**MECE E3028 Mechanical Engineering Laboratory II**
**Professor Qiao Lin**
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# Experiment E4: Steam Turbine

# LABORATORY REPORT

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# Contents

# Acknowledgements

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# Abstract

This experiment evaluates a subset of a traditional steam turbine power plant, in which the chemical energy of fuel is converted to thermal, mechanical, then electrical energy to develop understanding of the principals and theories of the Rankine cycle. Once steady state at each applied load was achieved in the experimental setup, the temperature and pressure were recorded at each point of the Rankine cycle, electrical power output and generator efficiency at each load, steam flow rate, and cooling water flow rate. The data was used to characterize the real, open thermodynamic cycle which was then contrasted with an ideal Rankine cycle. The raw data collected from the experiment were within the expected range yet some of the calculated efficiencies seemed to be slightly incorrect. The steam turbine efficiencies were unreasonable for some of the applied loads but all of the actual open cycle efficiencies were reasonable. There was some heat loss present from the condenser which was expected.

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# 1 Introduction

The experiment is intended to characterize the Rankine cycle by using an open steam cycle created by using a steam turbine system. Isentropic processes will be indirectly explored by observing the real-world effects of entropy in a thermodynamic cycle. Characterization of the cycle is dependent on measurements of pressure, temperature, and mass flowrate. These values are used to calculate enthalpic states and thus determine appropriate efficiency metrics.

Characterization of thermodynamic cycles is key because of their varied uses and applications. Specifically, their use in power generation is very important as the efficient heating and cooling of water is central to moving a turbine to generate electricity. The thermodynamic cycle of a steam turbine system such as the one in the experiment is used to efficiently heat water using thermal energy. This thermal energy changes water's state from liquid water to high-pressure and high-temperature steam. This steam passes by a turbine; as the steam passes the turbine, the turbine is heated up and rotates because of the movement of the steam. This rotation is then used to generate electricity. Characterizing these phenomena can help identify sources of inefficiency and help design other systems that operate within safety guidelines.

# 2 Theory

## 2.1 Processes in a Steam Cycle

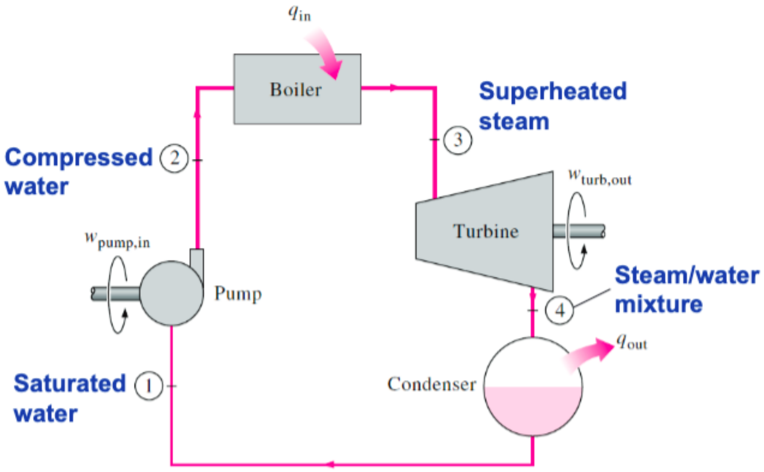

Figure 1: Steam Cycle Operation

As shown in Fig. 1 above, the steam cycle operates with several core components including a boiler, turbine, condenser, and pump.

### 2.1.1 Boiler

The boiler is a device that generates steam by applying heat energy to water. This device vaporizes water to saturated steam, and then further heats the steam in a superheater to remove droplets of water to prevent damaging the turbine.

### 2.1.2 Turbine

The turbine is a device that converts steam energy to mechanical power. It performs mechanical work on a rotating output shaft by extracting thermal energy from steam. The superheated steam in the boiler at high temperature and pressure initially gains kinetic energy as it passes through a nozzle. Then, it moves at a high velocity toward the blades of the turbine rotor. As it delivers work, the pressure and temperature of the steam drop.

### 2.1.3 Condenser

The condenser is a large heat exchanger that rejects heat from the steam to a cooling medium so that the steam may condense into liquid.

### 2.1.4 Pump

Finally, the pump is a device that compresses saturated water and sends it back into the boiler.

