

## **2006-681: LABORATORY-SCALE STEAM POWER PLANT STUDY -- RANKINE CYCLER EFFECTIVENESS AS A LEARNING TOOL AND A COMPREHENSIVE EXPERIMENTAL ANALYSIS**

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# Laboratory-Scale Steam Power Plant Study – Rankine Cyclers™ Effectiveness as a Learning Tool and a Comprehensive Experimental Analysis.

## Abstract

The *Rankine Cyclers*™ steam turbine system, produced by Turbine Technologies, Ltd., is a table-top-sized working model of a fossil-fueled steam power plant. It is widely used by engineering colleges around the world.

This is the second paper about the *Rankine Cyclers*, continuing the work started in 2004-05. In the first paper two important objectives were met. First, to determine the effectiveness of the *Rankine Cyclers* as a learning tool, an indirect assessment was performed (i.e., a measure of student opinion). The results were positive. Second, a parametric study of the effects of component losses on *Rankine Cyclers* thermal efficiency was performed. The results showed that the range of component losses used in the parametric study accurately reflect experimental thermal efficiencies, and pointed to future experimental work.

For this paper, two more objectives are met, contributing to the conclusions and recommendations from the first paper. First, a direct assessment (and further indirect assessment) of the *Rankine Cyclers* as a learning tool is performed. Student's laboratory reports were evaluated, so that ultimately the equipment can be used in the undergraduate curriculum in the best possible manner.

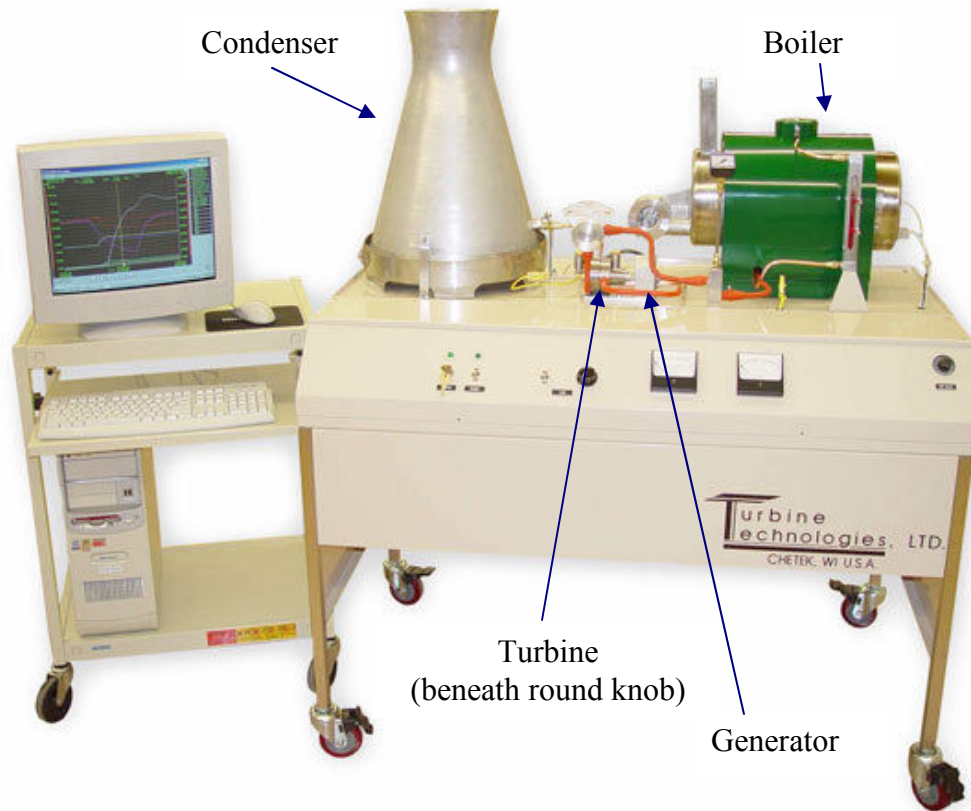
Inevitably, when a power generation plant is scaled-down and it has few efficiency-enhancing components (e.g. lack of feedwater heaters, etc.), energy losses in components will be magnified, substantially decreasing the cycle efficiency. Although the *Rankine Cyclers* is a useful tool for teaching fundamentals of thermodynamics, fluid mechanics, heat transfer, and instrumentation systems in an undergraduate laboratory, a comprehensive analysis of the equipment had not been completed. This analysis can be useful to faculty and students who use the equipment and can also be useful to potential customers of Turbine Technologies. Therefore, as a second objective, faculty and students at two different universities have continued a comprehensive analysis of the *Rankine Cyclers*. Significant experimental work was performed to characterize the *Rankine Cyclers*. Multiple steady state runs were performed to determine the optimum operating point (i.e., load at which turbine/generator performance is optimum). Also, methods for accurately measuring steam flow were studied. Finally, future work is outlined to complete a characterization of the Rankine Cyclers.

## 1. Introduction

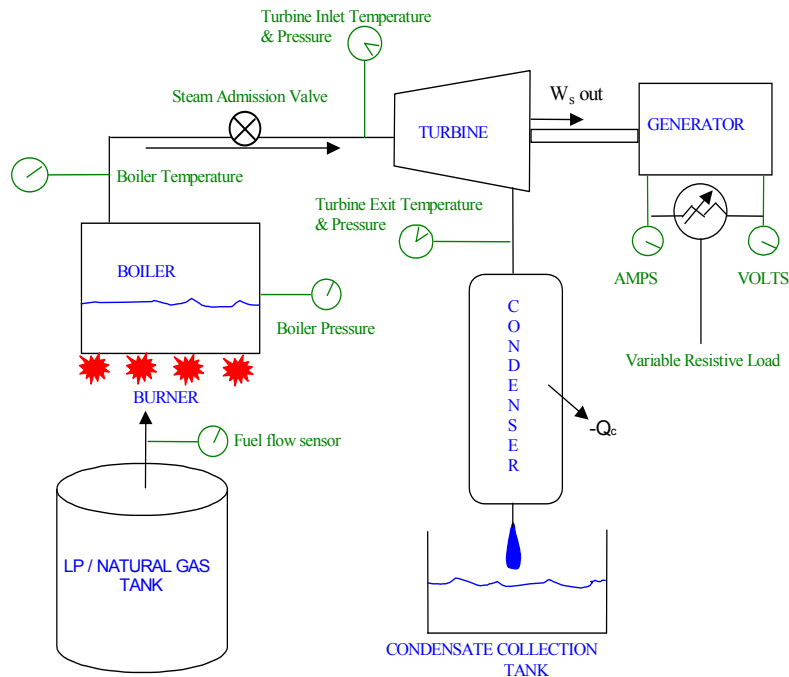
At colleges around the world, each mechanical engineering student is required to learn something about the thermodynamic cycle known as the Rankine cycle. Plants using this cycle with steam as the working fluid produce the majority of the electricity in the U.S. For many students, this is simply a pencil-and-paper exercise, and only ideal or theoretical Rankine cycles are analyzed. Therefore, unfortunately, many mechanical engineering graduates have only a vague understanding of this nearly ubiquitous method of power generation.

One of the best ways to enhance student learning about the steam power cycle is to visit an actual power plant and perhaps analyze some data from the plant. Many students do not have the option of visiting a power plant (because of location, time, or class size constraints), so the next best option is to operate a working model of a steam power plant in a laboratory. There are various arrangements of educational steam power generating laboratory models available, but all but one of these operate with a reciprocating piston engine instead of a turbine. These educational units employing a piston are very costly and often too large for many university laboratories. The “Rankine Cyler™”, produced by Turbine Technologies Ltd. of Chetek, Wisconsin (hereinafter called the “RC”), is a tabletop steam-electric power plant that looks and behaves similarly to a real steam turbine power plant (see Figure 1). It also has the advantage of relatively low-cost. About the size of an office desk, the plant contains three of the four major components of a modern, full-scale, fossil fuel fired electric generating station: boiler, turbine, and condenser. Using only propane and water, the plant will actually generate electricity. Note that the RC does not operate in a true cycle (there is no pump); it is a once-through unit (see Figure 2). Nonetheless, many of the key issues regarding steam power generation are illustrated by the device.

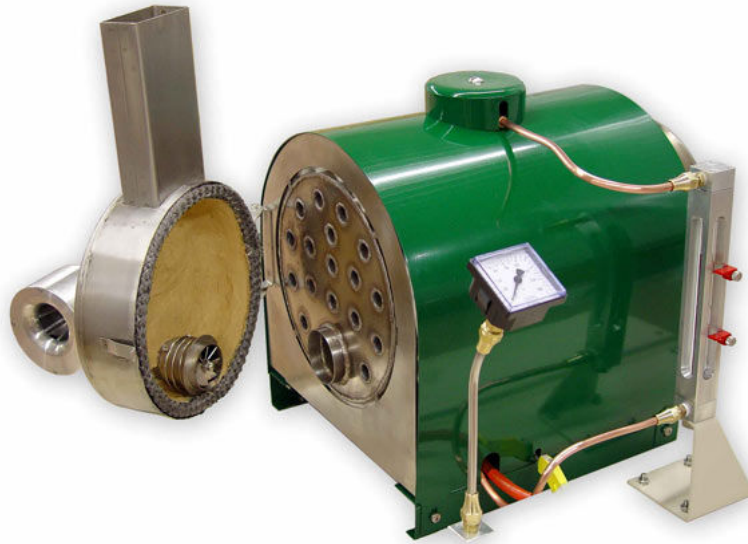
The RC is outfitted with sensors to measure key properties. The data is displayed in real time on a computer so that students can instantaneously observe the behavior of the plant under differing scenarios. The unit operates by burning propane to convert liquid water into high pressure, high temperature steam (over 450°F and 120 psia) in a constant volume boiler (see Figure 3). The steam flows into a turbine causing it to spin (see Figure 4). The turbine is attached to a generator which produces electricity when spun. The generator can produce up to approximately 4 Watts. The steam, after it has used up some of its energy to spin the turbine/generator, leaves the turbine and flows into a condenser which operates at atmospheric pressure and condenses about 1/6<sup>th</sup> of the steam into liquid water. The remaining steam is vented to the atmosphere. Because of the small scale of the unit, overall efficiency is inherently very low (on the order of a few hundredths of one percent).



