (N/m(^2))</th>
<th>( Re ) x10(^5)</th>
<th>( f )</th>
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<td>15</td>
<td>3.351</td>
<td>.0061</td>
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</tbody>
</table>

Figure 2. Effect of Reynolds number on pipe friction factor
Include the original data sheet used to record all data. This is where the data analysis process begins. It is necessary to have the original data in case transcription errors occur during data reduction. All group members may use the same data sheet (make copies for all group members).

<table>
<thead>
<tr>
<th>Test</th>
<th>m (kg/s)</th>
<th>T1 (°C)</th>
<th>P1 (kPa)</th>
<th>P2 (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.10</td>
<td>40</td>
<td>109</td>
<td>101</td>
</tr>
<tr>
<td>2</td>
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<td>3</td>
<td>0.20</td>
<td>40</td>
<td>116</td>
<td>101</td>
</tr>
</tbody>
</table>
Attachment 3
Sample Calculations

Notes:  1. Sample calculation may be done in pencil
2. Include units with all variables, particularly with the final result
3. Check that equations are dimensionally consistent

Compute the fluid density
\[
\rho = \frac{P}{RT} = \frac{109 \text{ kPa}}{(0.287 \text{ kJ/kg} \cdot \text{K})(313.15 \text{K})} = 1.21 \text{ kg/m}^3
\]

Compute the mean flow velocity
\[
V = \frac{m}{\rho A} = \frac{0.10 \text{ kg/s}}{(1.21 \text{ kg/m}^3)(0.04 \text{ m})^2/4} = 65.8 \text{ m/s}
\]

Compute the wall shear stress
\[
\tau_w = \frac{0.02 m (109 - 101) \text{ kPa}}{2 L} = \frac{0.008 \text{ kPa}}{10 \text{ m}} = 8 \text{ N/m}^2
\]

Compute the Reynolds number
\[
Re = \frac{\rho V D}{\mu} = \frac{1.21 \text{ kg/m}}{1.90 \times 10^{-5} \text{ N} \cdot \text{s/m}^2} \left(65.8 \text{ m/s}) (0.04 \text{ m}) \right) = 1.676 \times 10^5
\]

Compute the friction factor
\[
f = \frac{2 D \rho p}{\rho LV^2} = \frac{2(0.04 \text{ m})(109 - 101 \text{ kPa})(1000 \text{ Pa/kPa})}{(1.21 \text{ kg/m}^3)(10 \text{ m})(65.8 \text{ m/s})^2} = 0.0122
\]

Compute the theoretical friction factor
\[
f = \left(\frac{6.9}{0.020\log\frac{D}{3.7}}\right)^{1.11} \left(\frac{0.111}{0.4}\right)^{0.4} \left(\frac{6.9}{0.020\log\frac{D}{3.7}}\right)^{1.11} = 0.0160
\]
LAB 1 – SPARK IGNITION INTERNAL COMBUSTION ENGINE

PURPOSE AND OBJECTIVES:

This laboratory involves analysis of different forms of energy during the operation of a spark ignition internal combustion engine. The main objectives are:

1. To operate a spark ignition internal combustion engine and examine its performance by changing engine speed and compression ratio.
2. To quantify magnitudes of useful work, mechanical losses, heat losses, and miscellaneous losses.
3. To understand the First Law of Thermodynamics that applied to a spark ignition internal combustion engine.

EQUIPMENT:

The engine has a single cylinder with a swept volume of 0.148 L (65.1 mm bore, and 44.4 mm stroke), and compression ratios of 8.5:1, 7:1, and 5.5:1. The engine runs on 91 octane gasoline. Determining the magnitudes of energy input, energy output, and various losses occurring in the engine cycle as a function of rotational speed is useful since the efficiency of the engine is dependent upon these quantities. The figure below shows a schematic diagram illustrating the system, including its boundary, and all forms of energy which are of interest.

Figure 1. General Engine Schematic
PERFORMANCE ANALYSIS:

The fuel energy in is the amount of energy contained in the fuel entering the engine. The same amount of energy will be assumed to be released by the air-fuel combustion process.

\[ \dot{E}_\text{in} = \dot{m}_{\text{fuel}} LHV \text{ [kW]} \]  

(1)

The magnitude of fuel energy rate is the product of the mass flow rate of fuel and its lower heating value of 44.0 MJ/kg for regular gasoline. The Fuel density is 726 kg/m³.

Fuel volumetric flow rate is determined by measuring the volumetric amount of fuel used over a measured time interval during engine operation. This can be done with the fuel measurement tube on the test stand (CT 159).

\[ \dot{m}_{\text{fuel}} = \dot{V}_{\text{fuel}} \rho_{\text{fuel}} \text{ [kg/s]} \]  

(2)

The power output is calculated using a dynamometer (HM 365) connected to the engine via a belt and two pulley system. This dynamometer acts as the braking unit which applies the load to the engine. The dynamometer consists of a three-phase, asynchronous electric motor. An asynchronous motor produces a torque when the rotating speed of the rotor is different from the synchronous frequency speed in the stator. Sensors within the dynamometer are used to determine the current engine speed and torque output, which can be used to determine the break power output.

Mechanical losses are due to the inertial forces and friction required to move the crankshaft and piston of the engine. To determine these, the dynamometer is operated as a motor which rotates the engine crank shaft with no fuel supplied to the engine and with no combustion processes within. Mechanical losses are then determined at different speeds by recording the torque required to operate the dynamometer.

Heat losses are determined after all other contributions to the energy balance are determined. The losses are calculated as one term, and equal to the positive amount of energy that must be added to the losses in order to satisfy the energy conservation equation at steady-state. Steady state conditions prevail when no additional energy is stored or accumulates in the combustion chambers of the engine.

First Law (Energy Equation) for engine system:

\[ \dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}} \]

In addition to heat rejected to the surrounding air through convection, miscellaneous heat losses consist of all forms of energy which contribute to the energy balance but are not taken into account in the analysis. These include exhaust gas heat out, radiation heat loss to the surroundings, strain energy resulting in expansion of the materials and the built-up residual stresses, combustion inefficiency, and imperfect fuel-air mixing.
**PROCEDURE:**

**Part 1: Performance Characteristics and Energy**

Performance characteristics and different forms of energy are to be determined at 4 different engine speeds. The speed is controlled using the dynamometer while the throttle is kept in the open position. Changing the speed on the dynamometer without changing the throttle position will also cause a change in torque because the dynamometer acts as a brake while the engine is running. Measurements of all quantities listed below need to be made at five speeds ranging from 2,000 to 3,000 RPM while the throttle on the engine is in the open position.

For four dynamometer rotational speeds, measure the following quantities:

1. Rotational speed of drive and brake unit in RPM
2. Torque in N·m
3. Volumetric amount of fuel used over a measured time interval
4. Time interval over which the volumetric amount of fuel measured was used
5. Compression ratio used: ______
6. Inlet temperature and pressure of air

After all measurements are taken at all four speeds, care should be exercised to unload the engine before the dynamometer is shutdown.