## 2.2 Ideal vs. Real Rankine Cycles

### 2.2.1 Ideal Rankine Cycle

An ideal Rankine cycle consists of four processes, as displayed in the T-s diagram in Fig. 2. The **isentropic** (or constant entropy) processes occur in the pump and turbine, and the **isobaric** (or constant pressure) processes occur in the boiler and condenser. From state 1 to state 2, isentropic compression occurs, as work energy is inputted through the pump to raise the pressure of a given volume of liquid. From state 2 to state 3, the cycle operates under constant pressure as heat is added the boiler. The energy at this process increases the enthalpy of the working fluid. From state 3 to state 4, isentropic expansion occurs, as the turbine moves the system from a point of high temperature and pressure to a lower point of temperature and pressure at the same entropy. Finally, from state 4 to state 1, heat is rejected in a condenser at constant pressure.

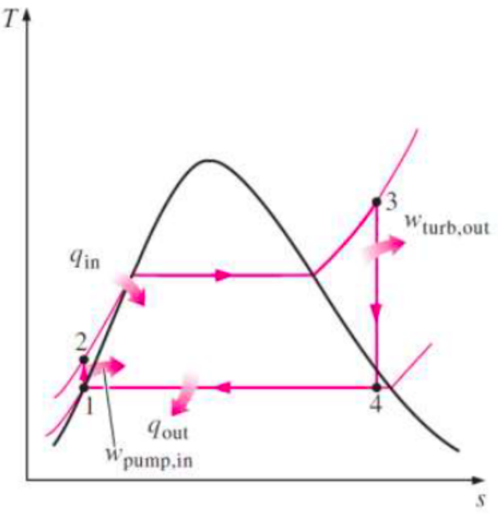

Figure 2: T-s Diagram of Ideal Rankine Cycle in Steam Power Plan

### 2.2.2 Real Rankine Cycle

As opposed to the ideal Rankine cycle, the real Rankine cycle does not include a pump nor boiler, and operates under an open loop system. This system is depicted in Fig. 3 and 4. Isentropic compression and isobaric heating no longer occur.

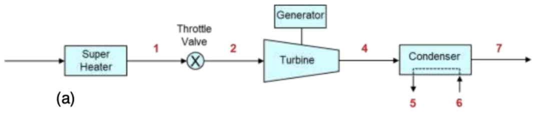

Figure 3: Block Diagram of Steam Turbine Experimental Apparatus

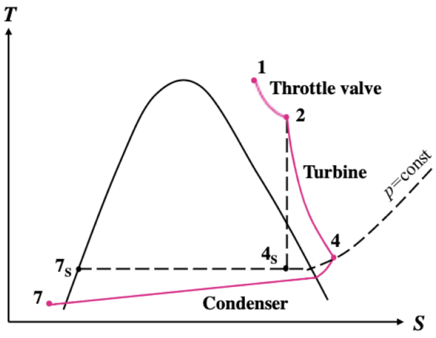

Figure 4: T-s Diagram of Real Rankine Cycle

The actual Rankine cycle deviates from the ideal cycle due to its irreversibilities in various components. These include the loss of the pump and turbine, fluid friction and heat loss, viscous pressure drops in components, and a greater heat requirement by the boiler.

## 2.3 Efficiencies and Other Equations

### 2.3.1 Carnot Efficiency

Based on Fig. 3, Carnot efficiency can be found using Eq. 1.

$$\eta_{carnot} = 1 - \frac{T_6}{T_1} \tag{1}$$

where $T_6$ is the cooling water inlet temperature and $T_1$ is the superheater outlet / throttle valve inlet temperature.

### 2.3.2 Net Work

Based on Fig. 2, the **net work** is defined by Eq. 2.

$$w_{net} = w_{out} - w_{in} = q_{in} - q_{out} \tag{2}$$

### 2.3.3 Compressor Work Input

The compressor work input or work from the pump $w_{in}$ is found by taking the difference between the enthalpy per unit mass of state 2 and state 1, as shown in Eq. 3. This quantity can also be found by multiplying the specific volume at stage 1 with the pressure drop at stages 1 and 2.

$$w_{in} = h_2 - h_1 = v_1(p_2 - p_1) \tag{3}$$

### 2.3.4 Turbine Work Out

The work out from the turbine is denoted by the difference between the enthalpy per unit mass of state 3 and state 4 in Eq. 4.

$$w_{out} = h_3 - h_4 \tag{4}$$

### 2.3.5 Boiler Heat In

The heat in from the boiler is measured by the difference between the enthalpy per unit mass of state 3 and state 2 in Eq. 5.

$$q_{in} = h_3 - h_2 \tag{5}$$

### 2.3.6 Condenser Heat Out

Eq. 6 yields heat out from the condenser as the difference between the enthalpy per unit mass of state 4 and state 1.