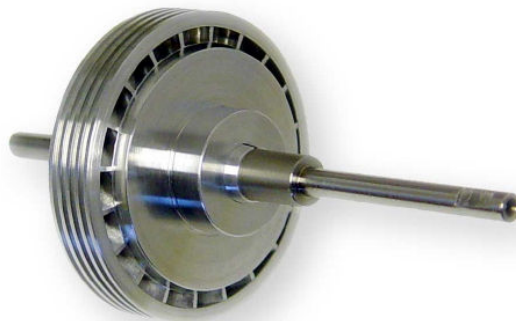
**Figure 1. The Rankine Cycler. Note that newer models include a USB port data acquisition system and laptop computer that is mounted to the tabletop<sup>1</sup>.**



**Figure 2: Schematic of the Rankine Cycler<sup>1</sup>.**



**Figure 3. The dual pass, flame-through tube type (constant volume) boiler, with super heat dome<sup>1</sup>. See Appendix A for more details.**



**Figure 4. Axial flow impulse steam turbine outside of its casing<sup>1</sup>. See Appendix A for more details.**

#### A. Previous Study and Current Objectives

Lawrence Technological University (LTU) and the University of Evansville (UE) want to ensure that each graduating mechanical engineer has a good understanding of power generation. To accomplish this goal, both schools use the *Rankine Cyclor* in an upper-level laboratory course, and have initiated a comprehensive study of the effectiveness of the RC. This is the second paper, continuing the work started in 2004-05. In the first paper<sup>2</sup>, two important objectives were met. First, to determine the effectiveness of the RC as a learning tool, an indirect assessment was performed ; students were surveyed to assess the RC as a learning tool. Preliminary results showed that the RC and the associated calculations and reports performed quite well as a learning tool, according to the students. They reported that their knowledge of the Rankine cycle (and its associated thermodynamic concepts) increased. They indicated that discussing and operating the RC are more valuable than performing calculations with the data. The level of the

material was appropriately challenging for upper-level engineering students. A few keys to successful use of the RC were also given in the paper.

Second, a parametric study of the effects of component losses on RC thermal efficiency was performed. The results showed that the range of component losses used in the parametric study accurately reflects experimental thermal efficiencies, and the results pointed to future experimental work that can be accomplished with the RC. The overall conclusion of the paper was that the benefits of the RC seem to outweigh the idiosyncrasies of the device. For its relatively low cost, the RC is useful in a mechanical engineering curriculum.

There are two objectives of the current paper which extend and support the conclusions and recommendations from the first paper. First, assessment of the RC's effectiveness as a learning tool is continued. The indirect assessment of the first paper is extended through more student surveys, and a more direct assessment is performed based on graded student reports. These assessment results help decide how the equipment can be used in the best possible manner in the undergraduate curriculum.

A second objective of the current paper is to extend the comprehensive technical analysis of the RC. Significant experimental work was performed to characterize the RC and its components. Multiple steady state runs were performed to determine the optimum operating point (i.e., the load at which turbine/generator performance is optimum). Also, methods for measuring steam flow more accurately were studied. Finally, future work is outlined to complete a characterization of the RC.

## B. Background

At LTU and UE, all mechanical engineering students learn about the Rankine cycle in their required Thermodynamics course during their sophomore or junior year. During their junior year (at UE) or senior year (at LTU), the students put the theory into practice by operating the RC in a required laboratory course. Consequently, it is hoped that every graduating mechanical engineering student will learn and understand electricity generation in fossil fueled plants.

## **2. Rankine Cyclor™ Effectiveness as a Learning Tool**

While the RC is the only cost-effective laboratory equipment on the market to introduce students to Rankine cycle power equipment similar to that they may encounter in practice (i.e., containing a turbine), it was unknown if the equipment is a good learning tool. A study has been completed to determine if the RC is a worthwhile and practical tool for the students to study fossil-fueled electricity generation and cycle efficiencies. Both indirect and direct assessments were performed.

### A. Indirect Assessment (Student Survey) Results

The RC was first evaluated as a learning tool based on an indirect assessment (i.e., a survey of student opinions). Various questions were asked of students on a survey after the laboratory exercises and subsequent written reports had been completed (but before they were graded).

Prior to distributing the survey, the instructors did their best to stay opinion-neutral toward the students as to the effectiveness of the RC as a learning tool; the students were made aware that this was a testing phase of the RC. Much of the survey was quantified using a 5-point Likert scale, but written responses were also gathered. While many different experiments are possible with the RC (see LTU sample laboratory assignment in Appendix B), the survey is general enough that it is likely applicable to any college using the unit. Questions asked on the survey are shown in Appendix C. The results compiled in this paper are derived from 19 LTU student surveys and 20 UE student surveys. The results are an indirect assessment because they indicate student perceptions based on self-surveys.

As shown in Table 1, before performing the RC exercise in lab, students felt fairly comfortable with the concepts related to the Rankine cycle. On a scale of 1 to 5, where 1 is “strongly disagree” and 5 is “strongly agree,” the average student response was 3.59. The median was 4 with a standard deviation of 1.21.

Also shown in Table 1, after completing the RC exercise (including the calculations), the students gained a slightly better understanding of the Rankine cycle, scoring an average of 3.82, a median of 4, and a standard deviation of 0.885.

|  | strongly disagree | disagree | no opinion | agree       | strongly agree |
|--|-------------------|----------|------------|-------------|----------------|
| Before performing the Rankine Cycle exercise in lab, I felt comfortable with the concepts related to the Rankine cycle       | 5.1               | 20.5     | 7.7        | <b>43.6</b> | 23.1           |
| After completing the Rankine Cycle exercise (including the calculations), I have a better understanding of the Rankine cycle | 2.6               | 2.6      | 25.6       | <b>48.7</b> | 20.5           |

**Table 1. Percentage of students agreeing with the statements concerning their understanding of the Rankine cycle before and after using the Rankine Cycler™**

After rating each part of the exercise, putting a 1 next to the most beneficial, a 2 next to the next beneficial, and a 3 next to the least beneficial, the average results are as follows:

Seeing real (lab-scale) components and their operation – 1.74

Discussing and using the RC with the instructor – 1.79

Performing the calculations/analysis – 2.29

Based on these results, the students did not believe they benefited as greatly from the calculations and analysis as they did from the in-lab exercise. This result is not surprising for three reasons. First, most of the students have already performed the required calculations in their Thermodynamics course. Second, the numbers calculated from the laboratory data are not representative of full-size plant data or of the values that appear in typical textbook exercises and therefore have little meaning to the students; possibly the results seem contradictory.

Considering that most students do not have an intuitive feel for quantities calculated from real

power plant data, the numbers that they generate have no significant meaning. Third, many students do not enjoy detailed “theoretical” calculations; they are looking for hands-on application. One student recommended “less calculations and more how does it work and why.”

For the calculations and analysis ratings (students put a 1 next to the most beneficial, a 2 next to the next beneficial, and so on, up to 7), the results are shown in Table 2. The number in parenthesis indicates rank.

| average | analysis exercise                              |
|---------|--|
| 3.1 (1) | T-s diagram generation                         |
| 3.9 (5) | turbine isentropic efficiency                  |
| 3.8 (4) | first law analysis                             |
| 3.6 (3) | Thermal efficiency / heat rate                 |
| 5.0 (6) | condensing tower efficiency                    |
| 3.2 (2) | power and energy                               |
| 5.4 (7) | suggest methods to increase thermal efficiency |

**Table 2: Calculation / Analysis Ranking Results**

As shown on Table 3, the students found the RC as experimental equipment as a useful tool for learning thermodynamics. On a scale of 1 to 5, where 1 is “strongly disagree” and 5 is “strongly agree,” the average student response was 3.74, the median was 4.0 and the standard deviation was 1.08.

Also shown on Table 3, the students found the in-lab procedure for using the RC was a useful exercise for furthering their knowledge and understanding of Thermodynamics with an average score of 3.79, a median of 4 and a standard deviation of 1.03.