**Part 2: Determining Mechanical Losses**

As mentioned earlier, this is done by operating the dynamometer as a motor which rotates the engine crank shaft with no fuel supplied to the engine and without any internal combustion process. All of the load is then due to the friction and inertia required to move the crank shaft and piston of the engine. Mechanical losses are then determined at different speeds by recording the torque required to operate the drive and brake unit.

For the four rotational speeds used above, note the following quantities:

1. Rotational speed in RPM
2. Torque in N·m

The speed and torque are needed to compute the power required to overcome friction and inertia. Because the friction and inertial loading vary almost linearly with RPM, determine a best fit linear regression line comparing speed and torque of the four measured data points using Matlab. **You will use this linear regression to determine the mechanical losses at the speeds used in Part 1 of the procedure.** The measured losses are used solely to determine the linear regression.

**DATA REDUCTION AND PRESENTATION OF RESULTS:**

From the raw data, for each speed, calculate:
(1) Engine output power in kW and horsepower.
(2) Rate of energy input to the engine in the fuel in kW and horsepower (note that a 1 cm drop in the flow tube has a volume of 5.1 cm$^3$).
(3) Rate of mechanical losses due to friction and inertia in kW and horsepower at each engine speed [RPM] using linear interpolation and/or linear extrapolation.
(4) Miscellaneous loss rate (heat rejected plus other losses) in kW and horsepower
(5) Thermal efficiency in %
(6) Mean Effective Pressure in kPa and psi
(7) Ideal Otto cycle thermal efficiency for the engine assuming the ratio of specific heats = 1.33

Tabulate all raw data and all of the above quantities for each of the four RPM values tested.

Construct the following six graphs:

(1) Torque [Nm] versus engine speed in RPM
(2) Power output [kW] versus engine speed in RPM
(3) (Fuel flow rate)/(useful power) [kg/s*kW] versus engine speed in RPM
(4) Thermal efficiency [%] versus engine speed in RPM
(5) Plot each of the following [kW] versus engine speed in RPM:
   a. Rate of fuel energy input
   b. Frictional and inertial losses
   c. Miscellaneous loss rate
(6) Mean Effective Pressure [kPa] versus engine speed in RPM

**DISCUSSION ITEMS:**

1. Discuss the energy balance, comparing the contributions of each energy term to the overall energy balance. Identify the terms that have the greatest and least contributions to the energy out of the system. Do the values of each energy term make sense to you? Are there any surprises when comparing the relative contributions of each term to the energy balance?

2. Discuss trends exhibited by all curves in each graph. Are these trends as expected?

3. Discuss the source of errors that have influenced your results. For unexpected results, hypothesize about what could have caused your values or graphs to produce the results you found.

4. Compare the calculated efficiency with that of an ideal Otto cycle. What assumptions have you made in the air standard analysis that might cause such discrepancies?

5. What would you recommend in order to improve the efficiency of the engine? For example, how would turbo-charging, inner cooling, split-fire spark plugs, and other hardware alterations change the efficiency of the engine?
6. Describe the importance of combustion engines in your day-to-day life. What are their drawbacks? List at least 2 benefits and 2 drawbacks. What would you suggest to mitigate the drawbacks?

7. We understand that combustion engines tend to release greenhouse gases like CO₂ into the environment. Based on your understanding, draw a diagram of carbon lifecycle. What are some other alternative solutions for reducing greenhouse gases emission from combustion engines? List at least 2 alternative solutions.

**Participation:** Describe your participation in the data gathering session. (Did you prepare equations or data sheets beforehand? Did you read or record measurements? Did you operate the equipment?)
LAB 1 – Spark Ignition Engine
Grade Sheet

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| **Introduction**                     | 5        |            |
| Purpose of the lab and objectives described (3) |          |            |
| Relevance to course work and/or real-world applications mentioned (2) |          |            |

| **Results**                          | 37       |            |
| Original data sheet (or clear copy) provided (2) |          |            |
| All data listed in data reduction, with units (10) |          |            |
| Graphs show correct trends, properly labeled, etc. (20) |          |            |
| Sample calculations fully represent calculation methodology (5) |          |            |

| **Discussion**                       | 35       |            |
| #1 (5)                               |          |            |
| #2 (5)                               |          |            |
| #3 (5)                               |          |            |
| #4 (5)                               |          |            |
| #5 (5)                               |          |            |
| #6 (5)                               |          |            |
| #7 (5)                               |          |            |

| **Conclusion**                       | 5        |            |
| Summary includes lessons learned and how the lab objectives were addressed |          |            |

| **Participation description**        | 3        |            |

| **Code and Computational Work**      | 8        |            |
| Original code shows appropriate calculation methods (4) |          |            |
| Printed as an included appendix in full (4) |          |            |

| **Grammar, Style, Neatness, and Clarity** | 4 |            |

**TOTAL:** 100

General comments from TA:
LAB 2 – VAPOR-COMPRESSION REFRIGERATION CYCLE

OBJECTIVES
An analysis of a vapor-compression refrigeration system is to be performed. The primary objectives of this experiment are:
1. To become familiar with an actual refrigeration system designed on the vapor-compression cycle.
2. To determine the coefficient of performance $COP_R$ using the First Law of Thermodynamics.
3. To study the performance of the refrigeration system as a function of refrigerant flow rate.

INTRODUCTION
A Scott air conditioning and refrigeration system, Model 9086, is used to evaluate the operational characteristics of a typical air conditioning and refrigeration system. The system operates on a closed vapor compression cycle with Refrigerant R-134a as the working fluid. The experimental apparatus is comparable to the most common commercial refrigeration and air conditioning systems and can be operated with reverse flow to demonstrate heat pump operation. Five sets of paired temperature and pressure gauges measure the properties of the refrigerant at critical state points in the cycle. By adjusting valves located at strategic positions, the refrigerant mass flow rate may be varied.

A schematic of the refrigeration system is shown in Figure 1 along with a typical $T$-$s$ diagram for an ideal vapor-compression refrigeration cycle. A typical $P$-$h$ diagram for the ideal vapor-compression refrigeration cycle is provided in Figure 2. Referring to the schematic and the actual components in the system, temperature and pressure gauges at five state point locations in the system provide the data shown in Table 1.

<table>
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<tr>
<th>Location</th>
<th>Pressure $P$ (psig)</th>
<th>Temperature $T$ (°F)</th>
</tr>
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<tr>
<td>compressor inlet</td>
<td>$P_1$</td>
<td>$T_1$</td>
</tr>
<tr>
<td>compressor outlet (condenser inlet)</td>
<td>$P_2$</td>
<td>$T_2$</td>
</tr>
<tr>
<td>condenser outlet (expansion valve inlet)</td>
<td>$P_3$</td>
<td>$T_3$</td>
</tr>
<tr>
<td>expansion valve outlet (evaporator inlet)</td>
<td>$P_4$</td>
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</tr>
<tr>
<td>evaporator outlet</td>
<td>$P_5$</td>
<td>$T_5$</td>
</tr>
</tbody>
</table>

Note that two measurement stations for temperature and pressure (locations 1 and 5) are located between the evaporator and compressor at slightly different positions. For the purposes of this experiment, use location 1 to represent both the evaporator outlet and the compressor inlet. Other measurements include refrigerant volumetric flow rate $V$ (gpm), two outlet air temperatures $T_{e1}$ and $T_{e2}$ (°C) from the evaporator and two outlet air temperatures $T_{c1}$ and $T_{c2}$ (°C) from the condenser.
PROCEDURE
Refrigerant flow rate is the primary control variable for this experiment. For steady state conditions at each flow rate (four in total), all dependent variables will be measured and recorded. The TA will be responsible for filling the system with refrigerant before the experiment and returning the refrigerant to its reservoir upon completion. Note that the system uses DuPont 134a refrigerant, which is a more ozone-layer friendly substance than the old R-12 Freon.

