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Steam Engine Laboratory

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Abstract

A full-scale small industrial power generation facility operating under the Rankine cycle was used in this lab. In this experiment, a closed Rankine cycle was used where the condensed water left the condenser and was sent to waste while the pump was fed from a reservoir. The power produced by the motor was found by applying a torque to the motor and multiplying that torque by the shaft speed in the motor. The power output of the cycle was found to be 69.8 Watts. Power losses were found from the Willans line produced from the experiment. Power losses in this experiment were found to be 84.44 Watts. Power losses occur due to friction in moving parts of the engine and the turbine. The thermal efficiency of the experiment was found to be 1.331% and the steam engine efficiency was found to be 45.254%. The dryness factor of the steam leaving the boiler and entering the boiler was found to be 97.965%.

Introduction

Since the discovery of the Rankine Cycle, mechanical engineers have been able to utilize it for everyday functions. In this lab the students used a full-scale small industrial power generation facility operating under the Rankine Cycle. Figure 1 shows the experimental setup used. Operating under the Rankine Cycle, the working fluid will undergo 4 separate processes. First, the fluid goes through a pump where it undergoes an increase in pressure. Next, the high pressure liquid goes into a constant pressure boiler where it vaporizes and becomes a dry vapor. After the boiler, the liquid goes through a turbine where it expands, which generates power. Finally, the fluid enters a condenser where it becomes a saturated liquid. In a closed cycle, the steam from the condenser is reused and sent back into the pump, but in this experiment the condensed water is collected as waste and the pump is fed from a reservoir. Figure 2 shows the cycle used in the experiment compared to a standard closed Rankine cycle. In this experiment, in order to measure the power produced from the cycle, the students use a dynamometer to apply torque to the motor. The product of the torque and the motor shaft speed gives the shaft power the motor consumes from the steam flow. The data collected in the experiment will be compared to the Willans line. The Willans line is a linear line formed by the steam used per hour over the power output of the cycle. This line will help determine efficiencies of the cycle as well as determine power losses which are caused by friction in the moving parts in the motor and turbine.