$$q_{out} = h_4 - h_1 \tag{6}$$

### 2.3.7 Condenser Heat Loss

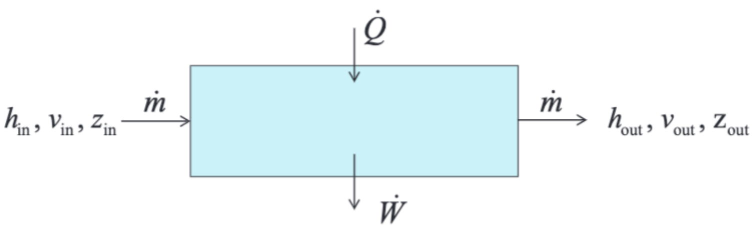

Figure 5: Energy Analysis Schematic

By applying the first law of thermodynamics to the steam and cooling water, respectively, the heat lost from steam to ambient in the heat exchanger can be found. Using Fig. 5 and the fact that all four components in the Rankine cycle operate on steady flow, the first law is simplified to yield the heat loss from the condenser by Eq. 7:

$$\dot{Q}_{loss} = \dot{m}_{coolingwater}(h_5 - h_6) \tag{7}$$

In this experiment, the mass flow rate $m_{coolingwater}$ is found using a flowmeter and stop watch.

### 2.3.8 Ideal and Actual Thermal Efficiencies

The thermal efficiency is found by the ratio of net work to heat in (i.e. heat from the condenser):

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} \tag{8}$$

By relating Fig. 4 and Eq. 8, the **ideal thermal efficiency** and **actual thermal efficiency** are found by equations 9 and 10, respectively.

$$\eta_1 = 1 - \frac{q_{out,s}}{q_{in,s}} = 1 - \frac{h_{4s} - h_{7s}}{h_1 - h_{7s}} \tag{9}$$

$$\eta_2 = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{h_4 - h_7}{h_1 - h_7} \tag{10}$$

### 2.3.9 Turbine Efficiency

The turbine efficiency, which compares the actual performance of the turbine to the ideal is given by Eq. 11:

$$\eta_{turbine} = \frac{h_2 - h_4}{h_2 - h_{4s}} \tag{11}$$

Factors affecting the steam's cycle overall performance include flu-gas exit temperature, excess air and burnout - which is directly connected to mechanical design of boiler and it's technology.

### 2.3.10 Overall Efficiency of Turbine-Generator Combination

The turbine is usually packaged together with a generator. The generator efficiency is found by the ratio of electric power output to mechanical power output in Eq. 12.

$$\eta_{gen} = \frac{\dot{W}_{elec,out}}{\dot{W}_{shaft,in}} \tag{12}$$

The overall efficiency of the turbine-generator can be found by multiplying the efficiencies of the turbine and generator, as shown by Eq. 13.

$$\eta_{turb-gen} = \eta_{turb}\eta_{gen} \tag{13}$$

## 2.4 Parameter use in Data Analysis

The steam flow rate of the measured condensed steam collected in a bucket allows us to calculate a mass flow rate operating within the steam turbine cycle. This will be used to calculate heat and work and thus efficiencies in the turbine cycle.

Finally the cooling water flow rate will be used alongside the flow rate of the steam such that through the use of the 1st law of thermodynamics we may find the rate of heat loss from the steam to the ambient in the heat exchanger or condenser in this case.

The temperatures and pressures at different points in the cycles will be used to construct a T-S diagram as well as a P-V diagram. These can be used to characterize the real thermodynamic cycle that occurs in the steam turbine which can then be compared to the Rankine cycle.

The DC voltages and DC currents measured in the experiment can be used to measure the power input and output of the steam turbine. Additionally, they can be used in conjunction with the steam flow rate to demonstrate how much mass can be moved per unit power. This can be further combined with the cooling water flow rate to determine how much cooling is required per unit of power.

# 3 Apparatus and Approach

The experiment relies on an open steam turbine as a real-world proxy for the Rankine cycle. Different temperatures and pressures in the steam turbine are measured in the experiment, as is the flow rate of steam moving through the turbine. This is accomplished using relevant sensors in the steam turbine.