Finally from Table 3, the students found the analysis and calculations associated with the RC exercise were useful for furthering their knowledge and understanding of thermodynamics with an average score of 3.69, a median of 4, and a standard deviation of 0.893.

|   | strongly disagree | disagree | no opinion | agree       | strongly agree |
|---|-------------------|----------|------------|-------------|----------------|
| The Rankine Cyler as experimental <u>equipment</u> is a useful tool for learning thermodynamics   | 2.6               | 13.2     | 18.4       | <b>39.5</b> | 26.3           |
| The <u>in-lab procedure</u> for using the Rankine Cyler was a useful exercise for furthering my knowledge and understanding of Thermodynamics               | 2.6               | 10.3     | 17.9       | <b>43.6</b> | 25.6           |
| The <u>analysis and calculations</u> associated with the Rankine Cyler exercise were useful for furthering my knowledge and understanding of Thermodynamics | 2.6               | 7.7      | 20.5       | <b>56.4</b> | 12.8           |

**Table 3. Percentage of students agreeing with the statements concerning the aspects of the Rankine Cyler™**



As a basis for ensuring that the quality of instruction was sufficient and that the equipment was being used in a worthwhile manner, the students rated the instructor's use of the RC. The results are shown in Table 4. On a scale of 1 to 5, where 1 is "unsatisfactory" and 5 is "excellent," the average student response was 4.20, the median was 4, and the standard deviation was 0.731.

|   | unsatisfactory | poor | satisfactory | good | Excellent |
|---|----------------|------|--------------|------|-----------|
| How do you rate the instructor's use of the Rankine Cycler? | 0              | 0    | 18.9         | 43.2 | 37.8      |

**Table 4. Percentage of students rating the instructor's use of the Rankine Cycler™**

As shown on Table 5, the level of material covered with the RC exercise was rated as just barely advanced with an average score of 2.77, where 1 is "too advanced," 3 is "just right," and 5 is "too easy." The median was 3 and the standard deviation was 0.583.

|   | too advanced | advanced | just right | easy | too easy |
|---|--------------|----------|------------|------|----------|
| The level of material covered with the Rankine Cycler exercise was: | 0            | 30.8     | 61.5       | 7.7  | 0        |

**Table 5. Percentage of students rating the level of material covered with the Rankine Cycler™**

Finally the students found the RC exercise slightly increased their interest in the thermal-fluid sciences (see Table 6). On a scale of 1 to 5, where 1 is "strongly disagree" and 5 is "strongly agree," the average student response was 3.33. The median was 3 and the standard deviation was 1.03. By their senior year, students have already decided where their interests and/or strengths lie. A single laboratory exercise is unlikely to change their perception. Therefore it is pleasantly surprising that 10.3% of the students "strongly agreed" that the exercise increased their interest in Thermal-Fluid Sciences.

|  | strongly disagree | disagree | no opinion | agree | strongly agree |
|--|-------------------|----------|------------|-------|----------------|
| The Rankine Cycler exercise increased my interest in the thermal-fluid sciences. | 7.7               | 7.7      | 38.5       | 35.9  | 10.3           |

**Table 6. Percentage of students agreeing with the statement concerning their interest in the thermal-fluid science field due to the RC.**

Overall, the RC and its associated calculations and reports performed quite well as a learning tool, according to the students. They reported that their knowledge of the Rankine cycle (and its associated thermodynamic concepts) increased. They found discussing and using the RC more valuable than performing calculations with the data. In addition, the level of the material was appropriately challenging for upper-level engineering students.

The survey results were also compared from university-to-university (LTU vs. UE). These results are useful for two reasons. First, the thermodynamics courses and thermal-science laboratory courses have different formats between LTU and UE. One of the goals for the UE thermal-science laboratory is for the students to perform a preliminary theoretical prediction exercise for the equipment. This allows the students time to review the RC and aspects of its performance before any experiments are performed. Additionally, the students at UE have more coverage of the Rankine cycle in their Thermodynamics course and the laboratory course is taken one semester after the Thermodynamics course, whereas at LTU, the laboratory is typically taken a year or more after Thermodynamics. Therefore the UE students would be expected to have a better understanding of the process and procedures before the experiment and data analysis. A final difference is that at UE, a complete uncertainty analysis is required with the final report.

Second, a comparison is useful because of the differing regions in which the universities are located. Evansville, Indiana is in the heart of a major Midwestern coal mining region, on the Ohio river, and coal-fired steam power plants are an integral part of the engineering landscape. Some of the UE students have had co-op or internship experience at a power plant. As a result, the UE students, in general, seem to be more “power plant savvy”. Industry in Southfield, Michigan (i.e., Detroit) is dominated, not by the Rankine cycle, but by different types of power cycles; the Otto and Diesel cycles take lead roles in the Southeastern Michigan engineering landscape because of the auto industry. LTU students tend to be less interested in coal-fired steam power generation and more interested in internal combustion engines.

As shown in Table 7, the UE students were more comfortable with the Rankine cycle before completing the RC exercises (as expected), while the LTU students were split fairly evenly. This is also shown in the average scores where 1 is “strongly disagree” and 5 is “strongly agree;” UE students scored an average of 4.1 whereas LTU students scored an average of 3.1. Nevertheless, students from both universities found that using the RC increased their understanding of the Rankine cycle with a UE average score of 3.9 and an LTU average score of 3.8.

After rating each part of the exercise, putting a 1 next to the most beneficial, a 2 next to the next beneficial, and a 3 next to the least beneficial, the average results for each university are shown in Table 8. The LTU students found the discussion and use of the RC of greatest benefit and UE students found the visualization of the component operations most beneficial. Both student groups found the calculations and analysis least beneficial (it should be noted that calculations were more extensive at UE, with a pre-lab theoretical prediction and an uncertainty analysis incorporated in the data analysis). The students likely ranked the calculations lowest, because

the quantities calculated are not comparable to full-scale Rankine power plants and because they are considered tedious.

|  | strongly disagree |    | disagree |    | no opinion |    | agree |    | strongly agree |    |
|--|-------------------|----|----------|----|------------|----|-------|----|----------------|----|
|  | LTU               | UE | LTU      | UE | LTU        | UE | LTU   | UE | LTU            | UE |
| Before performing the Rankine Cyclers exercise in lab, I felt comfortable with the concepts related to the Rankine Cycle       | 10.5              | 0  | 36.8     | 5  | 0          | 15 | 36.8  | 50 | 15.8           | 30 |
| After completing the Rankine Cyclers exercise (including the calculations), I have a better understanding of the Rankine cycle | 5.3               | 0  | 5.3      | 0  | 21.1       | 30 | 42.1  | 55 | 26.3           | 15 |

**Table 7. Percentage of LTU and UE students agreeing with the statements concerning their understanding of the Rankine Cycle before and after using the Rankine Cyclers™**

|  | LTU  | UE   |
|--|------|------|
| Discussing and using the RC with the instructor        | 1.53 | 2.05 |
| Seeing real (lab-scale) components and their operation | 1.63 | 1.84 |
| Performing the calculations/analysis                   | 2.47 | 2.11 |

**Table 8. LTU and UE student ranking of the Rankine Cyclers™ laboratory exercises**

For the calculations and analysis ratings, ( 1 = most beneficial, 2 = next beneficial, and so on, up to 7) the results are shown in Table 9. The number in parenthesis indicates rank. The most notable differences are that the UE students ranked the power and energy calculation as most beneficial, while LTU students ranked it 3<sup>rd</sup>, and the UE students ranked the first law analysis 5<sup>th</sup> while LTU students ranked it 2<sup>nd</sup>. Both groups of students considered the condenser efficiency calculation and speculating on methods for increasing thermal efficiency to be least beneficial. This result is not surprising. The condenser is not comparable to full-scale condensers and has a very low efficiency. Also, the “condenser efficiency” calculated for the experiment does not correspond to any parameter used in the power generation industry. The methods to increase thermal efficiency are useful for the RC, but not particularly useful to an actual full-scale Rankine cycle power plant. One student commented that methods of increasing the heat rate “seemed very obvious and logical,” and another simply stated, “was simple”; both students therefore ranked it least beneficial. The fact that the students recognize that it is obvious how to increase the RC efficiency indicates its benefit to students learning Thermodynamics! Of course, student suggestions were often comments like “increase the efficiency of the turbine”. While obvious at this level, how to actually accomplish an efficiency increase is not so obvious.

Table 10 indicates that both groups of students believe that the RC is a useful learning tool, and that the in-lab procedure and data analysis are useful. Note that the LTU students showed a stronger agreement for the RC usefulness. This likely reflects their somewhat more limited prior

exposure to power generation and the longer elapsed time between their classroom study and the RC experiment.

| LTU average | UE average | analysis exercise                              |
|-------------|------------|--|
| 3.0 (1)     | 3.1 (2)    | T-s diagram generation                         |
| 4.0 (5)     | 3.8 (4)    | turbine isentropic efficiency                  |
| 3.3 (2)     | 4.2 (5)    | first law analysis                             |
| 3.9 (4)     | 3.4 (3)    | Thermal efficiency / heat rate                 |
| 4.1 (6)     | 5.8 (7)    | condensing tower efficiency                    |
| 3.7 (3)     | 2.8 (1)    | power and energy                               |
| 5.9 (7)     | 4.9 (6)    | suggest methods to increase thermal efficiency |

**Table 9. LTU and UE student comparison of calculation / analysis ranking**

|  | strongly disagree |    | disagree |    | no opinion |    | agree       |           | strongly agree |    |
|--|-------------------|----|----------|----|------------|----|-------------|-----------|----------------|----|
|  | LTU               | UE | LTU      | UE | LTU        | UE | LTU         | UE        | LTU            | UE |
| The Rankine Cyclor as experimental <u>equipment</u> is a useful tool for learning thermodynamics   | 5.6               | 0  | 11.1     | 15 | 16.7       | 20 | <b>33.3</b> | <b>45</b> | <b>33.3</b>    | 20 |
| The <u>in-lab procedure</u> for using the Rankine Cyclor was a useful exercise for furthering my knowledge and understanding of Thermodynamics               | 5.3               | 0  | 10.5     | 10 | 10.5       | 25 | 31.6        | <b>55</b> | <b>42.1</b>    | 10 |
| The <u>analysis and calculations</u> associated with the Rankine Cyclor exercise were useful for furthering my knowledge and understanding of Thermodynamics | 5.3               | 0  | 10.5     | 5  | 15.8       | 25 | <b>52.6</b> | <b>60</b> | 15.8           | 10 |