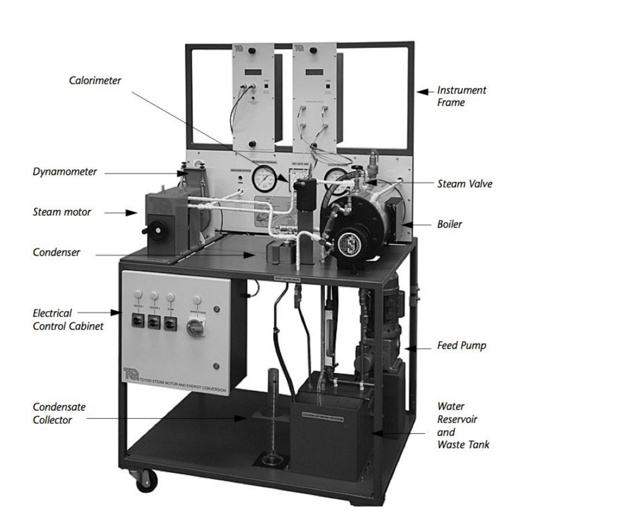

Figure 1: Experimental Setup of Motor

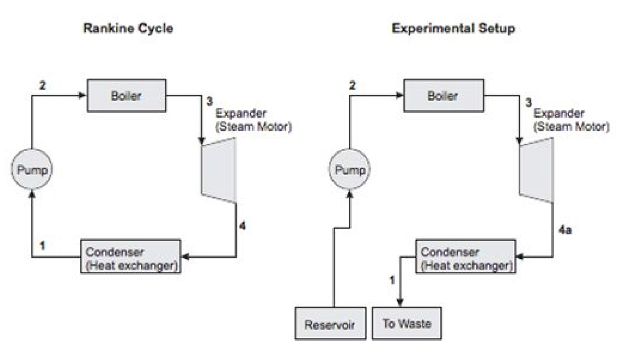

Figure 2: Closed Rankine Cycle Compared to Open Cycle Used In Experiment

Results and Discussion

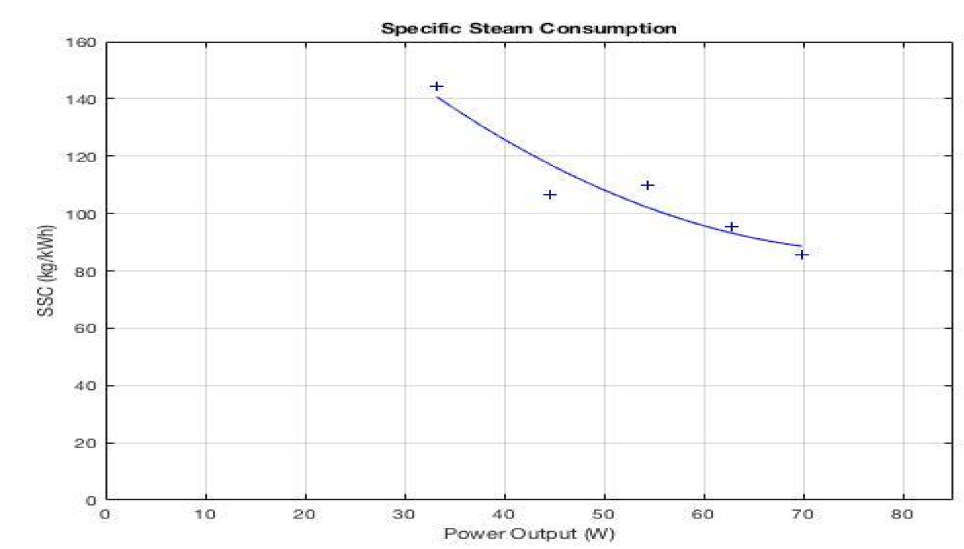

Figure 3: Specific Steam Consumption Curve

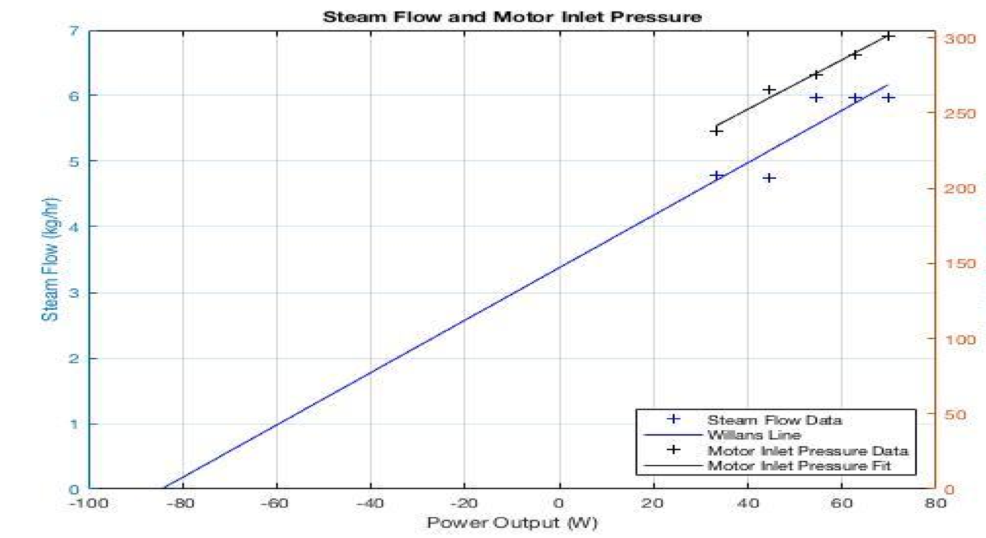

Figure 4: Willan's Line and Motor Inlet Pressure vs. Power Output

Component	Temperature (K)	Temperature (°C)	Enthalpy (kJ/kg)	Absolute Pressure (kPa)	Entropy (kJ/kg*K)
1-Boiler	405.63	132.48	556.97952	306.2	1.6606896
2-Calorimeter	375.57	102.42	102.42	301.1	7.325644
3-Cooling Water In	288.58	15.43	64.782238	100	0.230692
4-Cooling Water Out	318.16	45.01	188.4818	100	0.6387304
5-Condensate	293.15	20	83.915	100	0.2965

Table 1: Data Series 5 - Highest Power State Data

Component	Power (W)
W1 - Engine Power Output	69.8
Engine Losses	84.44
W1+Engine Losses	154.24
Q1 - Electrical Input to Boiler	4460
Q2 - Heat Loss Rate from Boiler	936.8231712
Q3+Q4 - Heat Loss Rate from Boiler and Condenser	158.398732
Q5 - Rate of Heat Transfer to Condenser Cooling Water	4080.2652

Table 2: Data Series 5 - Highest Power Calculations

Thermal Efficiency	1.331%
Dryness Factor	97.965%
Efficiency of Steam Engine	45.254%
Energy Balance	3.97904E-13