## 3.1 Apparatus

Figure 6: Steam Turbine

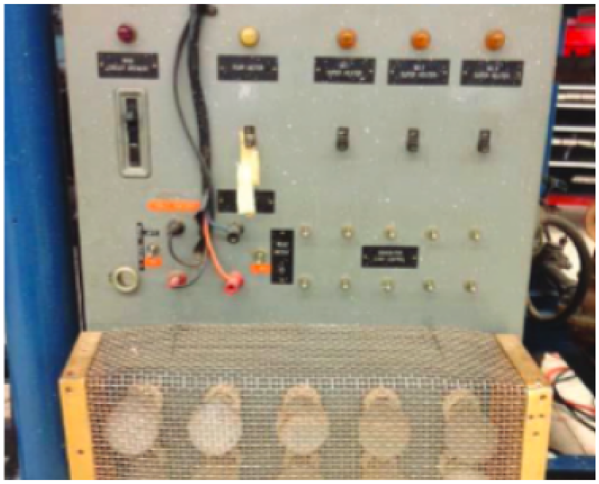

Figure 7: Generator and Load

The apparatus used in this experiment consist of the Westinghouse Steam Unit which works as our experiments Rankine Cycle; an ammeter and a voltmeter to measure the electrical power output from the Steam turbine; an EXTEECH Stroboscope Tachometer to match the RPM of the turbine to what it needs to be, thermocouples; and pressure gauges to respectively measure temperature and pressure and a Toledo scale and bucket to obtain the flow rate of steam in the turbine.

## 3.2 Approach

Prior to beginning the experiment, the laboratory staff will first open the cooling water valve. They will also check that the turbine Main Steam Valve is open and that the Manual Speed Adjustment valve is slightly open. The Main Steam valve will also be opened until the pressure reaches 90 psi in the first pressure gauge on the stream line, while simultaneously controlling the Speed Adjustment valve so that the pressure at the outlet of the super-heaters is generated by a turbine speed of 3750 rpm.

At the start of the experiment, measure the ambient pressure and temperature of the environment. Then check that all the light bulbs are off on the turbine and adjust the speed to 3750 rpm. To do so, set the strobe light to 3750 rpm and shine it on the turbine. Wait for steady-state before recording the measurements. When the turbine is at the right rpm, a white stripe will appear. To adjust the speed of the turbine, use the black knob on the turbine with caution as components may be hot. Once calibration is finished, turn the strobe light off.

After calibration, turn on all ten light bulbs. Adjust the speed to 3750 rpm and wait for steady-state. Record the temperature and pressure at points 1, 2, 4, 7, 5, and 6. Using the provided scale and timer, measure the steam flow rate by placing the bucket on the scale under the water valve exit, zeroing it, and using the stop watch. After turning the valve to let water out, time an interval and measure the change in weight. Then measure the cooling water flow rate using the dial at the top of the flow-meter.

At that load, determine the electrical power output and generator efficiency using the connected ammeter and voltmeter. Then reduce the load by increments of 200 W - the equivalent of turning off two light bulbs - and record the measurements. After finishing the experiment, the laboratory staff will shut it down properly.

# 4 Results

| | | 1 | 2 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| 1000 W | Temperature (F) | 328 | 283 | 223 | 79 | 43 | 109 |
| | Pressure (PSI) | 107 | 85 | 37.5 | | | 12 |
| | Steam flow rate | 1.85 lb/30s | | Voltage (V) | 112 | | |
| | Cooling flow rate | 10 gal/min | | Current (A) | 7.23 | | |
| 800 W | Temperature (F) | 329 | 281 | 215 | 75 | 43 | 102 |
| | Pressure (PSI) | 106 | 89 | 32 | | | 12 |
| | Steam flow rate | 1.65 lb/30s | | Voltage (V) | 110.5 | | |
| | Cooling flow rate | 10.5 gal/min | | Current (A) | 5.6 | | |
| 600 W | Temperature (F) | 331 | 291 | 216 | 73 | 43 | 98 |
| | Pressure (PSI) | 107 | 90.5 | 29 | | | 13 |
| | Steam flow rate | 1.5 lb/30s | | Voltage (V) | 110.5 | | |
| | Cooling flow rate | 10.05 gal/min | | Current (A) | 4.25 | | |
| 400 W | Temperature (F) | 336 | 305 | 223.5 | 70 | 43 | 95 |
| | Pressure (PSI) | 105 | 90.5 | 22.5 | | | 14 |
| | Steam flow rate | 1.3 lb/30s | | Voltage (V) | 110 | | |
| | Cooling flow rate | 9.5 gal/min | | Current (A) | 2.85 | | |
| 200 W | Temperature (F) | 337 | 310 | 230 | 66 | 43 | 93 |
| | Pressure (PSI) | 105 | 91 | 19 | | | 12 |
| | Steam flow rate | 1.15 lb/30s | | Voltage (V) | 110.5 | | |
| | Cooling flow rate | 10 gal/min | | Current (A) | 1.41 | | |
| 0 W | Temperature (F) | 339 | 313 | 234 | 62 | 43 | 91 |
| | Pressure (PSI) | 105.5 | 92.5 | 12 | | | 12 |
| | Steam flow rate | 0.9 lb/30s | | Voltage (V) | 111 | | |
| | Cooling flow rate | 10 gal/min | | Current (A) | 0 | | |