1. Spend a few moments prior to running the lab to identify these components:
   a. main power switch S2
   b. compressor
   c. compressor power switch S8
   d. condenser
   e. expansion valve
   f. evaporator
   g. refrigerant volumetric flow meter (gpm)
   h. fan for condenser
   i. fan for evaporator
   j. analog meters at the top of the panel for power into the system (only power $W$ will be used)
k. thermocouples \( T_{c1}, T_{c2}, T_{c1}, \) and \( T_{c2} \) for air temperature measurements at the condenser and evaporator outlets
l. digital thermometer (°C) with switch positions 1 (\( T_{c1} \)), 2 (\( T_{c2} \)), 3 (\( T_{c3} \)), 4 (\( T_{c4} \)), and 5 (\( T_{amb} \)).
m. analog thermometers for \( T_1 - T_5 \) (°F)

2. Make sure power cords (e.g., for the thermocouple meter) are clear of obstructions and that student packs and/or accessories will not cause interference with controls, cords, valves, or switches.

3. Verify that the TA has filled the system with refrigerant. Verify that \( T_2 \) is below, and remains below, 190°F. If \( T_2 \) ever exceeds 190°F, immediately decrease the flow rate in the system by adjusting valve V4.

4. Measure barometric pressure \( P_{amb} \) (mm Hg) and room air temperature \( T_{amb} \). The barometer is located by the front door of the lab. \( T_{amb} \) is provided by a thermocouple located near the inlet of the evaporator and condenser fans. It is read using position 5 on the thermocouple meter to the left of the refrigeration system.

5. Verify that main power switch S2 is on.

6. Verify that the digital thermocouple meter to the left of the apparatus is on.

7. Turn on the evaporator and condenser fans to high if not already on, using the switches labeled Fan Speed Control S5 and S6.

8. Measure the electrical power required for the fans \( \\dot{W}_f \). Record power \( \\dot{W}_f \) (W).


10. Measure the electrical power required for the combined fans and compressor \( \\dot{W}_{f+c} \). Record Power \( \\dot{W}_{f+c} \) (W).

11. Set the volumetric flow rate to 0.2 gpm (maximum) using valve V4 (which requires only a very small amount of valve rotation). Note that the rotameter is read using the center of the spherical float.

12. Allow the system to stabilize for approximately 3 minutes while closely monitoring \( T_2 \). Should \( T_2 \) exceed 190°F, decrease the refrigerant flow rate using valve V4.

13. Record the following data: \( T_{c1}, T_{c2}, T_{c1}, T_{c2}, T_1, T_2, T_3, T_4, T_5, P_1, P_2, P_3, P_4, P_5, W_{f+c}, \) and \( V \).

14. Repeat steps 11 – 13 for volumetric flow rates of 0.15, 0.1, and < 0.1 gpm. The flow rate is changed by slowly closing valve V4.

15. Turn off the compressor with switch S8.

16. Turn off the condenser and evaporator fans with switches S5 and S6, respectively.

17. Inform the TA that the experiment is complete. If necessary, the TA will drain the refrigerant from the system back to the reservoir.

18. Turn off the main power using switch S2.

DATA REDUCTION
Several different quantities are of interest in the analysis of refrigeration cycles. These include enthalpies at all state locations in the cycle, compressor work delivered to the refrigerant, heat loss from the compressor, and the coefficient of performance for the refrigerator \( COP_k \). Perform the following data reduction process for each data set corresponding to the different refrigerant volumetric flow rates.

1. Convert all data recorded in English units to SI units. These include \( T_1 - T_3 \) (from °F to °C), \( P_1 - P_5 \) (from psig to kPa), and \( V \) (from gpm to m³/s). **Note that the data from the pressure gauges must also be converted to absolute pressure.**

2. Compute the average air temperature at the condenser outlet \( T_{c,avg} \) from \( T_{c1} \) and \( T_{c2} \) and the average air temperature at the evaporator outlet \( T_{e,avg} \) from \( T_{e1} \) and \( T_{e2} \).

3. Determine enthalpy for all 5 states of the refrigerant and the absolute pressure (kPa) and temperature (°C) for each state. Note that state 4 is expected to be a saturated mixture. For state 4, \( T \) and \( P \) are not independent, so some other property (such as quality \( x \)) must be used to define the state. Alternatively, the process in the expansion valve can be evaluated to determine state 4. Assuming the expansion process is adiabatic, it can be shown that \( h_3 = h_4 \). **Apply the adiabatic assumption so that you may assume that \( h_4 = h_5 \).**

4. Determine the refrigerant specific volume \( v_3 \) (m³/kg) using \( T_3 \) and \( P_3 \).

5. Determine the mass flow rate of the refrigerant \( \dot{m} \) (kg/s) using the relationship

\[
\dot{m} = \frac{\dot{V}}{v_3}
\] (1)
6. The electrical power supplied to the compressor motor $\dot{W}_c$ can be determined as the difference between the power supplied to the compressors and fans and that supplied to the fans only.

$$\dot{W}_c = \dot{W}_{f+c} - \dot{W}_f$$  \hspace{1cm} (2)

7. The power supplied to the refrigerant by the compressor $\dot{W}_{in}$ is less than the electrical power delivered to the compressor $\dot{W}_c$ because of mechanical losses and losses in translating compressor rotor power to refrigerant power. Introducing mechanical efficiency $\eta_M$ and hydraulic efficiency $\eta_H$ allows one to account for both types of losses in the compressor.

$$\dot{W}_{in} = \eta_M \eta_H \dot{W}_c$$  \hspace{1cm} (3)

For the vapor-compression refrigeration system studied, the product of mechanical and hydraulic efficiencies is $\eta_M \eta_H = 78\%$.

