MEMO TO: Ryan Byrne

FROM: Seth Strayer

DATE: May 21, 2019

SUBJECT: TF1 – Steam Motor and Energy Conversion

On May 15, 2019, Noah Sargent, Aaron Esquino, and I conducted an experiment to determine the performance of the steam plant cycle and analyze it in comparison with the ideal Rankine Cycle. This experiment utilized the TD1050 Cycle. This cycle is an open cycle unlike the Rankine cycle which is closed. Therefore, it was important for us to recognize the differences between the two cycles because the TD1050 Cycle was evaluated as a Rankine Cycle. These differences are summarized in the Thermal Fluids (TF) Lab 1 Handbook. The first part of the lab involved calibration of the TD1050 cycle. This was necessary to ensure safe and accurate performance of the device. Next, the boiler heaters were turned on to reach the desired boiler pressure of 300 [kN/m^2]. The boiler steam valve was then given a one-quarter turn until we reached the desired Engine Inlet Pressure of 80 [kN/m^2]. The motor was started and calibrated to a warm-up speed of 1000 RPM. Once achieved, we used the steam valve to maintain a constant motor speed of 1800-2000 RPM while using the dynamometer to apply torque to the motor in six arbitrary steps. The boiler pressure was kept at 300 [kN/m^2] to the best of our ability throughout the entire experiment. At each load step, several state values were recorded as to allow us to perform a thermodynamic analysis on the TD1050 cycle. These values are recorded in Table 1. At the end of the experiment, the calorimeter valve was fully opened for about 30 seconds and the boiler steam pressure, temperature, and calorimeter temperature were recorded. This allowed us to measure the quality of the substance exiting the boiler. Once the data was recorded, the TD1050 cycle was safely shut down according to Section 2.3 of the TF Lab 1 Handbook.

Boiler pressure and temperature, motor inlet pressure, motor speed, motor power, condenser cooling temperatures and condensate flow rate were recorded at each load step. This data is listed in Table 1. Based on the condensate (steam) flow rate, motor power, and engine inlet pressure, two charts were created: one of steam flow rate and engine inlet pressure against motor power, and one of specific steam consumption against motor power. These charts are given by Figures 1 and 2, respectively. From Figure 1, we conclude that our data yields (roughly) a linear relationship between steam flow rate and engine inlet pressure vs. motor power.

Steam flow rate vs. motor power represents the Willans line. From literature, this line should be linear in nature and as such, we are satisfied with our data. The x-intercept of the Willans Line represents the mechanical losses present in this cycle. Using the trendline for the Willans Line, we find mechanical losses of 0.156 [kW] in magnitude. Figure 2 represents an exponential decay of specific steam consumption vs. motor power.

Most of the analysis for this experiment came in performing a steady-flow analysis where the applied motor torque was equal to 0.10 [N-m]. At this point, state values (enthalpy and entropy) were calculated for each point in the system using the temperature and pressure values given in Table 1 along with steam tables provided in Appendix B of Borgnakke and Sonntag [2014].[1] Where state values were not explicitly given in Borgnakke and Sonntag, Engineering

Equation Solver (EES) was used. These state values are summarized in Table 2. Using these state values, the quality at boiler output, boiler efficiency, and overall thermal efficiency were calculated via Equations (6), (5), and (4), respectively, of the TF Lab 1 Handbook. Heat transferred to the condenser was evaluated using elementary energy balance techniques. These values are given in Table 3.

The Rankine Cycle Efficiency, relative efficiency, and relative total efficiency were calculated via Equations (1), (2), and (3), respectively, from the TF Lab 1 Handbook using enthalpy values as previously determined. These results are also given in Table 3. Finally, using the entropy values as previously calculated, a temperature-entropy (TS) chart was created to demonstrate the differences between our results and an ideal Rankine Cycle (Figure 3).

There are several sources of error which may hinder the accuracy of our results. First, due to the high vibrations and delicacy of the system, our input values tended to change constantly, which made it difficult to record accurate measurements. Next, the calculated value of mechanical losses may differ slightly from its actual value. This is because mechanical loss is dependent on both steam consumption and motor output power; inaccurate measurements of these variables would lead to inaccuracies in the calculated value of mechanical losses. Note that the mechanical losses are used to calculate several other quantities, including total mechanical output and the enthalpy at the output of the motor. Thus, experiment measurement errors carry themselves throughout the system. It is also worth nothing that we calculated an overall thermal efficiency value of only 0.4%. This result is reasonable considering the fact that there were several sources of error present throughout our experiment and when considering the natural inefficiencies of a small, steam-powered motor.