**Table 10. Percentage of LTU and UE students agreeing with the statements concerning the aspects of the Rankine Cyclor™**

Both LTU and UE students agreed that the quality of instruction for the RC was sufficient and that the equipment was being used in a worthwhile manner (see Table 11).

|   | strongly disagree |    | disagree |    | no opinion |      | agree |             | strongly agree |      |
|---|-------------------|----|----------|----|------------|------|-------|-------------|----------------|------|
|   | LTU               | UE | LTU      | UE | LTU        | UE   | LTU   | UE          | LTU            | UE   |
| How do you rate the instructor's use of the Rankine Cyclor? | 0                 | 0  | 0        | 0  | 16.7       | 21.1 | 27.8  | <b>57.9</b> | <b>55.6</b>    | 21.1 |

**Table 11. Percentage of LTU and UE students rating the instructor's use of the Rankine Cyclor™**

As shown in Table 12, both groups of students found the level of material between “just right” and “slightly advanced” (with an average LTU score of 2.79 and an average UE score of 2.75, where 1 is “too advanced,” 3 is “just right,” and 5 is “too easy”).

|   | too advanced |    | advanced |    | just right |    | Easy |    | too easy |    |
|---|--------------|----|----------|----|------------|----|------|----|----------|----|
|   | LTU          | UE | LTU      | UE | LTU        | UE | LTU  | UE | LTU      | UE |
| The level of material covered with the Rankine Cycler exercise was: | 0            | 0  | 31.6     | 30 | 57.9       | 65 | 10.5 | 5  | 0        | 0  |

**Table 12. Percentage of LTU and UE students rating the level of material covered with the Rankine Cycler™**

Finally most students found the RC exercise slightly increased their interest in the thermal-fluid sciences (or kept it the same) (see Table 13). On a scale of 1 to 5, where 1 is “strongly disagree” and 5 is “strongly agree,” the average LTU student response was 3.11, and the average UE student response was 3.55.

|  | strongly disagree |    | disagree |    | no opinion |    | agree |    | strongly agree |    |
|--|-------------------|----|----------|----|------------|----|-------|----|----------------|----|
|  | LTU               | UE | LTU      | UE | LTU        | UE | LTU   | UE | LTU            | UE |
| The Rankine Cycler exercise increased my interest in the thermal-fluid sciences. | 15.8              | 0  | 10.5     | 5  | 26.3       | 50 | 42.1  | 30 | 5.3            | 15 |

**Table 13. Percentage of LTU and UE students agreeing with the statement concerning their interest in the thermal-fluid science field due to the RC.**

In general, students from two different regions ranked the RC and its exercises very similarly. These results indicate that the RC can be a useful learning tool for a varying student base. In addition, students who feel that they have a firm understanding of the Rankine cycle before performing experiments feel that use of the RC is nevertheless beneficial.

### B. Student Comments

Students had several worthwhile suggestions (written on the survey). One student commented, “It would be more beneficial to discuss [the RC equipment] after the [completion of the laboratory report], as the knowledge has sunk-in and [had already been] applied.”

Another student who found the operation of the RC as the most beneficial aspect of the exercise commented, “A picture or model is worth a lot.” That same student found the calculations and analysis least beneficial and commented, “Doing the calculations was aggravating. Units should

all be [in the] same [unit system]. It's one thing to see and read the theory and another to make sense of a mess of data...."

A student who found the generation of a T-s diagram most beneficial commented, "This shows the most information for the amount of work. If you understand the chart it can show (somewhat) most of the other information." This student found the condensing tower calculation least beneficial and added the comment, "The tower is not very accurate and doesn't work well."

Nine students commented that a pump should be added to complete the cycle. This is not feasible for the current RC configuration. First, all or most of the steam would need to be converted to liquid. Any condenser that could do this would be too large to be table-top sized and would require external cooling (e.g., fans or pumped cooling water). External cooling would require an external power source, which is counterproductive for studying the small-scale power cycle. Also the pump itself would require an external power source. Suddenly, the power produced by the turbine/generator would seem trivial. Also seven students commented that the condenser needed improvement. Again this would require an external cooling source and possibly a larger condenser that would not fit the nicely sized workbench.

A student noted that the equipment should have a method of viewing what is happening inside the components. The student commented, "need see-through panels or cut-aways of a model to see what is really happening inside. I would bet most students could not tell you what the turbine looks like and how it works. One needs to know how it works to understand the process." It would therefore be useful for Turbine Technologies, Ltd. to make available extra turbine rotors and/or boiler cut-aways that instructors could show and discuss with the students.

One student suggested that a better method of measuring water consumption was needed. This will be addressed later in this paper.

A student commented, "Rather than using the RC, the class could obtain real data from a [full-scale] power plant; this would give realistic results and provide a more useful experience." Another student suggested getting "data from an actual plant." While this may be true, the data alone does not show the operation of the components. A tour of a plant with a schematic would need to accompany the data.

One student noted that the equipment should more closely match real-world conditions and was "disappointed in the engineering of the test equipment." On the other hand this same student gave very high marks for the learning experience and his/her level of interest in thermal-fluid sciences strongly increased. The fact that the RC does not closely replicate actual plant conditions may actually benefit student learning, because it forces the student to think about power cycles and their application.

A student realized that, "The boiler efficiency is impossible to [calculate using standard methods] with the data recorded." Because the boiler is pre-filled and pre-heated and since it is not fed condensate, boiler efficiency as determined in a full-scale plant cannot be calculated by the students. Student calculation of boiler efficiency would require additional equipment such as oxygen and exhaust gas temperature sensors.

Another student suggested to “reuse wasted heat from [exhaust] stack.” This, of course, would require additional piping and the heat gained would likely not compensate for the additional pipe pressure drop. Asking students how to use this waste heat would be a good exercise.

There is some concern that the equipment is not a particularly active exercise for a group of students; the RC only requires one or two students to operate. A student commented, “I am an active learner and [RC use and instruction] is...passive learning.” Unfortunately, most thermal-fluids laboratory exercises are fairly passive with minimal user interaction. The only remedy to this problem would be to have lab groups of only 2 or 3 students, which is often impossible due to time constraints.

In contrast, many student comments are laudatory and reinforce the reason to include hands-on teaching. One student commented, “I learn better when I ‘see for myself’ instead of being taught concepts.” Another stated, “Bringing numbers and diagrams to a hands-on experiment is key to learning.” A third student commented, “Seeing these physical plants is enjoyable which encourages learning.”

### C. Direct Assessment

Multiple direct assessments were performed which evaluate students’ understanding of the Rankine cycle after using the RC and evaluate the value of the RC as a learning tool. First, direct assessment was performed by evaluating answers to final exam questions. At LTU, a final exam is given at the end of Thermal Science Laboratory course. The exam consists of 30 concept questions, of which each student must answer 20 of his/her choosing. Although the exam is closed book and closed notes, the exam questions are distributed a few days before the exam is administered, so that the students can investigate the questions ahead of time.

The two questions on the final exam pertaining to the Rankine Cycler are as follows:

- 1) “Without modifying the equipment whatsoever, what is a simple method to improve the power generating performance? Explain why.”
- 2) “With your 2 to 3 minutes of data, you calculated thermal efficiency and/or heat rate. With our equipment, the resulting values are never a true measure of efficiency/heat rate. Why? (HINT: Something besides the pump was neglected that contributes a significant source of error.)”

Each question is graded out of a possible 10 points. Over the course of two semesters, twenty-eight students answered the first question, and fifteen students answered the second question. Table 14 shows the results.

|                    | Question 1 | Question 2 |
|--------------------|------------|------------|
| Average score      | 8.6        | 4.7        |
| Median score       | 9          | 4          |
| Standard deviation | 1.5        | 3.3        |

**Table 14. Student final exam scores relating to the Rankine Cyclor™.**

The standard deviation of question 2 is high because three of the students received 0 points and two of the students received 10 points. Based on the average score of question 1, the students tend to understand the Rankine Cyclor and its inherently low efficiencies due to the small plant size. Based on the average score of question 2, the students do not seem to fully understand how the RC compares to a full-sized power plant. This conclusion is debatable considering the small sample size and the limited focus of the question.

Besides examining the average scores, a target score of 7 (out of 10) was established for each problem; 89% of the students obtained this score for question 1, while only 27% of the students scored a 7 on question 2.