8. Determine the specific work to the refrigerant $w_{in}$ (kJ/kg) using

$$w_{in} = \frac{\dot{W}_{in}}{m}$$  \hspace{1cm} (4)

9. If the compressor were adiabatic, the enthalpy value at the compressor exit would be $h_1 + w_{in}$. However, we know that the compressor can transfer heat to its surroundings. Determine the heat loss from the compressor $q_{loss}$ (kJ/kg) by applying the First Law of Thermodynamics to the device. Assuming steady flow, the energy balance gives

$\text{………………………………………………………………………………………..}$  \hspace{1cm} (5)

10. Determine the heat rejection from the refrigerant in the condenser $q_H$ from an energy balance on the device

$$q_H = h_3 - h_2$$  \hspace{1cm} (6)

and the heat transferred to the refrigerant in the evaporator $q_L$ also from an energy balance as

$\text{………………………………………………………………………………………..}$  \hspace{1cm} (7)

11. Determine $COP_R$ from the enthalpy change across the evaporator and the specific work applied to the refrigerant.

$$COP_R = \frac{q_L}{w_{in}} = \text{……………….}$$  \hspace{1cm} (8)

12. Now, determine the enthalpy at the compressor exit for an isentropic compression process, $h_2s$, assuming state 1 is fixed.

Next, compute the isentropic efficiency of the compressor $\eta_s$ given as isentropic work divided by the actual work to compress from state 1 to state 2. Your energy balance (Equation 5) can also be used to express actual work in terms of measured enthalpy at the compressor exit, $h_2$, and heat loss to the surroundings, $q_{loss}$.

$$\eta_s = \frac{w_s}{w_{in}} = \frac{h_2 - h_1}{h_2 - h_1 + q_{loss}}$$  \hspace{1cm} (10)
PRESENTATION OF RESULTS
1. Tabulate all raw data and all computed quantities for each of the four refrigerant volumetric flow rates.
2. On a single graph, plot refrigerant temperature at the condenser outlet ($T_3$), refrigerant temperature at the evaporator inlet ($T_4$), air temperature exiting the condenser ($T_{c,avg}$), and air temperature exiting the evaporator ($T_{e,avg}$) as functions of refrigerant mass flow rate.
3. On a single graph, plot $q_L$, $q_H$, $q_{loss}$ and $w_{in}$ as functions of $m$.
4. Plot COP as a function of refrigerant mass flow rate.
5. For the greatest refrigerant mass flow rate, plot the actual cycle processes on a $P-h$ diagram using the following method:
   
   Locate the four state points and draw in the process paths on the attached $P-h$ diagram (Fig. 4). Use a color (or colors) other than black when creating the process paths. Note that the enthalpy reference state for the $P-h$ diagram and data in the book are different. Thus, before locating the state points on the diagram, enthalpy values must be adjusted according to the following relationship.
   
   \[ h_{\text{Fig. 4}} = h_{\text{EES or booklet}} + 148.98 \text{ [kJ/kg]} \]  
   
   In other words, add 148.98 to the $h$ values obtained by interpolation using data from the booklet or EES, then locate the values and state points on the $P-h$ diagram.

DISCUSSION ITEMS
1. Discuss the differences between $T_3$ and $T_{c,avg}$ and between $T_4$ and $T_{e,avg}$ and their trends as functions of $m$ in the first plot. Do these data exhibit expected behavior? What physical processes cause the trends shown?
2. Discuss the trends of COP, $w_{in}$, $q_L$, $q_H$, and $q_{loss}$ as functions of $m$. Why do these data change with $m$ as depicted in the plots?
3. Compare the actual cycle with an ideal cycle (as depicted in Fig. 2) operating between the same upper and lower pressures shown on the $P-h$ diagram. Explain the differences between the two cycles, concentrating on the causes for the differences in the 4 processes.
4. Discuss the effect of $m$ on the isentropic compressor efficiency $\eta_c$.
5. Consider the difference between enthalpy values at states 5 and 1, $h_5 - h_1$. What is the reason for any differences noted? How does this effect, translated to the entire cycle, affect the system performance as expressed by COP?
6. What are your suggestions to improve the COP of the system? List at least two suggestions and explain how each of them works.
7. What are some popular refrigerants that used in refrigeration systems? What are their environmental impacts? List at least two refrigerants and two environmental impacts.

REFERENCES
Figure 4. Pressure-Enthalpy Diagram for HFC-134a (SI Units).
# LAB 2 – Refrigeration
## Grade Sheet

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**General comments from TA:**
LAB 3 – COOLING TOWER

OBJECTIVES
This experiment analyzes the operation and performance of a laboratory-size water cooling tower. Performance will be assessed for varying water inlet temperatures. The main objectives of this exercise are:

1. To observe the operation of a water cooling tower.
2. To assess the performance of the cooling tower in terms of its ability to cool hot water.
3. To perform a mass balance and energy balance on the cooling tower.

INTRODUCTION
The cooling tower is a free-standing, open, recycling evaporative cooling device. Its purpose is to cool liquid water, and it does so by two mechanisms. The primary cooling mechanism is through evaporation, in which water undergoes a phase change from a liquid to a vapor. The heat of vaporization is provided by the hot water, which is cooled as a result of this heat loss. The secondary mechanism is a combination of convection and radiation heat transfer from the liquid water to air (and the surroundings in the case of radiation), which is a result of the temperature difference between the two.

The cooling tower operates in a counter-flow mode with the air traveling upward over the downward moving water. In an actual application, the water cooled by the tower is re-circulated to a condenser where it absorbs heat, thereby increasing its temperature before being returned to the cooling tower to complete the cycle. In the present experiment, the condenser (used in industrial applications) is replaced by a set of two individually-controlled water heaters. These heaters along with the inlet water flow and air flow rates can be adjusted so that a fixed temperature is established for the water entering the cooling tower. Also, according to the equipment manual, the amount of heat added to the water due to the water pump is 100 W.

The cooling tower is equipped with thermocouples, a flow meter, and a manometer so that all quantities contributing to both mass and energy balances can be measured. Control variables include air flow rate, water flow rate, and heating rate. These variables will all contribute to the inlet water temperature. Cooling tower performance will be evaluated primarily as a function of inlet water temperature. Schematic diagrams of the cooling tower are shown in (figs. 1 – 3). The water flow loop is shown in (fig. 1). The air distribution system, including a fan and an orifice, and temperature measurement locations, are shown in (fig. 2). The primary controls for system operation are shown in (fig. 4).

PROCEDURE
Cooling tower operation requires the control of three different sub-systems: (1) the water supply, (2) the air flow, and (3) water heaters. The water loop will be started at a constant flow rate of approximately 40 g/s by either the lab technician or the TA and will be varied later in the lab. The pump is turned on by the main switch (fig. 4). A volumetric flow meter (shown in figs. 1 and 4) provides a measurement of the water flow rate to the cooling tower. The flow is controlled by the valve on top of the meter.

The fan is also started with the main switch (fig. 4). The air flow entering the fan can be adjusted using the intake damper (fig. 2). In this experiment the damper should be set so the orifice at the outlet of the
**tower has a pressure difference of 10 mmHg.** This pressure difference can be read with the manometer (fig. 4) on the control panel by attaching the long hose to the top pressure tab on the tower (fig. 3).