However, we are still satisfied with the results of this experiment. In particular, the TS diagram (Figure 4) demonstrates the irreversibility's present in the TD1050 Cycle when compared to that of an ideal Rankine Cycle. Also, perhaps the most important yet simplest verification of the accuracy of our results is ensuring that our system satisfies conservation of energy. We note that, based on our calculations, the boiler heat input is roughly equal to the total work output plus heat transferred across the condenser. We conclude that our system satisfies conservation of energy laws, and thus must yield fairly accurate measurements. Overall, this lab gave us a thorough introduction to the TD1050 Cycle and enabled us to recognize the differences between the real and ideal Rankine Cycles.

Table 1: Cumulative Experimental Data

Torque [N-m]	Motor Speed [rpm]	Motor Power [kW]	Heater Power [kW]	Condensate Flow [L/min]	Condensate Temp [C]	Boiler Pressure [kN/m^2]	Engine Inlet Pressure [kN/m^2]	Boiler (T1) [C]	Calorimeter (T2) [C]	Coolant Inlet (T3) [C]	Coolant Outlet (T4) [C]
0	1980	0.001	4.4	0.1	33	300	80	141.6	102.6	16.4	37.7
0.02	2010	0.007	4.4	0.105	32.8	300	80	141.6	102.4	16.4	39.3
0.10	1950	0.018	4.4	0.115	28.4	280	85	140	102.4	16.6	41.1
0.15	1990	0.032	2.4	0.125	33.8	315	120	141.6	103.2	16.5	43.6
0.20	2000	0.043	4.4	0.125	37.9	260	140	137.4	105.2	16.5	45.9
0.25	2015	0.052	4.4	0.135	40	240	140	134.6	105.4	16.6	47.5