Table 1: Raw Data collected from Experiment

The results of the experiment are shown in Table 1. These values converted to metric units - as well as their corresponding enthalpies and entropies - are reported in Tables The results are categorized by the load applied to the steam turbine system. Measurements of the steam flow rate and cooling flow rate are included alongside the standard temperature and pressure measurements. Pressure values for points 5 and 6 in the steam turbine are not included because analysis of the steam turbine's thermodynamic cycle is not dependent on the pressures present at the condenser. The results are fairly reasonable; according to the T-S diagram for the open Rankine cycle presented in this experiment, the temperatures should be decreasing as the steam travels through the turbine. The tables with these values are reported in the Appendix in Table 2 through Table 7.

# 5 Discussion

The efficiency results displayed in this report indicate a number of possible conclusions about the how the cycle operates as a function of its power output. These results do not however reflect the reasonable conclusions. With the major error in calculating the efficiencies being how the enthalpies were derived. Although reference was made to thermodynamic tables in order to obtain accurate readings for enthalpy and entropy at each state, improper tables were interpolated from. The state of the steam within a Rankine cycle does not remain in the form of super heated steam, however all values of enthalpy and entropy were calculated as though it did stay in this state. When in fact following it only remain as super heated vapor prior to its interaction with the turbine after which it becomes a saturated vapor, to which separate tables are dedicated. And after going through the condenser is in fact liquid water. This is a major oversight in the results but one that was pinpointed and observed by the analysis of the unreasonable data acquired. This error in calculation, ultimately lead to T-s diagrams that were blatantly inaccurate as well as efficiency vs wattage diagrams that did not correctly reflect what the true characteristic form of the steam turbine's thermodynamic cycle.

There were several key errors in the implementation of this experiment. The most relevant error present was adjusting the turbine's revolutions. This was an exercise of pure estimation and thus provided low precision and low accuracy for actually attaining the desired speed of 3750 RPM.

Furthermore, despite the lab instructions and the team's best intentions, it was impossible to operate the steam turbine entirely safely. There was no way of ensuring that the turbine's speed did not exceed 3800 RPM using the apparatuses made available to the team. An additional safety concern was that the steam turbine was not technically designed to exceed 90 PSI yet there was no indicator for the gauge pressure within the steam turbine system to indicate that this pressure limit was not exceeded.

Tables 2 to 7 in Appendix **??** show results for the ideal and real thermodynamic states in the steam turbine at varying loads. The relationships between the temperature and entropies across the different loads can also by seen in the T-s diagrams in figures 8 to 12 in Appendix **??**. All T-s diagrams display a similar temperature drop with increasing entropy.

From Fig. **??** in Appendix **??**, it can be seen that the Carnot Efficiency generally decreases as the load increases. The Ideal efficiency remained constant across all the loads, whereas the actual efficiency tended to increase with increasing loads. The turbine efficiency also exhibited this directly proportional relationship with load percentage, as it similarly tended to increase with higher loads, as shown in Fig. **??**.

The condenser heat loss remains constant for the most part, but decreases as electrical load increases, which was expected to be the case. As the mass flow rate increases, there is more friction present throughout the walls of the turbine.

## 5.1 Uncertainties

For this experiment, to calculate the uncertainty, the partial derivative uncertainty propagation method was used. This means that for some value $F = f(a, b, ..., n)$, the uncertainty is:

$$\sigma_F = \sqrt{\left(\frac{\delta F}{\delta a}\right)^2 \sigma_a^2 + \left(\frac{\delta F}{\delta b}\right)^2 \sigma_b^2 + ... + \left(\frac{\delta F}{\delta n}\right)^2 \sigma_n^2} \tag{14}$$

In this experiment, there is uncertainty in the Carnot efficiency, ideal Ranking cycle efficiency, actual thermal efficiency, and power of the generator. By applying equation 14 to Carnot efficiency, we can obtain the following equation:

$$\sigma_{\eta_{Carnot}} = \sqrt{(\frac{\delta \eta_{Carnot}}{\delta \sigma_{T_6}})^2 \sigma_{T_6}^2 + (\frac{\delta \eta_{Carnot}}{\delta \sigma_{T_1}})^2 \sigma_{T_1}^2} \tag{15}$$