Water collected in a basin beneath the cooling tower is pumped back to the main water tank. In the main tank there is a 0.5 kW heater and a 1.0 kW heater giving options of 0.5 kW, 1.0 kW, and 1.5 kW to heat the water. These heaters can be controlled by switches on the control panel (fig. 4). The heaters can be used to adjust the water inlet temperature. **In this experiment the heaters will be set to 1.5 kW the entire time.**

The water inlet temperature ($T_5$ on the temperature indicator on the control panel) should never exceed 50°C (122°F). Thermocouples for water inlet and outlet along with air inlet and outlet wet and dry bulb temperatures are connected to a multi-point (push button) digital temperature indicator located on the control panel. The wet bulb reservoirs will have already been filled with water by either the TA or the lab technician. Channels and corresponding temperatures for the indicator are:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Symbol</th>
<th>Position</th>
<th>Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$T_1$</td>
<td>Air inlet (A)</td>
<td>Dry-bulb temperature</td>
</tr>
<tr>
<td>2</td>
<td>$T_2$</td>
<td></td>
<td>Wet-bulb temperature</td>
</tr>
<tr>
<td>3</td>
<td>$T_3$</td>
<td>Air outlet (B)</td>
<td>Dry-bulb temperature</td>
</tr>
<tr>
<td>4</td>
<td>$T_4$</td>
<td></td>
<td>Wet-bulb temperature</td>
</tr>
<tr>
<td>5</td>
<td>$T_5$</td>
<td>Water inlet</td>
<td>Water temperature</td>
</tr>
<tr>
<td>6</td>
<td>$T_6$</td>
<td>Water outlet</td>
<td>Water temperature</td>
</tr>
</tbody>
</table>

Water and dry and wet bulb temperatures for air will be measured at three locations inside the cooling tower (F, G, H in fig. 3) using a temperature indicator mounted on the side of the column. Channels and corresponding temperatures for the side mounted temperature indicator are:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Symbol</th>
<th>Position</th>
<th>Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$t_1$</td>
<td>H ($H_t = 71.8$ cm)</td>
<td>Air, wet-bulb</td>
</tr>
<tr>
<td>2</td>
<td>$t_2$</td>
<td></td>
<td>Air, dry-bulb</td>
</tr>
<tr>
<td>3</td>
<td>$t_3$</td>
<td></td>
<td>Water</td>
</tr>
<tr>
<td>4</td>
<td>$t_4$</td>
<td>G ($H_t = 48.3$ cm)</td>
<td>Air, wet-bulb</td>
</tr>
<tr>
<td>5</td>
<td>$t_5$</td>
<td></td>
<td>Air, dry-bulb</td>
</tr>
<tr>
<td>6</td>
<td>$t_6$</td>
<td></td>
<td>Water</td>
</tr>
<tr>
<td>7</td>
<td>$t_7$</td>
<td>F ($H_t = 24.8$ cm)</td>
<td>Air, wet-bulb</td>
</tr>
<tr>
<td>8</td>
<td>$t_8$</td>
<td></td>
<td>Air, dry-bulb</td>
</tr>
<tr>
<td>9</td>
<td>$t_9$</td>
<td></td>
<td>Water</td>
</tr>
</tbody>
</table>

Note that in the write-up lower case $t$ refers to temperature readings on the side mounted indicator and upper case $T$ refers to temperature readings on the indicator on the control panel.

The procedure for establishing the desired test conditions and conducting the data acquisition follows. State points for the air outlet and inlet, liquid water outlet and inlet, and air/water vapor mixture are identified in Figs. 1-3.

1. Make sure make up tank is filled to the mark. Check make up tank frequently.
2. Set the air damper so the orifice differential pressure is approximately 10 mmHg.
3. Make sure both heaters are on so there is 1.5 kW of heat.
4. Adjust the flow valve so the water inlet flow rate is approximately \( g/s \). When changing the flow rates it may take 10 to 15 minutes to reach steady state. Check the flow rate indicator and adjust it if necessary to maintain a steady flow rate.

5. Record the following data.
   a) Barometric pressure \( P_{\text{amb}} \) (mm mercury) using the barometer next to the door of the lab.
   b) Water temperature at the cooling tower inlet \( T_3 \) and outlet \( T_6 \) using the indicator on the control panel.
   c) Water flow rate into the cooling tower using the flow meter.
   d) Dry bulb temperatures \( (t_2, t_3, t_6) \) and wet bulb temperatures \( (t_1, t_4, t_7) \) of the air/water vapor mixture along with water temperatures \( (t_5, t_8, t_9) \) within the cooling tower at the three different vertical positions (F, G, H; fig. 3) using the temperature indicator mounted on the side of the column.
   e) Dry bulb temperatures \( (T_1 \) and \( T_3 \) and wet bulb temperatures \( (T_2 \) and \( T_4 \) of the air/water vapor mixture at the inlet (A) and exit (B) of the cooling tower using the digital temperature indicator on the control panel.
   f) Difference from ambient pressure and the bottom pressure tap using the manometer at the inlet of the tower: \( \Delta P_A \)
   g) Orifice differential pressure using the manometer at the outlet of the tower, \( \Delta P_B \) (should be about 10 mmH\(_2\)O as stated above)

6. Repeat steps 5(b)-5(g), for water inlet flow rates of \( g/s \) and \( g/s \). Wait for temperatures to stabilize before recording. This can take 10 to 15 minutes. Do not adjust the air damper or the heater settings.

7. Turn off the heaters using the switches on the control panel.
8. Turn of the main switch.
9. Further system shut-down procedures will be conducted by the TA or the lab technician.

DATA REDUCTION
The following data reduction process should be completed for each data set corresponding to the three water inlet flow rates. Refer to figs. 1-3 for temperature locations. Assumptions and idealizations for this analysis include: the system is operating at steady state, changes in potential and kinetic energy are negligible, the dry air and water vapor are ideal gases, total pressure for the air/water vapor mixture within the cooling tower is equivalent to the measured atmospheric pressure, and properties of compressed liquid water can be approximated using properties at the saturated liquid state at the same temperature.

1. Determine the mass flow rate of dry air using the following procedure.
   a. Use the attached psychrometric chart (for ambient pressure \( \frac{P_{\text{amb}}}{T} = 84.6 \text{kPa} \)) or EES to determine the specific volume \( (\nu) \), relative humidity \( (\phi) \), and absolute humidity \( (\omega) \) at the tower inlet (A) and outlet (B).
   b. Determine the saturation pressure of the water vapor \( P_{vA} \) at temperature \( T_1 \) and \( P_{vB} \) at temperature \( T_3 \) from the following general correlation for water [1].

\[
\nu = 22.064 \times 10^3 \exp \left\{ 647.096 / T \ast \left( -7.85951783 \xi + 1.84408259 \xi^{3.5} - 11.7866497 \xi^3 \\
+ 22.6807411 \xi^{3.5} - 15.9618719 \xi^4 + 1.80122502 \xi^{7.5} \right) \right\}
\]

with \( T \) in (K) and \( P_s \) in (kPa) and \( x = 1 - T/647.096 \).

c. Determine the absolute humidity \( (\omega) \) at the tower inlet (A) and outlet (B) using the appropriate relationship from [2].
\[
\omega_a = \frac{0.622 \phi P_{\Delta \phi A}}{P_A - \phi A_{g A}} \quad \text{and} \quad \omega_b = \frac{0.622 \phi P_{\Delta \phi B}}{P_B - \phi B_{g B}}
\]  

