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School of Engineering

Steam Engine Laboratory

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Abstract

In this experiment, the cycle of a steam engine was analyzed. The steam engine used operates under the Rankine cycle. Along with the steam power generating apparatus, a data acquisition system was used to collect data. The data collected in the lab was used to calculate the efficiency of the boiler and the overall thermal efficiency of the pump. The Willans line was used to calculate the power losses from the curve that relates steam flow to power output. The power output was also compared to the motor inlet pressure and the specific steam consumption. The rates of heat transfer at each stage were calculated, and these values determined efficiencies and the dryness factor. The dryness factor was calculated to be .98, which is an appropriate value for a steam engine. The overall thermal efficiency is very low, about 1.69%, however a low efficiency such as this one is to be expected. Finally, the boiler efficiency was found to be about 65%. This number seems reasonable. While the results seem reasonable, factors of potential error and uncertainty were analyzed as well.

Introduction

The application of steam in the energy industry has been pivotal since its emergence during the Industrial revolution. Although it has been used in practice for hundreds of years, it has only been a short time since we've understood the fundamentals of the processes the steam undergoes. These fundamentals include the thermodynamic cycles the steam goes through when changing phases. The Rankine Cycle is an idealized example of one of these cycles. It is modeled through the use of four devices.

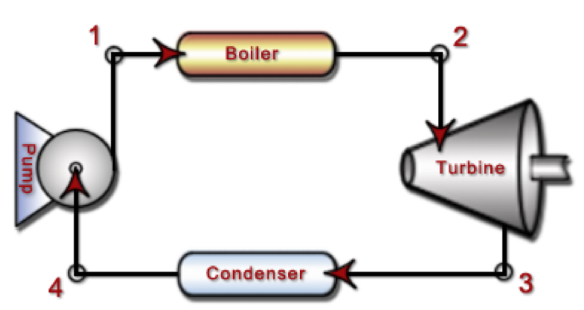

Figure 1: Rankine Cycle (closed)

We will be running a power generator that closely replicates this process but is open, meaning the water leaves the cycle after the turbine and new water is put through the pump. We will then use data from sensors and thermocouples on the engine to analyze the function of each device in order to better understand the steam engine's operation and efficiency.

The Turbine is replaced with a steam motor that has adjustable friction we can incrementally control via a dynamometer. If we assume the pump and steam motor operate isentropically (no change in entropy), we can solve for the enthalpies through each device. After that, we will use equation [1] to calculate the steady flow energy generation, and plot a curve that represents the specific steam consumption.

Results & Discussion

The first part of the analysis involves taking the condensate flow rate and motor power and converting them into kg/h and kW respectively. By taking the ratio of the two, the specific steam consumption can easily be obtained in kg/kWh. These values are tabulated in Figure 1.

Specific Steam Comsumption (kg/kWh)
191.52
81.81818182
108.6545455
76.62857143
72

Figure 1. Specific Steam Consumption at different Power Outputs

The specific steam consumption curve can be made by graphing these values versus the values for motor power. This graph is shown in Figure 2. Another useful comparison is steam flow rate versus motor inlet pressure. This is important to look at because in a sense this represents the performance of the machine. It shows how much energy it uses from the steam flowing through it. The comparison is usually linear and the line that forms is called the Willans line. By extending this line to the horizontal axis, the power losses in the engine can be determined. Based off the equation given for the Willans line in the graph on Figure 3. Plugging in zero for y, it is shown that the power losses in the engine are about 142 Watts. This is almost double what the average power loss is in this type of experiment. Several errors could have accounted for this, and will further be discussed later. Another curve, Figure 4, compares motor inlet pressure to power output. It can be seen from this that the higher the pressure is at the motor inlet, the higher power output the engine has.

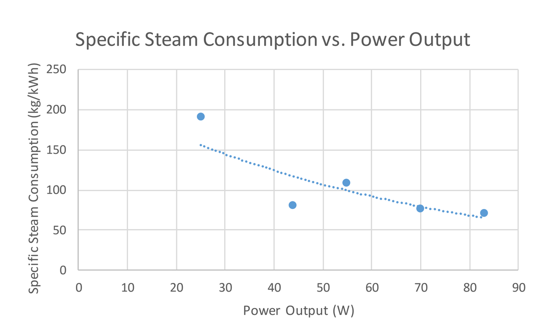

Figure 2. Specific Steam Consumption vs. Power Output

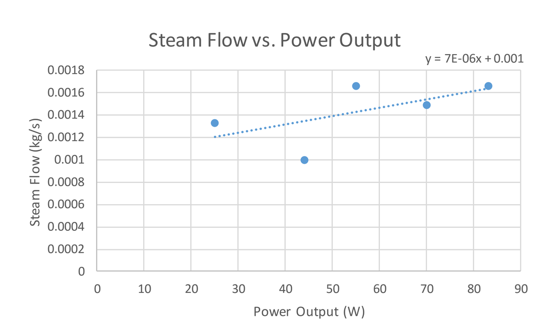

Figure 3. Condensate Steam Flow vs. Power Output

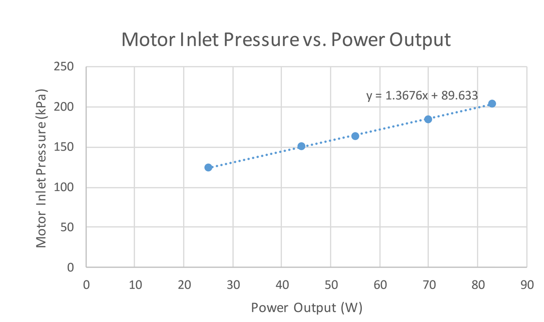

Figure 4. Motor Inlet Pressure vs. Power Output

For the highest setting on the motor, about 83 Watts, some analysis was done to determine the entropy, temperature, pressure and enthalpy at each point in the cycle. These values are tabulated in Figure 5. In Figure 6, the engine power output, electrical power input, heat rate loss from boiler, sum of heat rate loss from motor an condenser combined and the rate hear transfer to the cooling water are all tabulated for the highest setting, These values were calculated using the values listed in Figure 5. Finally, for the entire cycle, the boiler's efficiency can be calculated along with the overall thermal efficiency of the cycle and the dryness factor of the cycle. These values are tabulated in Figure 7. As mentioned, although low, the overall thermal efficiency of the engine seems to have a reasonable value. There are, however, several methods to increasing the thermal efficiency of the steam engine.

FIGURE 5 GOES HERE

Figure 5. s, h, T, and P at each stage of the cycle.

Q_1= 4350 W	mh_3= 167.6 W
Q_2= 1527 W	W_1= 83 W
Q_3+Q_4= -798.6 W	W_2= 142 W
Q_5= 3970 W	
mh_1= 3564 W	mh_w= 741 W

Figure 6. Heat Rate values tabulated

Thermal Efficiency	1.69%
Dryness Factor	0.98
Boiler Efficiency	64.90%

Figure 7. Dryness factor and efficiencies tabulated.

- Lower Condenser Pressure – this allows for more expansion of the steam in the turbine and therefore more net work.
- Increasing the Superheated Steam to a higher Temperature – doing this while maintaining a constant pressure in the boiler also results in greater net work

Discussion of Error

The two most error prone steps in this experiment were the torque and the steam valve speed. These were both maintained with controls that weren't exact and varied by significant amounts. For example, the speed of the steam was meant to stay at 2000 rev/min, but our values range from 1912-2029 rev/min. Also, the torque was supposed to increase in .5 Nm increments, but would steadily increase during operation causing an increase in the load in the steam motor. Both of these errors could have negatively affected the accuracy of our calculations.

References

Lab Manual
http://www.learnthermo.com/T1-tutorial/ch09/lesson-B/pg02.php

Equations

$$W_1 = Q_1 - Q_2 - Q_3 - Q_4 - Q_5 + mh_0 - mh_3 \quad [1]$$

$$W_1 = Q_1 - Q_2 - Q_3 - Q_4 - Q_5 + m(h_w - h_3) \quad [2]$$

$$\eta_{th} = \frac{W_1}{Q_1 + m(h_w - h_3)} \quad [3]$$

$$Q_1 + mh_0 = Q_2 + mh_1 \quad [4]$$

$$Q_1 + mh_w = Q_2 + mh_1 \quad [5]$$

$$mh_1 = W_1 + mh_2 + Q_3 \quad [6]$$

$$\eta_b = \frac{m(h_1 - h_w)}{Q_1} \quad [7]$$

$$mh_2 = Q_4 + Q_5 + mh_3 \quad [9]$$

$$x = \frac{h_{g2} - h_{f1}}{h_{fg1}} \quad [10]$$

Conclusions

After completion of this experiment, we successfully ran a steam engine under the Rankine cycle and analyzed it's efficiency. We found a high quality steam leaving the boiler at 98%. The thermal efficiency was low at 1.69% while the boiler efficiency reached 69%. The low thermal efficiency could be a result of heat leakage. Also, we found a power loss of 142 Watts in the engine. We expect some error mainly due to variations in our settings of torque and speed. The efficiency of the Rankine cycle in this case could be increased by lowering the pressure in the condenser and increasing the temperature of the superheated steam.