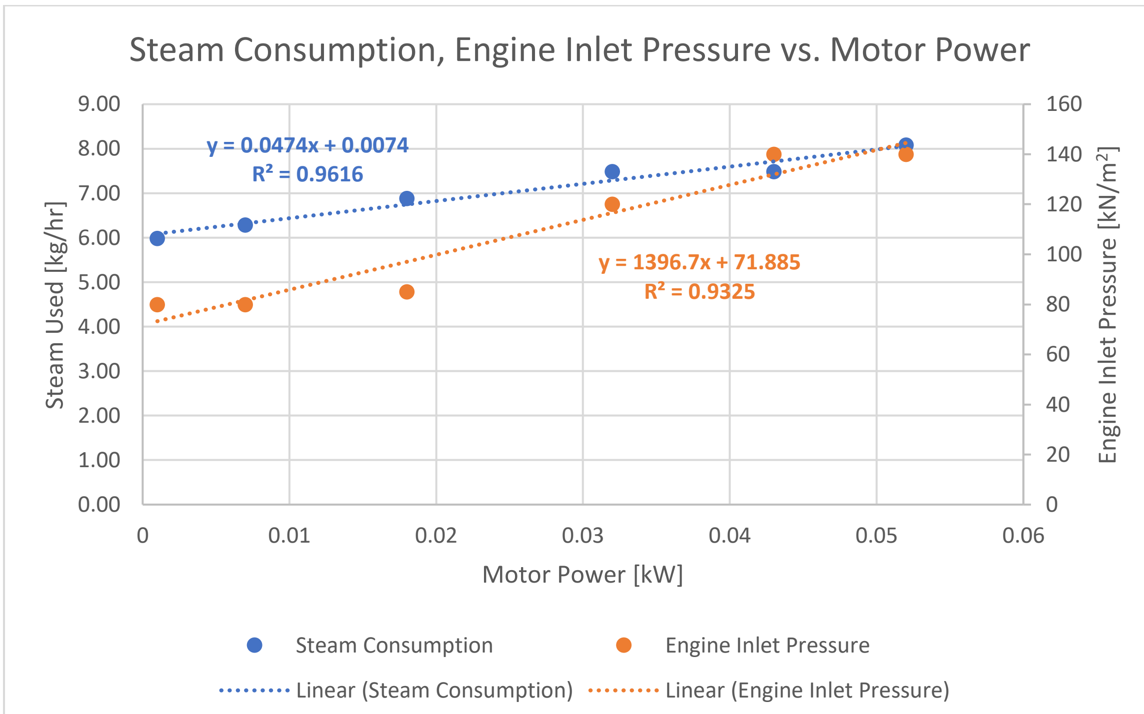

Figure 1: Steam Consumption and Engine Inlet Pressure vs. Motor Power

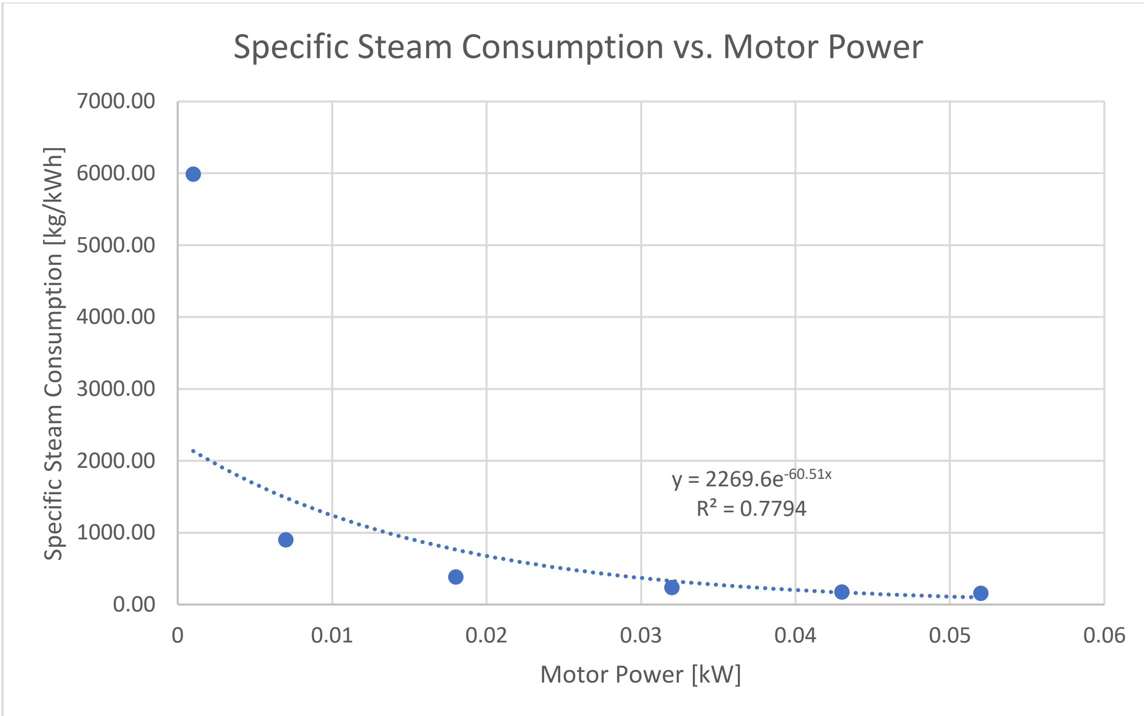

Figure 2: Specific Steam Consumption vs. Motor Power

Table 2: Calculated State Values

Parameter	Value	Equation
Motor Inlet Enthalpy [h_1]	2711.20 [kJ/kg]	$h_1 = h\|_{P=\,280kPa,\ x=0.995}$
Motor Outlet Enthalpy [h_2]	2620.17 [kJ/kg]	$\dot{W}_{out} = \dot{m}(h_1 - h_{2a})$
Condenser Outlet Enthalpy [h_3]	398.60 [kJ/kg]	$h_3 = h\|_{P=85kPa,\ x=0}$
Boiler Input Enthalpy [h_4]	551.60 [kJ/kg]	$h_4 = h\|_{P=280kPa,\ x=0}$
Motor Inlet Entropy [s_1]	6.998 [kJ/(kg-K)]	$s_1 = s\|_{P=280kPa,\ x=0.995}$
Motor Outlet Entropy [s_2]	7.283 [kJ/(kg-K)]	$s_2 = s\|_{P=85kPa,\ h=2620.17}$
Condenser Outlet Entropy [s_3]	1.252 [kJ/(kg-K)]	$s_3 = s\|_{P=85kPa,\ x=0}$
Boiler Input Entropy [s_4]	1.648 [kJ/(kg-K)]	$s_4 = h\|_{P=280kPa,\ x=0}$