(2)

Compare these values with the values found using the attached psychrometric chart.

d. Use Amagat’s law of additive volume to compute the air/water vapor mixture specific volume \( \nu_1 \) (m\(^3\)/kg dry air) from the following equation, which was derived by dividing the total volume by \( \dot{m}_a \) [3]:

\[
\nu_A = \nu_{a A} + \omega_A \nu_{v A} \quad \text{and} \quad \nu_B = \nu_{a B} + \omega_B \nu_{v B}
\]  

(3)

The specific volume (m\(^3\)/kg) for dry air \( \nu_a \) and for the water vapor \( \nu_v \) at the tower inlet (A) and outlet (B) from the ideal equation of state and the appropriate values of pressure and gas constant [1]:

\[
\nu_{a A} = \frac{R_A T_1}{P_A} \left( \text{or} \quad \nu_{v A} = \frac{R_A T_1}{P_A} \right) \quad \text{and} \quad \nu_{a B} = \frac{R_A T_1}{P_B} \left( \text{or} \quad \nu_{v B} = \frac{R_A T_1}{P_B} \right)
\]  

(4)

where the gas constant for air \( R_a = 0.287 \text{ kPa·m}^3/\text{kg·K} \) and the gas constant for water vapor \( R_v = 0.4615 \text{ kPa·m}^3/\text{kg·K} \). It should be noted that \( P_A \) and \( P_B \) are the pressure of the air/water vapor mixture at the inlet and outlet of the tower, respectively, and can be expressed as \( P_A = P_{amb} + \Delta P_A \) and \( P_B = P_{amb} + \Delta P_B \), where \( \Delta P_A \) and \( \Delta P_B \) are measured pressure values with the manometer.

Compare these values with the values found using the attached psychrometric chart.

f. Use the orifice calibration below to calculate the mass flow rate of dry air.

\[
\dot{m}_a = 0.0137 \sqrt{\frac{\Delta P_B}{(1 + \omega_B) \nu_B}}
\]  

(5)

where \( \Delta P_B \) is the orifice pressure differential in mmH\(_2\)O, \( \omega_B \) is the absolute humidity at the tower exit, and \( \nu_B \) is the specific volume of the air/water vapor mixture leaving the tower.

2. Use the water property tables in [2] or EES to determine the specific enthalpy of the liquid water at the tower inlet (5) and outlet (6).

3. Use the attached psychrometric chart or EES to determine the absolute humidity \( \omega \) for the 3 state points within the tower (F, G, H) associated with the air/water vapor mixture.

4. Determine the mass flow rate of water vapor at states A and B, \( \dot{m}_{v A} \) and \( \dot{m}_{v B} \) (kg/s), using the following equation (shown for state A):

\[
\dot{m}_{v A} = \omega_A \dot{m}_a
\]  

(7)

5. Determine the enthalpy of the air/water vapor mixture at states A and B, \( h_A \) and \( h_B \) (kJ/kg), from the following equation (shown for state A):

\[
h_A = c_p T_1 + \omega_A h_{g A}
\]  

(8)

where \( c_p = 1.005 \text{ kJ/kg-K} \) for dry air, \( T_1 \) (°C) and \( h_{g A} \) (kJ/kg) can be approximated by
\[ h_{sA} = 2500.9 + 1.82T_1 \quad (T_1 \text{ in } ^\circ\text{C}) \]

Also, determine these values of enthalpy using the attached psychrometric chart and compare them to your results using eq. (8) above.

6. Determine the mass flow rate of liquid water exiting the cooling tower at state 6, \( \dot{m}_6 \) (kg/s), by applying the mass conservation of water vapor and of liquid water in the cooling tower. Use the calculated values above.

7. Determine the required mass flow rate of makeup water, \( \dot{m}_{\text{makeup}} \) (kg/s), to the main tank by applying conservation of mass (rate form) on the liquid water in the tank. Use the calculated values above for this.

8. Determine the total heat gain of the air, \( \dot{Q}_{\text{air}} \) (kW), as it passes through the tower and compare this result to the total input power of the setup. Note that the pump input is approximately 100 W.

\[ \text{PRESENTATION OF RESULTS} \]

1. Tabulate all raw data and variables from the previous section for each of the three cooling tower water inlet flow rates.

2. On the same graph, plot absolute humidity as a function of cooling tower height (4 positions; A, F, G, H) for all three water inlet flow rates. (A = 0 cm, F = 24.8 cm, G = 48.3 cm, H = 71.8 cm)

3. On the same graph, plot dry bulb temperature as a function of cooling tower height (4 positions; A, F, G, H) for all three water inlet flow rates.

4. Plot the ratio of the water outlet mass flow rate \( \dot{m}_6 \) to water inlet mass flow rate \( \dot{m}_5 \) as a function of \( T_5 \).

5. Plot \( \dot{Q}_{\text{air}} \) and \( \dot{Q}_{\text{amb}} \) as a function of \( T_5 \).

\[ \text{ITEMS FOR DISCUSSION} \]

1. Discuss how \( \omega \) changes with height \( H_5 \) within the cooling tower. What type of trend is exhibited for \( \alpha(H_5) \)?

2. Discuss the changes in air/water vapor dry bulb temperature with height \( H_5 \) within the cooling tower. What type of trend is exhibited for dry bulb temperature?

3. How do the trends for the dry bulb temperature and absolute humidity as a function of height compare with each other? Describe briefly what happens to the air passing through the tower from A to B.

4. Discuss the effect that \( T_5 \) has on \( \dot{m}_6 \) and \( \dot{m}_{\text{makeup}} \). Provide a physical explanation for the exhibited trend.

   Is there a connection to the change in absolute humidity (\( \omega_B - \omega_A \)) for the air/water vapor mixture?

5. Discuss how \( \dot{Q}_{\text{amb}} \) is affected by changes in \( T_5 \). Provide a physical explanation for the effect.

6. Discuss environmental impacts of cooling towers and possible solutions to reduce the environmental impact. List at least two impacts and two solutions.
REFERENCES

Footnotes:
1. In Amagat’s model, component $T = \text{mixture } T$, component $P = \text{mixture } P$, mixture volume = sum of component volumes. This model is used because in Lab 3 the mixture $P$ is easy to measure.
2. The mixture specific volume, $v$ in Eq. (5), is defined as: mixture volume/mass of dry air.