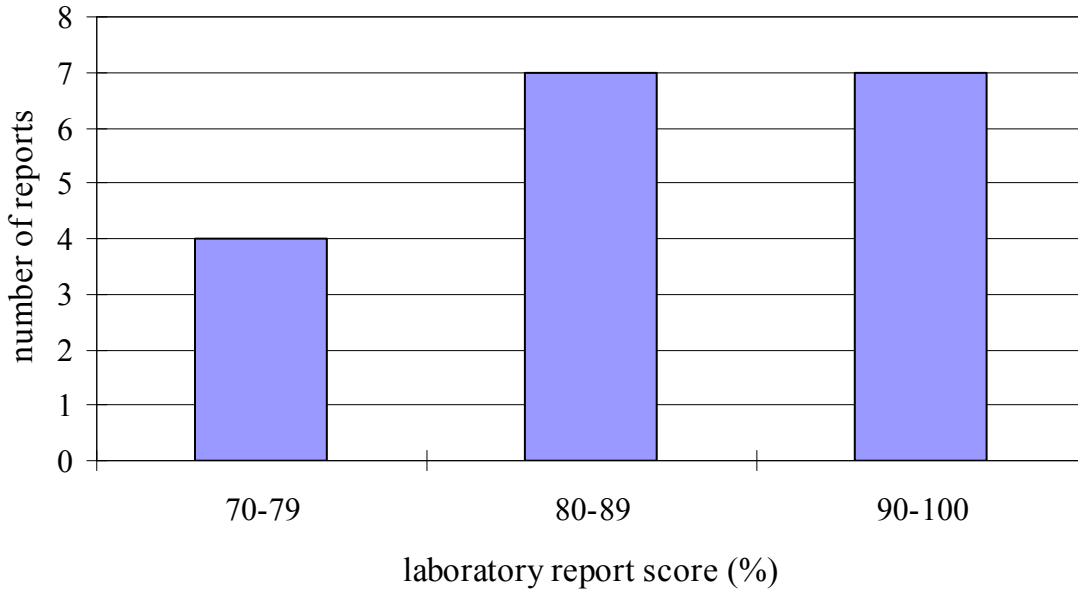
The second method of direct assessment was to evaluate the graded laboratory reports. Although the data reduction and performance calculations are the same between LTU and UE students, parts of the lab reports have differing objectives and formats. While LTU reports are concerned with collecting experimental data and analyzing it, UE reports also require uncertainty analysis and pre-lab predictions of performance. Also each LTU lab report is generated by an entire team of 2 to 5 students, although a set of sample calculations are performed by each student. UE reports are the work of each individual student (although the experimental work was completed as a group). For the current assessment, there are 15 LTU student lab reports, 4 UE student lab reports, and 47 LTU student sample calculations. This sample size is fairly small but it constitutes the work of 60 students. More direct assessment including more reports will be evaluated for a future paper.

Figure 5 shows the distribution of the scores for the laboratory reports. The average score is 86.7%, the median is 87.5% , and the standard deviation is 7.0%. A target score of 77.5% was established; this target score was chosen because this is the logical minimum score which constitutes above-average work (i.e., a C+ or B-). Assessment determined that 94.4% of the reports reached this target. These data indicate that the students gain a firm understanding of the Rankine cycle concepts through use and analysis of the RC. Upon inspection of the reports, the calculations, plots, and supporting text are typically well established by the students and the RC appears to be a good learning tool for the steam power cycle. Note that, in general, the scores reflect the work of groups of students (i.e., not individual work). A weaker student can lean on the support of the stronger student. Therefore it is worthwhile to assess individual student sample calculations.

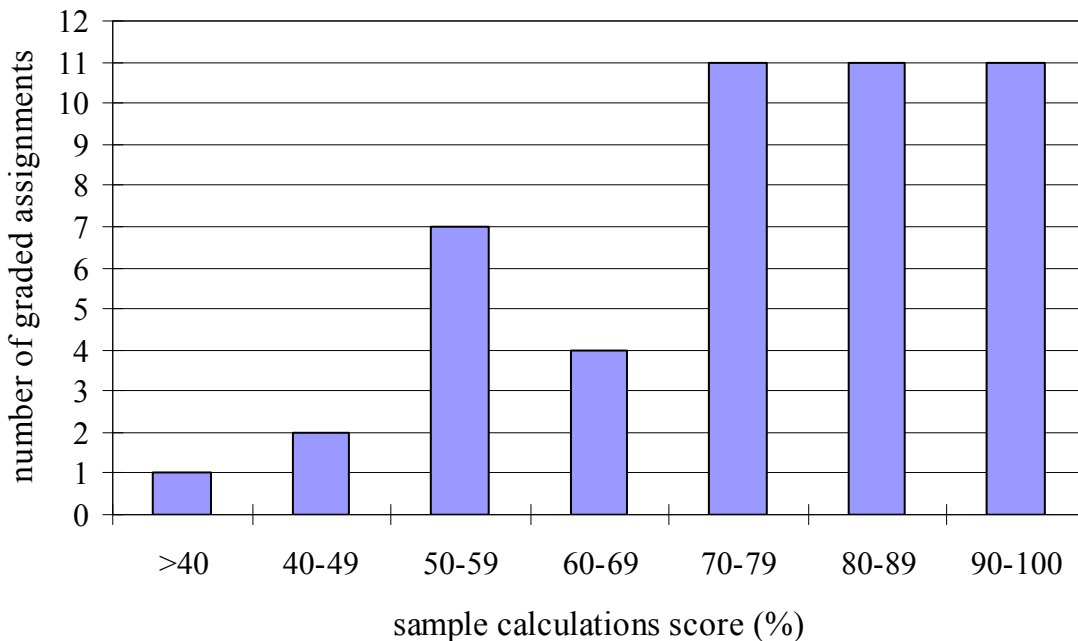
Figure 6 shows the distribution of the scores for the sample calculations. The average score is 77.9%, the median is 80%, and the standard deviation is 18%. A target score of 77.5% was again established; 57.4% of the students reached this target. As noted, the data from the sample calculations may be more indicative of the RC as a learning tool since they represent work from



individual students. The wide score distribution and standard deviation of 18% indicates the wide range of scores, and little more than half of the students earned better than a C+. This is not necessarily an indication that the RC does not reinforce the concepts of the steam power cycle or the concepts of thermodynamics. It more likely indicates that some students are less interested in the thermal-fluids aspects of engineering or that some students are not putting forth a best effort.



**Figure 5. Distribution of students' RC laboratory report scores.**  
 (Note that there were no scores less than 70%)



**Figure 6. Distribution of students' sample calculation scores.**

Evaluation of the UE reports indicates that students are most capable of reducing data and using data to make performance calculations. Numerical results of pre-laboratory performance predictions do not agree well with actual performance because students do not realize how inefficient the small-scale equipment actually is. Also, the required uncertainty analysis is much less sophisticated than the performance calculations.

#### D. Keys to Meaningful Instruction

There are a few potential pitfalls to avoid when using the RC as a learning/teaching tool. First, the instructor should gauge the amount of Rankine cycle coverage that the students received in their Thermodynamics course. At a smaller college where all of the students have had the same instructor for Thermodynamics, this is a simple task of asking the instructor or looking at the syllabus. At a college where multiple sections of Thermodynamics are offered each semester with a variety of instructors, this task may be more difficult. If the students received very little instruction on the Rankine cycle in Thermodynamics, the terminology and experimental process becomes intimidating. Be sure to allow ample laboratory class time to describe and use the RC if this is the case.

The condenser looks very similar to a hyperbolic natural draft cooling tower. Convey to the students that it is not a cooling tower but a very simple atmospheric baffle condenser. It is shaped like a cooling tower for visual impact, and the shape has little to no impact on the heat transfer occurring within the tower. (By the way, the hyperbolic shape of an actual natural draft cooling tower also has little impact with the heat transfer occurring within the tower. They are built that way “to offer superior strength and resistance to ambient wind loadings<sup>3</sup>.”)

While heat rate is more commonly used in the (U.S.) power industry as a measure of plant and cycle performance, Thermodynamics texts and instructors typically spend more time discussing thermal efficiency. If the students will be using heat rate, be sure to properly introduce the concept and its meaning. The heating value of propane may be useful for this calculation.

One of the most tedious tasks for the students while doing the calculations is determining steam properties. Usually students only have access to steam tables in the back of a text book. These tables are sufficient for classroom calculation, but for actual data, a significant amount of interpolation is necessary. The excessive interpolation is tedious and not particularly meaningful. Therefore, the students should have access to accurate electronic tables. This is also a good opportunity to introduce students to “professional level” data sources such as the full ASME Steam Tables.

All of the RC pressure measurements are reported in gage pressure. The students often forget or do not know that steam tables are based on absolute pressure. Forewarn the students of this.

If the students are plotting their results on a T-s diagram, they will have some difficulty. The T-s diagrams that they experienced in their Thermodynamics course have greatly exaggerated scales making them easier to visualize.

Finally, the steam exiting the turbine is sometimes wet (a mixture). Since only pressure and temperature are measured at the turbine outlet, there is no way to determine the steam quality and therefore no way to determine the enthalpy and entropy. It may be best to use settings that ensure superheated steam is exiting the turbine.

### 3. Experimental and Analytical Study to Characterize the Rankine Cyclor™ and its Components

The RC has several significant differences from both an ideal and a real-world full-sized plant. One of the most significant is the fact that the RC does not use a pump. This means that truly cyclic operation is not possible. It is possible, however, to obtain (limited time) nearly steady-state flow operation of the turbine and generator. Another significant difference lies with the boiler. The water is heated at constant volume by a flame fueled with liquid propane (LP). The heat addition process under constant volume conditions causes a pressure increase in the boiler. The steam flow from the boiler can be maintained for some time period until the boiler pressure falls below an acceptable level. It is important to note that this “no-pump” feature of the RC makes it different from the real-world power plant as well as the ideal cycle.

The other ways that the RC differs from the ideal cycle also show up as differences between the ideal cycle and actual operating power plants. In almost all cases, these are “non-ideal” effects that cause the efficiency (or heat rate) of the real RC to be poorer (*lower* efficiency or *higher* heat rate) than the ideal model. A partial catalog of these effects was given in the previous paper<sup>2</sup>. The results from that paper of a parametric study of the effects of component losses on RC thermal efficiency helped to pinpoint what combinations of various component losses account for the poor performance (i.e., low thermal efficiency or high heat rate) of the RC. The greatest RC losses were attributed to boiler-to-turbine line pressure drop and poor turbine/generator efficiency (perhaps only 5% to 10%). The parametric study gave the authors a rough guide for the limitations of the RC, so that the proper experimental work could be performed.

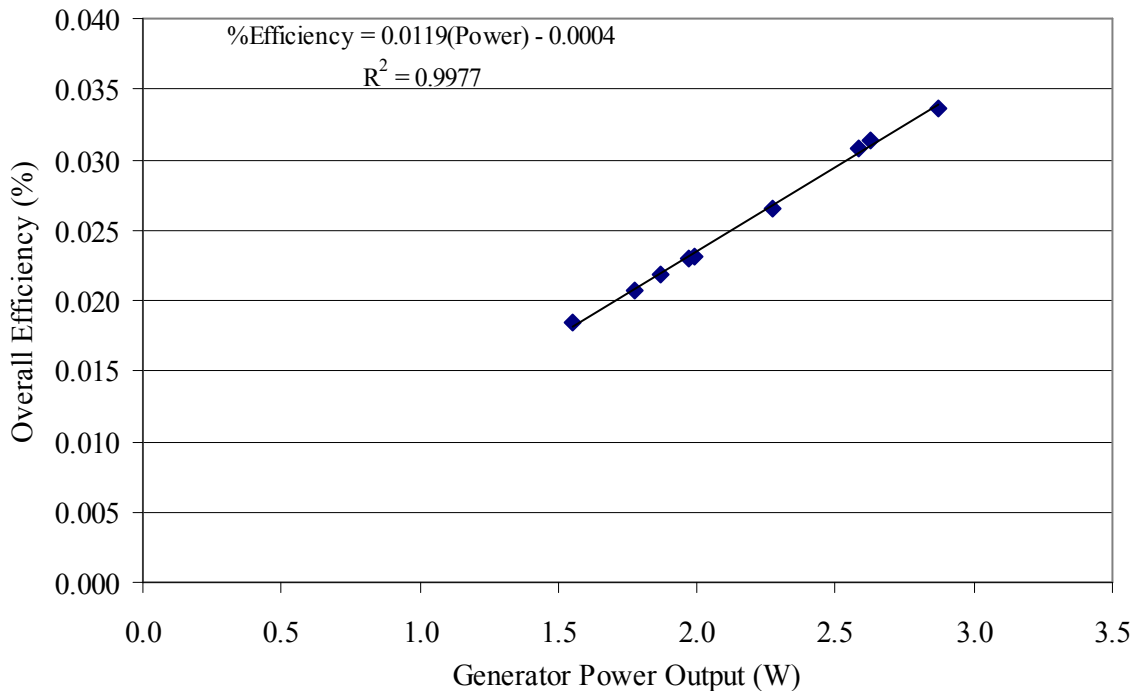
#### A. Optimum Operating Point

Typical ranges of data gathered from the RC are shown in Table 15. Because the RC has several significant differences from and is much smaller than both an ideal and real-world full-sized plant, the efficiencies calculated from the data are inherently low. It would therefore be most beneficial for the students to use the RC at its highest overall efficiency or optimum operating point.

|                          | <b>Boiler</b> | <b>Turbine Inlet</b> | <b>Turbine Outlet</b> |
|--------------------------|---------------|----------------------|-----------------------|
| Pressure (psia)          | 90 – 120      | 20 – 25              | 17 – 18               |
| Temperature (°F)         | 350 – 600     | 300 – 450            | 275 – 390             |
| Steam mass flow (lb/sec) | 0.006 – 0.013 |                      |                       |
| Fuel flow rate (lb/sec)  | 0.00038       |                      |                       |
| Generator power (W)      | 2 - 4         |                      |                       |

**Table 15. Typical ranges of RC experimental data.**

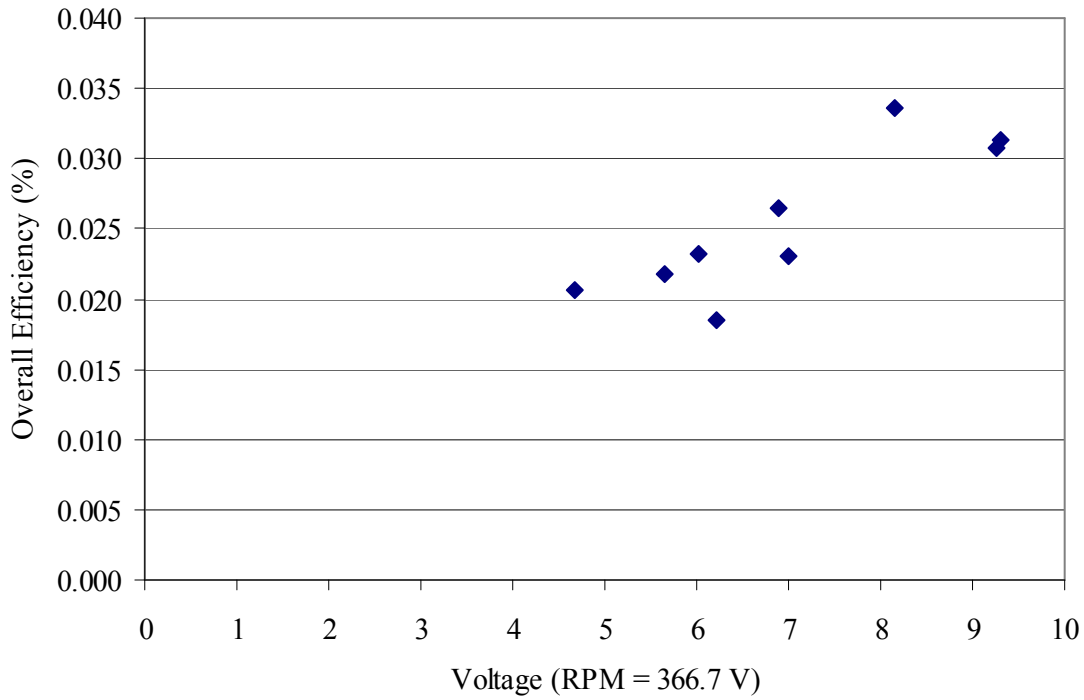
Multiple steady state runs were carefully performed to determine the optimum operating point (i.e., turbine/generator performance versus load). There are multiple experimental parameters to investigate to determine optimum operating point. Figures 7 through 9 display three variations. Figure 7 shows overall efficiency (generator power divided by fuel energy input) plotted against generator power output. The relationship appears linear, so a straight line has been fit to the data. The linear equation is shown on the figure along with the Pearson product moment correlation coefficient (also known as the “r-squared value” which gives an indication of the quality of the line fit with 1.0 being a perfect fit). The figure implies that there is not an optimum point at which to operate the RC; it should simply be run at the highest possible load. However, at some power output, the efficiency would begin to drop. The data collected may not have covered the maximum operating load (according to generator manufacturer’s specifications) which may be the point at which the generator RPM is nearly 4500. The data shown only covers a range up to 3400 RPM. Unfortunately, it may not be possible to maintain a generator RPM over 3500 and maintain steady state conditions. The RC runs to date have proven attaining 4000 RPM is difficult. Continued higher load RC runs will be attempted as a supplement to the current data sets. At present, this data would indicate that the RC should be operated at the highest achievable steady power output.



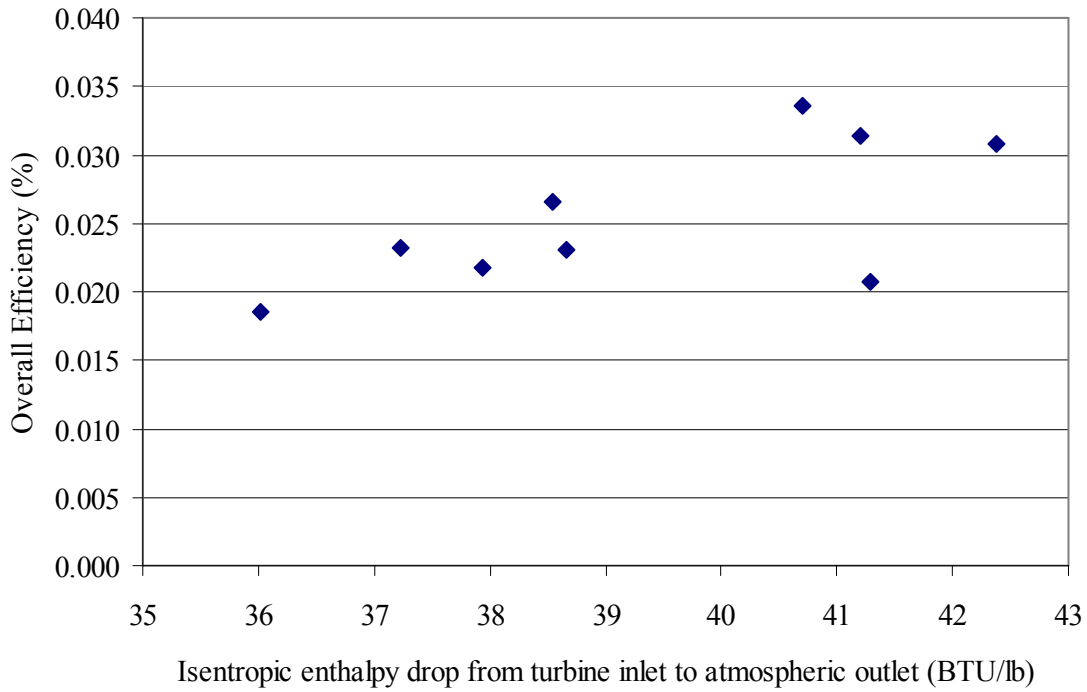
**Figure 7. Overall Efficiency vs. Power Output**

Figure 8 shows overall efficiency plotted against generator voltage. Generator RPM is implicitly indicated since it is related to DC output voltage by  $RPM = 366.7 V$  (information supplied by Turbine Technologies, LTD.). The efficiency vs. voltage trend is similar to the one in Figure 7 but not as distinct. This reinforces the idea that the RC should be run at maximum loading (maximum speed) for optimum conditions.

Figure 9 shows efficiency plotted with isentropic enthalpy drop from turbine inlet to atmospheric outlet. The increasing trend is very faintly indicated with one obvious outlier near 41 BTU/lb.



**Figure 8. Overall Efficiency vs. Voltage/RPM**



**Figure 9. Overall Efficiency vs. Isentropic Enthalpy Drop from turbine inlet to atmospheric outlet**

## B. Using Turbine Exhaust Tube Pressure Drop to Measure Steam Flow

Possibly the least satisfying aspect of running an experiment with the Rankine Cycle is determining the steam flow rate. This requires marking the boiler water level (using a sight-glass) at the beginning and end of the data collection period, waiting a few hours for the system to cool, then draining and refilling the boiler, noting the volume of water added to move the level between the two points on the sight-glass. The volume flow rate for the test is then determined by dividing the make-up water volume by the elapsed time for the run; mass flow would then be obtained by multiplying by liquid water density. Steam mass flow rate determined by this method is highly inaccurate because of the uncertainty involved in marking the water level, in draining and refilling the boiler, and in the differences in density between hot and cold water. The uncertainty in steam flow rate is likely no better than 10% - probably higher when inexperienced students are making the measurements. Steam flow measurement may be the largest contributor of error in the analysis of the RC data. Clearly, a more direct and real-time steam mass flow measurement is highly desirable.

Possible approaches to obtaining such measurements would involve the installation of a small-scale flow meter such as an orifice or turbine meter. This would be problematic because it would require purchasing another instrument and would introduce yet another pressure drop into an already highly inefficient system. Such devices would also require calibration, especially a turbine meter which would be required to operate at elevated temperatures in the steam environment.

An alternate approach that shows considerable promise is to use the turbine-to-condenser exhaust line pressure drop to indicate the steam flow rate. The exhaust tube is a surprising 88 centimeters long and contains several bends, making the effective length about 1.4 m. The steam pressure drop along the tube is the order of  $4 \text{ lb/in}^2$  (28 kPa). In a typical experimental run, the steam at the turbine exit is superheated, and the pressure drop along the tube ensures that it remains superheated – facilitating modeling the steam as a gas. In addition to giving a potentially reliable measurement of steam flow, the evaluation of the flow rate requires students to apply methods from fluid mechanics (compressible or incompressible), providing one more link between the laboratory and the classroom.

Experimental measurements required to estimate steam mass flow from exhaust tube pressure drop are turbine outlet pressure and temperature (already available from the standard RC data) and the atmospheric pressure. Physical measurements required are the tube length (about 88 cm), tube inside diameter (about 0.8 cm), and the number and types of bends (five  $90^\circ$  bends and two  $45^\circ$  bends, all with  $r/D \approx 4$ ). Other information required is the equivalent length for the bends and the friction factor for the tube (available from fluid mechanics texts or handbooks; perhaps requiring iteration because of Reynolds number dependence).

At least four different models can be used to evaluate the steam flow from the data. In increasing order of complexity (and increasing order of accuracy), they are:

- Model as incompressible flow, using steam density determined from turbine exhaust conditions
- Model as incompressible flow, using steam density averaged between tube inlet (turbine exhaust) and tube exhaust conditions. This requires using the energy equation to determine tube exhaust temperature, use of the steam tables, and a couple of cycles of iteration.
- Model as compressible, adiabatic, frictional flow (Fanno flow); treat steam as an ideal gas
- Model as compressible, adiabatic, frictional flow (Fanno flow); treat steam as a real gas, using the adiabatic exponent from steam tables and a compressibility factor ( $p v = ZRT$ )

Preliminary calculations with all of these methods indicate that results agree within a few percent, especially among the latter three methods. In addition, the calculations yield values comparable to the standard Rankine Cycle “boiler refilling” method (that were carefully controlled and monitored).

A critical factor effecting the accuracy of the steam flow evaluated from exhaust tube pressure drop is the friction parameter for the exhaust tube,  $fL_{eq}/D$ , where  $f$  is the Darcy/Moody friction factor,  $L_{eq}$  is the equivalent length of the tube and  $D$  is the inside diameter. All calculations to date have used the Colebrook-White formula for  $f$  (equivalent to the Moody Chart), the actual tube geometry, and standard tables for equivalent length of bends. Accuracy of this method can easily be improved by determining the effective friction parameter by calibrating the tube. The most effective method would be to derive the entire parameter ( $fL_{eq}/D$ ) rather than, say,  $f$  and  $L_{eq}$  separately. Because the Mach numbers involved are low (on the order of 0.3) an incompressible flow calibration of the tube, using cold water or air, should be sufficient. Such calibrations will be investigated during Spring semester 2006 at the authors’ institutions and results should be available with the presentation of this paper, and in a subsequent follow-up paper.

It is expected that using the exhaust tube pressure drop method together with a calibrated value for the friction parameter will yield “real-time” steam mass flow data with an uncertainty the order of 1%; a full order of magnitude better than the “cool, drain, and refill” method currently in use.

### C. Turbine Calculations Compared to Generator Output Power

It should be noted that the power output from the generator is an order of magnitude lower than the power calculated from the enthalpy drop and steam flow rate through the turbine (e.g.,  $P_{gen} \approx 3W$ , while  $P_{enthalpy\ drop} \approx 150W$ ). Initially, there was some concern that kinetic energy change (i.e., velocity change) of the steam flow should be taken into account when an energy balance is performed on the turbine. Investigation revealed that the sensors for turbine inlet steam properties ( $p, T$ ) and outlet steam properties ( $p, T$ ) are located in (relatively) large volume “plenum” regions. The inlet and outlet properties are nearly stagnation properties, so kinetic energy change does not account for the discrepancies. Until further investigative work is completed, the differences between enthalpy drop work/power and generator values are assumed to be due to heat loss to the relatively massive turbine housing and the surroundings, together

with mechanical and generator inefficiency. (Significant heat loss would be another obvious discrepancy between the RC and a real-world power plant.)

#### **4. Future Work**

Some experimental work remains to complete a characterization of the RC. This experimental work will be an important contribution to potential customers of the unit, faculty/technicians using the equipment with students, students performing experiments, and for future upgrades by Turbine Technologies, LTD. The following four studies would enhance the usefulness of the RC to determine parameters such as output, efficiency, and flow rates.

1. **Component Performance:** Experiments should be performed on individual components of the RC. Specifically, boiler efficiencies should be determined for various operating conditions. Boiler efficiency determination will require exhaust gas temperature and oxygen ( $O_2$ ) measurements. An investigation of generator efficiency, separate from the turbine should be made. In addition, the turbine and generator interaction should be investigated to characterize any discrepancies in power output.

2. **Steam flow measurement:** As stated above in Section 4B, the turbine exhaust tube can be calibrated to allow determination of steam flow rate from exhaust line pressure drop.

3. **Second Law Analysis:** An exercise of considerable educational value would be to conduct a Second Law analysis of the unit. Because of its small scale, and high losses together with the rather complete set of thermodynamic data available, the RC is an excellent device for performing a second law analysis. Not only would the students benefit from performing a second law analysis (a topic that receives little or no coverage in the required Thermodynamics courses at LTU and UE), it would also give a better understanding of scaling drawbacks and help identify the major sources of losses.

4. The fuel (LP) flow is measured by a pre-installed turbine meter. Calibration of the meter may be problematic because it is performed on air prior to installation so an independent verification of fuel flow is desirable. UE will investigate using a scale under the propane tank in an attempt to verify the fuel flow measurement by cross-checking against a mass used divided by elapsed time measurement.

In addition, continued experimental runs will be performed with the RC to include higher voltages (or generator RPM) to attempt to identify, or verify the lack of, an optimum operating point. Also, additional student surveys, calculations, reports, and exam questions will be assessed to determine the effectiveness of the Rankine Cycler as a learning tool.

#### **5. Conclusion**

Students were surveyed to indirectly assess the RC as a learning tool. Overall, the RC and its associated exercises performed quite well as a learning tool, according to the students. They reported that their knowledge of the Rankine cycle (and its associated thermodynamic concepts) increased. They found discussing and using the RC hardware more valuable than performing



calculations with the data. The level of the material was appropriately challenging for upper-level engineering students. Students from different universities and geographic/economic regions ranked the RC and its exercises very similarly. These results indicate that the RC can be a useful learning tool for a varying student base. In addition, students who feel that they have a firm understanding of the Rankine cycle before performing experiments feel that use of the RC is nevertheless beneficial. Students that have used the RC and performed its associated analysis gave multiple suggestions for equipment improvements and commented on the RC's educational value.

Multiple direct assessments were performed to evaluate students' understanding of the Rankine cycle after using the RC and to evaluate the value of the RC as a learning tool. Based on laboratory final exam scores, the students understand the Rankine Cyclers equipment and that its efficiency is inherently low due to the small plant size, but they do not seem to fully understand how the RC compares to a full-sized power plant. More assessment will be performed to confirm these conclusions. Based on laboratory report scores, the students gain a firm understanding of the Rankine cycle concepts through use and analysis of the RC. Upon inspection of the reports, the calculations, plots, and supporting text are typically well established by the students and the RC appears to be a good learning tool for the steam power cycle. Based on individual student sample calculations scores, the RC reinforces the concepts of the steam power cycle and/or the concepts of thermodynamics for the majority of students (although it is apparent that some students are less interested in the thermal-fluids aspects of engineering or that some students are not putting forth a best effort).

In addition to assessment, a few keys to successful use of the RC were noted.

Multiple experimental parameters were investigated in an attempt to determine an optimum operating point of the RC. The analysis implies that an optimum point at which to operate the RC is not attainable with current component limitations. The RC should simply be run at the highest possible load (i.e., wattage, voltage, etc.).

Four methods for accurately determining steam flow rate using the measured turbine exhaust pipe pressure drop were suggested. Preliminary calculations with all of these methods indicate that results agree within a few percent. In addition, the calculations yield values comparable to the currently used steam flow rate determination method. The new methods of steam flow rate calculation are expected to improve uncertainty. A cold fluid calibration of the friction parameter for the exhaust tube is being contemplated.

Future work is outlined to complete a characterization of the Rankine Cyclers. In conclusion, the educational benefits of the RC seem to outweigh the idiosyncrasies of the device. For its relatively low cost, the RC is useful to the mechanical engineering curriculum. Further experimental and analytical work is being performed to fully characterize the RC so that it can be used most effectively for the students.

### **Acknowledgements**

The authors would like to thank Turbine Technologies, Ltd.; Wolfgang Kutrieb, Perry Kuznar, and Toby Kutrieb for their helpfulness, insights, and contributions to ensuring a smooth running

device; and Juan Neira (LTU), Jonathan Corbett (UE), and Jesse Kahle (UE) for their experimental work and initial set-up of the analysis Excel spreadsheets.

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1. Turbine Technologies, Ltd., *Steam Turbine Equipment*, 2002.
2. Gerhart, A. L. and Gerhart, P. M., 2005, "Laboratory-Scale Steam Power Plant Study – Rankine Cyclor™ Effectiveness as a Learning Tool and its Component Losses," Proceedings of the 2006 American Society for Engineering Education Annual Conference and Exposition.
3. Black and Veatch, Edited by Drbal, L.F., *Power Plant Engineering*, 1996, Chapman & Hall, NY, p. 363.

## Appendices

### A. Experimental Apparatus Descriptions<sup>1</sup>

The experimental hardware (Rankine Cyclor™) consists of multiple components that make up the necessary components for electrical power generation (utilizing water as the working fluid). These components include:

#### 1. Boiler

A stainless steel constructed, dual pass, flame-through tube type boiler, with super heat dome, that includes front and rear doors. Both doors are insulated and open easily to reveal the gas fired burner, flame tubes, hot surface igniter and general boiler construction. The boiler walls are insulated to minimize heat loss. A side mounted sight glass indicates water level.

#### 2. Combustion Burner / Blower

The custom manufactured burner is designed to operate on either LP or natural gas. A solid-state controller automatically regulates boiler pressure via the initiation and termination of burner operation. This U.L. approved system controls electronic ignition, gas flow control and flame sensing.

#### 3. Turbine

The axial flow steam turbine is mounted on a precision-machined stainless steel shaft, which is supported by custom manufactured bronze bearings. Two oiler ports supply lubrication to the bearings. The turbine includes a taper lock for precise mounting and is driven by steam that is directed by an axial flow, bladed nozzle ring. The turbine output shaft is coupled to an AC/DC generator.

#### 4. Electric Generator

An electric generator, driven by the axial flow steam turbine, is of the brushless type. It is a custom wound, 4-pole type and exhibits a safe/low voltage and amperage output. Both AC and DC output poles are readily available for analysis (rpm output, waveform study, relationship between amperage, voltage and power). A variable resistor load is operator adjustable and allows for power output adjustments.

### 5. Condenser Tower

The seamless, metal-spun condenser tower features 4 stainless steel baffles and facilitates the collection of water vapor. The condensed steam (water) is collected in the bottom of the tower and can be easily drained for measurement/flow rate calculations.

### 6. Data Acquisition (Note: Newer RC models have an updated system that will operate through the USB port of any newer PC.)

The experimental apparatus is also equipped with an integral computer data acquisition station, which utilizes National Instruments™ data acquisition software (modified 2004 models).

The fully integrated data acquisition system includes 9 sensors. The sensor outputs are conditioned and displayed in “real time”- on screen. Data can be stored and replayed. Run data can be copied off to floppy for follow-on, individual student analysis. Data can be viewed in Notepad, Excel and MSWord (all included).

The system is test run at the factory prior to delivery and the “factory test run” is stored on the hard drive under the “My documents” folder. This file should be reviewed prior to operation, as it gives the participant an overview of typical operating parameters and acquisition capability.

### 7. Sensors

Nine (9) sensors are installed at key system locations. Each sensor output lead is routed to a centrally located terminal board. A shielded 64-pin cable routes all data to the installed data acquisition card. This card is responsible for signal conditioning and analog to digital conversion. Software and sensor calibration is accomplished at the factory prior to shipment.

Installed sensor list includes:

- Boiler pressure
- Boiler temperature
- Turbine inlet pressure
- Turbine inlet temperature
- Turbine exit pressure
- Turbine exit temperature
- Fuel flow
- Generator voltage output
- Generator amperage output

### 8. Overall System Dimensions

Length: 48.0 inches (122 cm)  
Width: 30.0 inches (77 cm)  
Height: 58.0 inches (148 cm)

### **B. LTU laboratory exercise calculations/analysis**

After completing a 2 or 3 minute steady state run at around 3 to 4 Watts, the following data reduction is completed by the students:

1. The measured or weighted re-fill mass of water represents the boiler's total steam production during your run. This can be correlated as the steam rate by dividing the weight of the water replaced by the time duration of your run.
2. Create a T-s diagram showing the actual cycle and the ideal Rankine cycle for the steady-state process.
3. Provide a first law analysis of each stage of the actual process.
4. Calculate the isentropic efficiency for the turbine.
5. Calculate the thermal efficiency for the entire process. Also calculate the heat rate for the plant during your experiment. You will need the heating value of propane and the fuel flow rate.
6. Calculate the tower efficiency. The purpose of the tower is to reclaim the working fluid (in this case water). In other words, the amount of condensate collected, minus the starting amount of water, gives an indication of the effectiveness of the cooling tower, or tower efficiency. What was the condensing tower efficiency for your experiment?
7. You were able to record the instantaneous values of voltage and amperage. What is the average power produced? What is the total energy that was produced during your experiment?
8. Suggest some practical methods to increase the thermal efficiency of the apparatus (with little to no expense (money or power)).

### C. Student Survey Sample

Following is the survey/questionnaire distributed to the laboratory students.

The following survey is used purely for assessment. It will remain confidential and will not contribute to your grade. Be honest in your responses. The goal of this survey is to assess the effectiveness of the Rankine Cycler as a learning tool. The equipment, the experimental process, and the analysis/calculations will be assessed.

I took Thermodynamics in: Fall Spring Summer of (year) \_\_\_\_\_ Grade: \_\_\_\_\_

I took Fluid Mechanics in: Fall Spring Summer of (year) \_\_\_\_\_ Grade: \_\_\_\_\_

I took Heat Transfer in: Fall Spring Summer of (year) \_\_\_\_\_ Grade: \_\_\_\_\_

The Rankine Cycle was covered in my Thermodynamics course. Yes \_\_\_\_\_ No \_\_\_\_\_

The Rankine Cycle was covered in my Thermodynamics course. Yes \_\_\_\_\_ No \_\_\_\_\_

Before performing the Rankine Cycler exercise in lab, I felt comfortable with the concepts related to the Rankine Cycle:

|                   |          |            |       |                |
|-------------------|----------|------------|-------|----------------|
| Strongly disagree | disagree | no opinion | agree | strongly agree |
| 1                 | 2        | 3          | 4     | 5              |

After completing the Rankine Cycler exercise (including the calculations), I have a better understanding of the Rankine Cycle.

|                   |          |            |       |                |
|-------------------|----------|------------|-------|----------------|
| Strongly disagree | disagree | no opinion | agree | strongly agree |
|-------------------|----------|------------|-------|----------------|



Strongly disagree      disagree      no opinion      agree      strongly agree  
1                              2                              3                              4                              5

Suggested changes?

How do you rate the instructor's use of the Rankine Cyclor?

Unsatisfactory      poor      satisfactory      good      excellent  
1                              2                              3                              4                              5

The level of material covered with the Rankine Cyclor exercise was:

Too advanced                              just right                              Too easy  
1                              2                              3                              4                              5

The Rankine Cyclor exercise increased my interest in the thermal-fluid sciences.

Strongly disagree      disagree      no opinion      agree      strongly agree  
1                              2                              3                              4                              5

The students were also asked for "Additional comments/observations."