Table 3: Calculated Quantities of Interest

Parameter	Value	Equation
Quality $[x_1]$	0.995	$x = \frac{h_{cal} - h_{f1}}{h_{fg1}}$
Boiler Efficiency $[\eta_b]$	0.939	$\eta_b = \frac{\dot{m}(h_1 - h_w)}{Q_1}$
Overall Thermal Efficiency $[\eta_{th}]$	0.004	$n_{th} = \frac{W_1}{Q_1 + \dot{m}(h_w - h_3)}$
Heat Transfer to Condenser $[Q_3]$	4.25 [kW]	$Q_3 = \dot{m}(h_2 - h_3)$
Rankine Cycle Efficiency $[\eta_R]$	0.039	$\eta_R = \frac{h_1 - h_2}{h_1 - h_3}$
Relative Efficiency $[\eta_{rel}]$	0.103	$\eta_{rel} = \frac{W_1}{\dot{m}(h_1 - h_2)}$
Relative Total Efficiency $[\eta_{relt}]$	1.000	$\eta_{relt} = \frac{W_1 + W_2}{\dot{m}(h_1 - h_2)}$

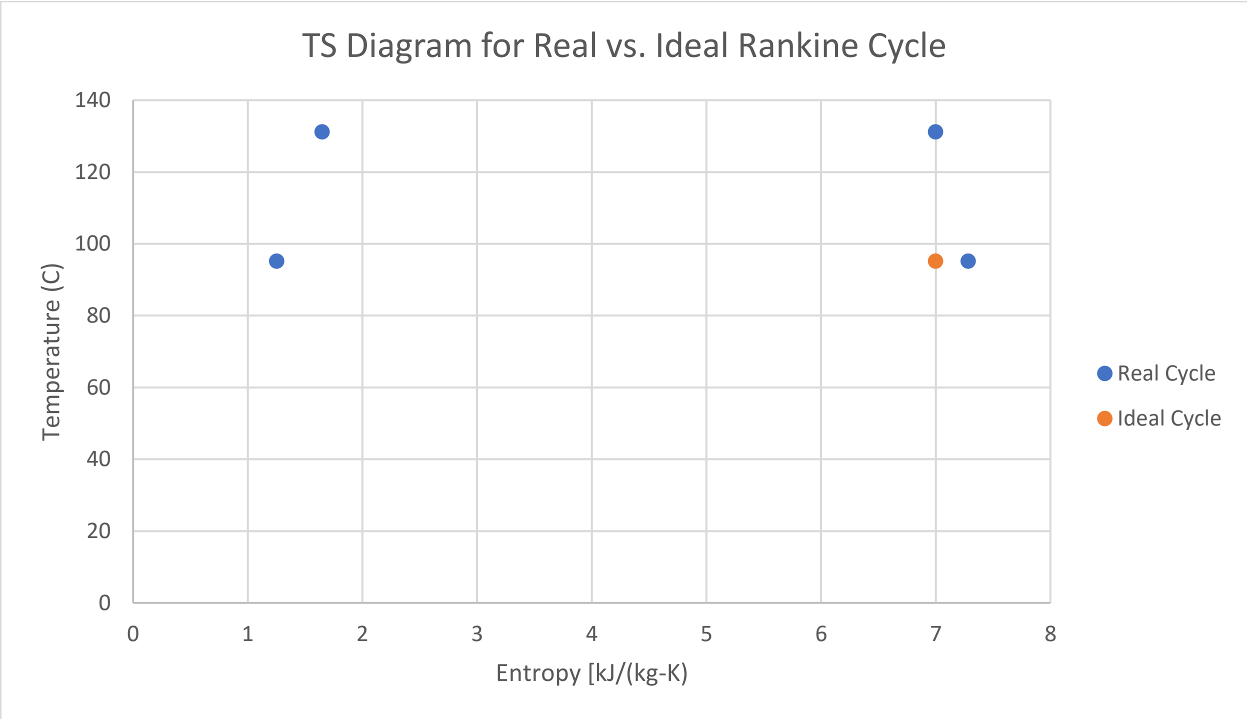

Figure 4: TS Diagram for Real vs. Ideal Rankine Cycle

References

[1] Borgnakke, C., and Richard E. Sonntag. Fundamentals of Thermodynamics. Wiley, 2014.