Figure 1. Cooling Tower Water Loop.
Figure 2. Cooling Tower Air Path
Figure 3. Tower Column

Figure 4. Control Panel
# LAB 3 – Cooling Tower
## Grade Sheet

<table>
<thead>
<tr>
<th>Category</th>
<th>Possible</th>
<th>Your Score</th>
</tr>
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<tr>
<td><strong>Format</strong></td>
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<td>According to Lab Syllabus: Spacing, headings, grade sheet attached, etc.</td>
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<td>Purpose of the lab and objectives described (2)</td>
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<tr>
<td>Relevance to course work and/or real-world applications mentioned (2)</td>
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<td>Original data sheet (or clear copy) provided (2)</td>
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<td>All data listed in data reduction, with units (10)</td>
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<td>Graphs show correct trends, properly labeled, etc. (20)</td>
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<td>Sample calculations fully represent calculation methodology (5)</td>
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<tr>
<td><strong>Conclusion</strong></td>
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<td>Summary includes lessons learned and how the lab objectives were addressed</td>
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<td></td>
<td>3</td>
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**General comments from TA:**
LAB 4 – PROPANE BURNER

OBJECTIVES
This experiment considers the operation and analysis of a combustion process in a gas burner using propane (C₃H₈) as the fuel. The three main objectives are:
1. To calculate performance characteristics of the actual combustion process and compare these to theoretical values,
2. To analyze the composition of the combustion products using a gas analyzer, and
3. To observe the operation and performance of a gas burner.
Laboratory measurements and subsequent data reduction provide 1) an assessment of the chemical components in the combustion products, 2) a volumetric analysis of combustion products CO, CO₂ and O₂, 3) the air/fuel ratio, 4) the theoretical heat transfer per kmol of fuel for the combustion process, and 5) the flame temperature. These experimental data will be compared to theoretical values of the same quantities, except for measured flame temperature, which will be compared to the theoretical adiabatic flame temperature.

INTRODUCTION
The combustion process in the laboratory gas burner is similar to those in devices such as gas turbines, turbofans, ramjets, and rockets. A number of engineering parameters are important in the performance analysis of these devices including enthalpy of combustion, heat transfer, and flame temperature. When no heat transfer occurs from the combustion chamber to the surroundings, the temperature of the combustion products reaches a maximum, referred to as the adiabatic flame temperature. The maximum adiabatic flame temperature is greatest for complete combustion with stoichiometric (theoretical) air.

PROCEDURE
The experiment apparatus consists of a blower, an instrumented propane gas burner with orifice plate and thermocouples, a gas analyzer containing electrochemical O₂ and CO sensors (CO₂ is calculated by the analyzer), and an exhaust fan. Manual controls for the combustor system are located on 1) the system control panel (the SYSTEM POWER switch and the gas flow rate control valve labeled “M” on the bottom of the volumetric flow meter), 2) the panel adjacent to the air blower (blower on/off switch), 3) the blower (rotating speed control), 4) the propane tank outlet (gas shut-off valve) and 5) the west wall of the laboratory (on/off switch for the exhaust fan). An autonomous burner control system evaluates burner performance and will shut off the gas and air delivery systems should flame burn-out be detected. Electronics for the burner control system are located on the system control panel. Five chromel-alumel Type-K thermocouples on the burner measure the flame temperature. Locations of all burner components, including the five thermocouples, are given in Table 1.

Table 1. Burner component locations

<table>
<thead>
<tr>
<th>Component</th>
<th>Distance from burner outlet (cm)</th>
<th>Distance from fuel inlet (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T/C 1</td>
<td>7.62</td>
<td>44.45</td>
</tr>
<tr>
<td>T/C 2</td>
<td>15.24</td>
<td>36.83</td>
</tr>
<tr>
<td>T/C 3</td>
<td>27.86</td>
<td>24.21</td>
</tr>
<tr>
<td>T/C 4</td>
<td>30.48</td>
<td>21.59</td>
</tr>
<tr>
<td>T/C 5</td>
<td>38.10</td>
<td>13.97</td>
</tr>
<tr>
<td>Flame sensor</td>
<td>34.29</td>
<td>17.78</td>
</tr>
<tr>
<td>Spark plug</td>
<td>43.18</td>
<td>8.89</td>
</tr>
<tr>
<td>Fuel inlet</td>
<td>52.07</td>
<td>0.00</td>
</tr>
<tr>
<td>Orifice meter</td>
<td>76.84</td>
<td>-24.77</td>
</tr>
</tbody>
</table>
The procedure for the complete experiment follows.
1. Spend a few moments prior to running the lab to identify these components:
   a. Blower and blower speed control
   b. Propane tank with shut-off valve
   c. Gas burner pipe, flame control, and temperature readout panel
   d. Gas analyzer mounted adjacent to inclined liquid manometer
   e. Exhaust fan and switch
   f. Tachometer for fan speed (RPM)
2. Measure the room temperature and barometric pressure in the laboratory.
3. Your TA will replace the gas analyzer filter. The filter holder is a transparent cylinder on the gas analyzer pipe. Old filters should not be replaced. (The filter only needs to be replaced once per day before the first lab).
4. The TA will check for water in the water trap below the gas analyzer filter. If water is present, the TA will open the filter holder to empty the water from the trap.
5. Turn the gas analyzer on by pressing the ON/OFF button.
6. Turn on the propane tank valve (counter-clockwise). It should read about 80 psi. Do not adjust the regulator valve.
7. Turn the exhaust fan on, using the right-most rotary switch on the wall.
8. Verify that all personnel are clear of the flame-end of the burner and behind the guard rails.
9. Turn burner system power on using the SYSTEM POWER switch on the control panel by the burner. This initiates an automatic flame ignition sequence similar to that used in a gas home-heating furnace. The sequence takes 15-30 sec before flame emerges from the end of the burner:
   a. The blower turns on automatically.
   b. Propane gas is admitted to the burner.
   c. An automatic lighter ignites the flame.
   d. The propane is automatically turned off if the flame burns out or fails to ignite.
10. If the red light on the burner controller is lit, press the reset button on the controller to restart the blower and automatically ignite the flame.
11. The “fuel pressure” gauge should read approximately 65 psi. If it is not 65 psi, pull out and then turn the knob and adjust until 65 psi is read on the gauge.
12. Fuel flow in the flow meter on the burner control panel should be approximately 5.75 L/min maximum. If necessary, adjust the flow rate to the desired value.
13. Adjust the blower speed to the desired value. Blower speed (RPM) is read on the analog meter above the blower speed controller. Do not exceed 2000 RPM or the flame might be extinguished. Do not adjust the speed control if the blower is not running.
14. Allow approximately one minute for the system to stabilize. Then record the following data:
   a. Orifice pressure drop in the burner tube (in \( \mathrm{H}_2\mathrm{O} \)) using the inclined manometer on the burner control panel.
   b. Fuel flow rate (L/min) using the volumetric flow meter on the burner control panel.
   c. Temperatures at 5 locations from the burner propane inlet to the outlet using the “Omega Digicator” at the top of the burner control panel.
   d. Combustion products CO, CO\(_2\), and O\(_2\) from the gas analyzer mounted adjacent to inclined liquid manometer (average of several readings).
15. Repeat steps 15 and 16 for 3 other blower speeds (2000 RPM or less).
16. Shutoff the system with the following actions.
   a. While the blower and flame are still operating, decrease the blower speed to a minimum.
   b. Turn the SYSTEM POWER switch on the control panel to “off.” This turns the blower and flame off.
   c. Turn off the gas analyzer by pressing the ON/OFF button.
   d. Close the main valve on the propane tank.
   e. Turn off the exhaust fan.