This can then be simplified into which is the form in which other uncertainty equations will be given as:

$$\sigma_{\eta_{Carnot}} = \sqrt{(-\frac{1}{T_1})^2 \sigma_{T_6}^2 + (\frac{T_6}{T_1^2})^2 \sigma_{T_1}^2} \tag{16}$$

For the ideal Rankine cycle efficiency uncertainty, the following equation was used:

$$\sigma_{\eta_1} = \sqrt{(-\frac{1}{h_1 - h_{7s}})^2 \sigma_{h_{4s}}^2 + (\frac{h_1 - h_{4s}}{(h_1 - h_{7s})^2})^2 \sigma_{h_{7s}}^2 + (\frac{h_{4s} - h_{7s}}{(h_1 - h_{7s})^2})^2 \sigma_{h_1}^2} \tag{17}$$

Similarly, the following equation was used for the uncertainty of the actual thermal efficiency.

$$\sigma_{\eta_2} = \sqrt{(-\frac{1}{h_1 - h_7})^2 \sigma_{h_4}^2 + (\frac{h_1 - h_4}{(h_1 - h_7)^2})^2 \sigma_{h_7}^2 + (\frac{h_4 - h_7}{(h_1 - h_7)^2})^2 \sigma_{h_1}^2} \tag{18}$$

The thermal efficiency uncertainty equation is as follows:

$$\sigma_{\eta_{thermal}} = \sqrt{(-\frac{h_{4s}}{h_2 - h_{4s}})^2 \sigma_{h_2}^2 + (\frac{1}{(h_2 - h_{4s})^2})^2 \sigma_{h_4}^2 + (\frac{h_2 - h_4}{(h_2 - h_{4s})^2})^2 \sigma_{h_{4s}}^2} \tag{19}$$

Lastly, the uncertainty for the power of the generator can be found with the following equation:

$$\sigma_P = \sqrt{(V\eta_{gen})^2 \sigma_I^2 + (I\eta_{gen}))^2 \sigma_V^2 + (IV)^2 \sigma_{\eta_{gen}}^2} \tag{20}$$

All uncertainty calculations are show in Table 14 in Appendix A.3.

# 6 Conclusions

Steam turbines are the most widely used forms of generating power and electricity. In this experiment a Westinghouse steam turbine was studied under various power loads as to investigate the Rankine cycle to better understand its thermodynamic characteristics. Using the temperatures and pressures across the differing states of the steam cycle a characterization can be made of the thermodynamics cycles in accordance with varying outputs of power. These states being through the super heater, throttling valve, turbine and condenser, as the Westinghouse Unit available for experimentation omitted other portions of the cycle.

Observation of these cycles were targeted toward how the efficiencies of the system compare to their ideal counterparts. Some of the efficiencies listed were reasonable and expected; others were clearly miscalculated or the instruments measuring the steam turbine were miscalibrated or otherwise damaged. The condenser heat loss remains constant for the most part, but decreases as electrical load increases, which was expected to be the case.

The steam cycle that was analyzed in this experiment was an approximation of the Rankine cycle. Since the apparatus did not include a pump and boiler, the cycle could not be approximated as a closed-loop Rankine cycle. Instead, the cycle resembled an open-loop system containing a superheater, turbine, and condenser.

Contributions by section:

- Abstract: Sam, Bruno
- Introduction: Ashton, Bruno
- Theory: Arlene, Axel
- Apparatus and Approach: Christine
- Results: Christine, Arlene, Anton, Bruno
- Discussion: Christine, Bruno, Anton, Arlene
- Conclusions: Bruno, Anton, Axel, Sam, Arlene
- Appendix: Bruno, Arlene, Christine

# A Appendix

| Point | T (K) | p (Pa) | h (kJ/kg) | s (kJ/kgK) |
|---|---|---|---|---|
| 1 | 437.5944444 | 737738.999 | 2761.765 | 6.715 |
| 2 | 412.5944444 | 586054.345 | 2732.15 | 6.939 |
| 4 | 379.2611111 | 258553.3875 | 2684.94 | 7.284 |
| 4s | 383.5227556 | 143300 | 2691.07 | 7.238 |
| 7s | 383.5227556 | 143300 | 2691.07 | 7.238 |
| 7 | 315.9277778 | 82737.084 | 2578.89 | 8.2 |

Table 2: 1000 W Load Values

| Point | T (K) | p (Pa) | h (kJ/kg) | s (kJ/kgK) |
|---|---|---|---|---|
| 1 | 438.15 | 730844.242 | 2762.8 | 6.707 |
| 2 | 411.4833333 | 613633.373 | 2730.84 | 6.948 |
| 4 | 374.8166667 | 220632.224 | 2678.2 | 7.334 |
| 4s | 376.4264068 | 143300 | 2680.7 | 7.315 |
| 7s | 376.4264068 | 143300 | 2680.7 | 7.315 |
| 7 | 312.0388889 | 82737.084 | 2571.54 | 8.277 |

Table 3: 800 W Load Values

| Point | T (K) | p (Pa) | h (kJ/kg) | s (kJ/kgK) |
|---|---|---|---|---|
| 1 | 439.2611111 | 737738.999 | 2763.84 | 6.698 |
| 2 | 417.0388889 | 623975.5085 | 2738.29 | 6.894 |
| 4 | 375.3722222 | 199947.953 | 2679.03 | 7.328 |
| 4s | 377.0972028 | 143300 | 2681.68 | 7.308 |
| 7s | 377.0972028 | 143300 | 2681.68 | 7.308 |
| 7 | 309.8166667 | 89631.841 | 2567.58 | 8.319 |

Table 4: 600 W Load Values

| Point | T (K) | p (Pa) | h (kJ/kg) | s (kJ/kgK) |
|---|---|---|---|---|
| 1 | 442.0388889 | 723949.485 | 2766.78 | 6.674 |
| 2 | 424.8166667 | 623975.5085 | 2747.91 | 6.822 |
| 4 | 379.5388889 | 155132.0325 | 2685.54 | 7.279 |
| 4s | 375.0526676 | 143300 | 2678.56 | 7.331 |
| 7s | 375.0526676 | 143300 | 2678.56 | 7.331 |
| 7 | 308.15 | 96526.598 | 2564.58 | 8.352 |

Table 5: 400 W Load Values

| Point | T (K) | p (Pa) | h (kJ/kg) | s (kJ/kgK) |
|---|---|---|---|---|
| 1 | 442.5944444 | 723949.485 | 2767.34 | 6.67 |
| 2 | 427.5944444 | 627422.887 | 2751.15 | 6.797 |
| 4 | 383.15 | 131000.383 | 2691.07 | 7.238 |
| 4s | 371.869819 | 143300 | 2673.55 | 7.369 |
| 7s | 371.869819 | 143300 | 2673.55 | 7.369 |
| 7 | 307.0388889 | 82737.084 | 2562.59 | 8.374 |

Table 6: 200 W Load Values

| Point | T (K) | p (Pa) | h (kJ/kg) | s (kJ/kgK) |
|---|---|---|---|---|
| 1 | 443.7055556 | 727396.8635 | 2768.44 | 6.66 |
| 2 | 429.2611111 | 637765.0225 | 2753.07 | 6.783 |
| 4 | 385.3722222 | 82737.084 | 2694.43 | 7.213 |
| 4s | 360.2496747 | 143300 | 2654.78 | 7.516 |
| 7s | 360.2496747 | 143300 | 2654.78 | 7.516 |
| 7 | 305.9277778 | 82737.084 | 2560.59 | 8.396 |

Table 7: 0 W Values

## A.1 Efficiencies

| Efficiency | Value |
|---|---|
| Carnot | 0.9628378378 |
| Ideal | 1 |
| Actual | 0.4200956938 |
| Turbine | 1.149221032 |

Table 8: 1000 W Efficiencies

| Efficiency | Value |
|---|---|
| Carnot | 0.962962963 |
| Ideal | 1 |
| Actual | 0.4423298128 |
| Turbine | 1.049860391 |

Table 9: 800 W Efficiencies

| Efficiency | Value |
|---|---|
| Carnot | 0.9632107023 |
| Ideal | 1 |
| Actual | 0.4321308468 |
| Turbine | 1.046811517 |

Table 10: 600 W Efficiencies

| Efficiency | Value |
|---|---|
| Carnot | 0.9638157895 |
| Ideal | 1 |
| Actual | 0.4017804154 |
| Turbine | 0.8993511175 |

Table 11: 400 W Efficiencies

| Efficiency | Value |
|---|---|
| Carnot | 0.9639344262 |
| Ideal | 1 |
| Actual | 0.3725030525 |
| Turbine | 0.7742268041 |

Table 12: 200 W Efficiencies

| Efficiency | Value |
|---|---|
| Carnot | 0.9641693811 |
| Ideal | 1 |
| Actual | 0.3560740919 |
| Turbine | 0.5966018924 |

Table 13: 0 W Efficiencies

## A.2 T-s diagrams

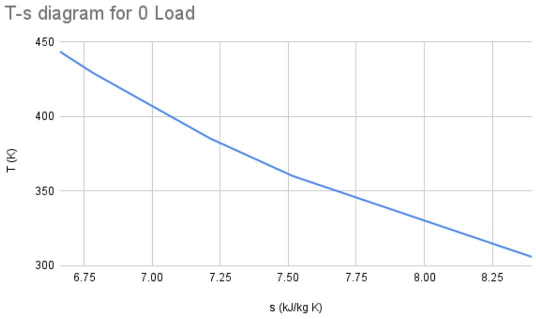

Figure 8: T-s diagram for 0 Load

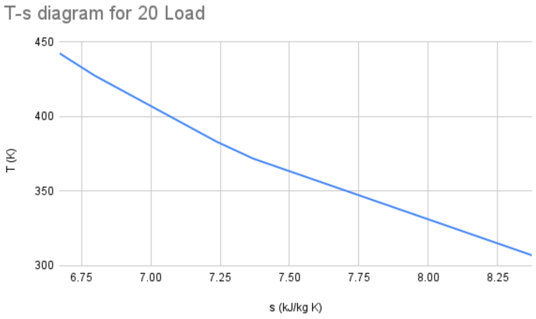

Figure 9: T-s diagram for 20 Load

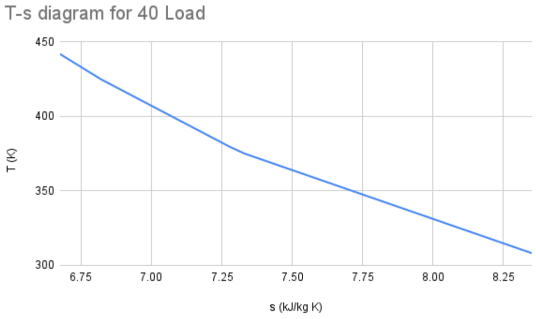

Figure 10: T-s diagram for 40 Load

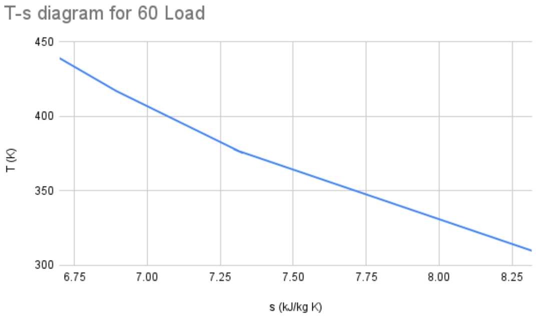

Figure 11: T-s diagram for 60 Load

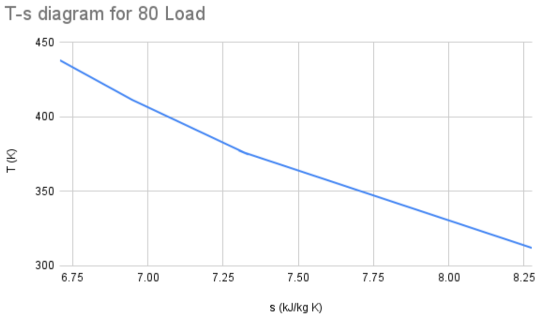

Figure 12: T-s diagram for 80 Load

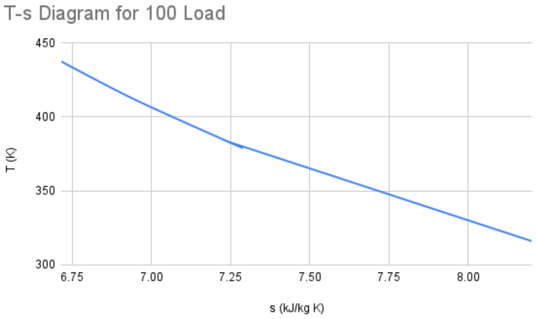

Figure 13: T-s diagram for 100 Load

## A.3 Uncertainty calculations

| | 0% | 20% | 40% | 60% | 80% | 100% |
|---|---|---|---|---|---|---|
| $\sigma_{carnot}$ | 0.003 | 0.027 | 0.027 | 0.027 | 0.027 | 0.027 |
| $\sigma_{\eta 1}$ | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 |
| $\sigma_{\eta 2}$ | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 |
| $\sigma_{\eta thermal}$ | 5.754 | 5.898 | 5.937 | 5.962 | 5.954 | 6.043 |
| $\sigma_{P}$ | 0.222 | 1.937 | 4.272 | 6.965 | 9.668 | 13.214 |

Table 14: Uncertainties per load