Table 3: Data Series 5 - Highest Power Findings

As seen in figure 3, the specific steam consumption curve (s.s.c.) aligns well with what a s.s.c. is supposed to look like. However, we notice that this s.s.c. is significantly closer to the power output axis, indicating that a great amount of steam must be consumed to generate a given power out, as compared to that of a power plant. This curve for a steam power plant would be approximately the same shape, but shifted up and right. In figure 4, we see a plot of steam flow versus power output on the left y-axis and motor inlet pressure versus power output on the right y-axis. In regards to the steam flow versus power output portion of the plot, we notice that the data follows a linear trend. Upon fitting a linear fit line to the data and extending it down to the x-axis, we form the Willans line. This line tells us the power losses within the motor, which is 84.4W, or where the steam flow is equal to 0. We also can see that the motor inlet pressure also increases at about the same rate as the Willans line and follows a similar linear increasing trend as power output increases. This is expected, since we know from Thermodynamics that the power output of a turbine or motor will increase if the pressure entering it is increased. After analyzing all the data sets as a whole, we focused solely on data series 5, which is the series with the highest power output. After referencing thermodynamic water tables, the enthalpies and entropies at each point in the Rankine cycle was determined, and reported in table 1. Using this data along with the flow rates of the condensate and cooling water, the work (W) and heat transfer rate (Q) values were determined using the equation in the equations section. These results are tabulated in table 2. Then, using these values, overall cycle properties could be calculated as shown in table 3. For example, the thermal efficiency of the cycle was calculated from equation 2 to be 1.331%, as reported in table 3. This is a very low efficiency, and would not be useful in a practical situation like in a power plant. This efficiency indicates that we are only changing about 1/100 of the energy input into the cycle into motor power. The rest is lost in motor losses and heat loss. Another value that we calculated was the dryness factor using equation 7. This value of 97.965% tells us that the steam going into the engine is very dry steam. There is some water droplets,however, that will erode the components of the motor over time, but not as quickly as if the dryness factor was lower. Also calculated was the steam engine efficiency, which was 45.254%. This is the efficiency of the steam engine itself. The efficiency here means that a little less than half of the energy into the engine is converted into the work done by the engine. This value is much higher than the overall thermal efficiency of the cycle and closer to the efficiency of a typical Rankine cycle power plant, indicating that there are greater losses elsewhere in the cycle. As you can see, with simple measurements of temperature, pressure, and flow rate, different characteristics about a cycle can be determined. Just from these values, the overall efficiency of a cycle can be calculated, which is very useful in determining whether equipment should be upgraded or replaced in a power plant.

References

1. https://www.rutgers.edu/sites/default/files/RU_SHIELD_RED_th.png - Rutgers Shield
2. http://weekshall.rutgers.edu/sites/default/files/rutgers-logo.png - Rutgers School of Engineering Logo
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4. Ã§engel, Yunus A., and Michael A. Boles. *Thermodynamics: an Engineering Approach*. McGraw-Hill Education, 2015.

Equations

$$W_1 = Q_1 - Q_2 - Q_3 - Q_4 - Q_5 + m(h_w - h_3) \quad [1]$$

$$\eta_{th} = \frac{W_1}{Q_1 + m(h_w - h_3)} \quad [2]$$

$$Q_1 + mh_0 = Q_2 + mh_1 \quad [3]$$

$$\eta_b = \frac{m(h_1 - h_w)}{Q_1} \quad [4]$$

$$mh_1 = W_1 + mh_2 + Q_3 \quad [5]$$

$$mh_2 = Q_4 + Q_5 + mh_3 \quad [6]$$

$$x = (h_1 - h_w)/h_{fg} \quad [7]$$

$$s.s.c. = \text{Steam Flow/Power Out} \quad [8]$$

Error Analysis Discussion

Another value calculated in table 3 is the energy balance, which is calculated through equation 1. Subtracting W1 from the right side of the equation yields 3.97904E-13, which is approximately 0. This indicates that the calculations that we performed and measurements that we took are very accurate. However, there is still some error present. This could be due to leaks in the system, fluctuation in the engine losses, and changes in the electrical input to the boiler. Steam or condensate leaking out would change the values measured, altering energy balance. Engine losses may change over time due to changes in friction coefficients as water condensates in the engine. The electricity from the wall is not always providing a constant voltage and amperage, which causes the input power to change as well, which is not accounted for. Changing the power source to a steady, isolated, DC power source would help solve the power fluctuation issue. To solve the issue of the condensate, the dryness factor has to be increased by increasing the temperature or pressure of the calorimeter, increasing h1. This should all be done after checking the system over for leaks and sealing any that are found. Fixing these sources of error should improve the results of this experiment.

Conclusion

In this experiment, a full-scale small industrial powerplant was analyzed. By taking measurements of pressure, temperature, and flow rate at different locations in the Rankine cycle that the plant operates on, we were able to find enthalpies at each point. At different torque values, these data points were collected. A specific steam consumption plot was generated, and indicated to us that this plant is inefficient, due to how low the curve was on the y-axis. Using the plot of steam flow versus power output, the Willans line was able to be fit to the data points and allow us to find the engine losses value of 84.4W. The highest torque output value was analyzed more in depth with the other equations, which led us to a thermal efficiency of the cycle of 1.331%, pretty inefficient for a Rankine cycle. This, however, was expected due to the amount of steam that is needed to provide a small amount of power. The 97.965% dry steam entering the engine allowed for an engine efficiency of 45.254%, indicating that a majority of the losses in the cycle are elsewhere in the system. Finally, we were able to confirm that our measurements and calculations were accurate, since the energy balance was essentially 0. This experiment helped us to understand the Rankine cycle more in depth and how powerplants are quantified.