**DATA REDUCTION**
For each of the four data sets, complete the following data reduction procedure.
1. Convert propane volumetric flow rate \( \dot{V}_{C_3H_8} \) (L/min) to mass flow rate \( \dot{m}_{C_3H_8} \) (kg/s) using the standard density of propane at 1 atm and room temperature (\( \rho_{C_3H_8} = 1.81 \text{ kg/m}^3 \)) using the necessary unit conversions. The flowmeter has been calibrated to produce a flow rate in terms of this standard density.
\[ m_{\text{C3H8}} = V_{\text{C3H8}} \rho_{\text{C3H8}} \quad (1) \]

2. Determine the air mass flow rate \( m_{\text{air}} \) (kg/s) using the following relationship applicable to an orifice meter.

\[ m_{\text{air}} = C_d A \sqrt{\frac{2}{\gamma \rho}} \Delta P \quad (2) \]

where \( \Delta P \) = pressure drop across the orifice plate (Pa), \( \rho \) = density of air assuming an ideal gas (kg/m³), \( A \) = cross-sectional area of the orifice plate hole (m²), \( \gamma \) = expansion coefficient to account for compressibility of the air, \( X_3 \) = discharge coefficient.

For this orifice meter, recommended values for the empirical constants are \( X_3 = 0.64 \) and \( \gamma = 0.95 \). The orifice plate hole diameter is \( A_o = 5.72 \) cm (for calculation of \( A \)).

3. Determine the experimental air/fuel ratio \( A_{\Phi_{\text{exp}}} \) using data from parts 1 and 2.

4. Write out and balance the chemical reaction equation for the combustion process. Assume an incomplete combustion process such that the products consist of CO₂, CO, O₂, N₂, and H₂O. Assume that the combustion products are dry (no H₂O) when analyzed. Note that the unmeasured products, which can be combined in the analysis into the N₂ volumetric fraction. The final form of the chemical reaction equation should have the stoichiometric coefficients expressed in terms of kmol/kmol of C₃H₈.

With the assumptions given in the previous paragraph, the **chemical reaction equation** is written

\[
a C_3H_8 + b (O_2 + 3.76 N_2) \rightarrow x CO_2 + \delta CO + \phi N_2 + \gamma H_2O \quad (3)
\]

Recall that volumetric percentage is equivalent to mole fraction for each species. Assuming 100 kmol of measured products, \( x, \delta, \) and \( \gamma \) are known and equivalent to the measured volumetric percentages of CO₂, CO, and O₂, respectively. Mass balances on C, H, and O will provide \( a, \gamma, \) and \( b \), respectively. Given the assumptions and the fact that the measurements of volumetric percentages of product gases are not perfect, it is unlikely that the combustion equation can be perfectly balanced as in a textbook problem. Since the measured products are assumed to be dry, \( \gamma \) can then be determined by noting that \( x + \delta + \gamma = 100 \). The number of kmol of N₂ determined from the volumetric analysis (\( \phi \) will most likely not be equal to the number of kmol of N₂ in the reactants (3.76\( \beta \)). Regardless, use this “unbalanced” reaction equation in your analysis.

5. Determine the error (%) in the reaction equation by comparing the moles of N₂ in the products to that in the reactants (basis for comparison).

6. Determine the theoretical air/fuel ratio, \( A_{\Phi_{\text{theory}}} \) using data from the reaction equation in part 4. Compute the percentage difference between \( A_{\Phi_{\text{theory}}} \) and \( A_{\Phi_{\text{exp}}} \) using \( A_{\Phi_{\text{exp}}} \) as the base.

7. Determine the percent of excess air, \( E_A \), for the reaction from the results of part 4 and the stoichiometric reaction equation for C₃H₈.

8. Determine the heat transfer, \( Q_{\text{out}} \) per kmol of C₃H₈ that would occur from a combustion chamber for the reaction analyzed assuming that a) the air and reaction products are ideal gases, b) the flow is steady, c) all of the reactants enter the combustion chamber at 25°C and 1 atm, d) there is no work, and e) all of the products are at the measured maximum flame temperature. The energy balance for the steady flow combustion process is

\[
Q_{\text{out}} = \sum N_j \left( h_j^o + \bar{h} - \bar{h}^o \right) \rho_j \left( h_f + \frac{-y}{h} - \bar{h} \right) \quad (4)
\]

9. Determine the adiabatic flame temperature, \( T_{\text{ad}} \) from eq. (4) assuming a) \( \Theta_{\text{exp}} = 0 \) and b) that all reactants enter the combustion chamber at 25°C and 1 atm. The evaluation of \( T_{\text{ad}} \) requires iteration when working with data from the textbook.
10. Determine adiabatic flame temperatures, \( T_{\text{ad},100} \) and \( T_{\text{ad},140} \), assuming complete combustion with 100\% and 140\% theoretical air. Use the stoichiometric reaction equation from part 7 for these calculations.

PRESENTATION OF RESULTS
1. Tabulate all raw data and calculated variables for each of the four values of \( A\Phi_{\xi,60} \).
2. On a single graph, plot the flame temperature, \( T_{\text{bituq}(\xi)} \), as a function of the location within the flame \( \xi \) for all four air/fuel ratios.
3. On a single graph, plot \( A\Phi_{\xi,60} \) and \( A\Phi_{\text{cpoqpy}} \) as functions of percent excess air \( EA \).
4. Plot measured maximum flame temperature \( T_{\text{bituq,macz}} \) as a function of \( A\Phi_{\xi,60} \). On the same graph, plot adiabatic flame temperatures \( T_{\text{ad}, T_{\text{ad},100}}, \) and \( T_{\text{ad},140} \).
5. Plot \( \Theta_{\text{macz}} \) as a function of \( A\Phi_{\xi,60} \).

ITEMS FOR DISCUSSION
1. Discuss the change if flame temperature with distance from the burner. Is the trend reasonable? Explain the physical process that produces the trend.
2. Discuss the trend exhibited by \( A\Phi_{\xi,60} \) with \( EA \). Does this trend seem reasonable? Provide a physical explanation for the trend. Discuss the differences between \( A\Phi_{\xi,60} \) and \( A\Phi_{\text{cpoqpy}} \) using the percentage difference data. Does the difference change with \( EA \)? Present physical reasons for the differences noted.
3. Discuss the change in \( T_{\text{bituq,macz}} \) as a function of \( A\Phi_{\xi,60} \). Provide an explanation for the trends noted.
4. Compare \( T_{\text{bituq,macz}}, T_{\text{ad}, T_{\text{ad},100}}, \) and \( T_{\text{ad},140} \). Provide a physical rationale for the relative magnitudes of each. Why are the measured flame temperatures different from each of the theoretical flame temperatures?
5. Discuss the trend of \( \Theta_{\text{macz}} \) as a function of \( A\Phi_{\xi,60} \). Provide a physical explanation for this trend.
6. Discuss the error in the reaction equation and provide an explanation for the sources of this error.
7. Besides the combustion products that we measured in the experiment, what are some other emission products from combustion systems? List at least 3 products. What are their potential environmental impacts from combustion products and how to improve the situation?

REFERENCES
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General comments from TA: