The University of Calgary

Faculty of Engineering

ENME 485 Mechanical Engineering Thermodynamics Laboratory

Experiment 4: Rankine Cycle Experiment

Objective:

To demonstrate the principles of a vapor power cycle (Chapter 9 of Cengel and Boles).

Introduction:

The Rankine cycle is the vapor power cycle used in most large industrial power plants. It operates by boiling a working fluid (most often water) using a heat source (coal combustion, nuclear fusion, solar energy), expanding the high pressure steam through a turbine to produce mechanical work, condensing of the steam back into the liquid phase, and pumping it back into the boiler to complete the cycle. Although the experiment performed in this laboratory is not a closed cycle, it demonstrates many of the aspects of the closed Rankine cycle. The RankineCycler experimental apparatus manufactured by Turbine Technologies is shown in Fig. 1, consisting of a boiler, a turbine and generator, a condenser, and instrumentation including a flow meter, thermocouples, pressure transducers, and a PC data-acquisition system.

Figure 1: Picture of Rankine Cycle Experiment

The Rankine Cycle Experiment is a fossil-fuel burning steam electric power plant. It was designed solely for educational purposes and yields data in a quantitative and qualitative form in a manner easily understood by the student regardless of their level of interest in the subject. The equipment is compact, bench mounted and instrumented sufficiently for students to make measurements and perform calculations. All instruments are located at the actual point of measurement and connecting pipes are open to view to allow the lab instructor to conveniently describe the sequence of events occurring in the vapor power cycle.

System Components:

Boiler

The RankineCycler boiler is a dual-pass, flame through tube-type unit as shown in the left in Fig. 2. A forced air gas burner fires it. The burner fan speed is electronically adjustable to operate with a minimum of excess air. The system's purpose-built burner fan results in extremely clean combustion while burning LP gas. A vortex disc, located downstream of the blower unit as illustrated in the right of Fig. 2, mixes fuel and air and sets up a vortex gas flow that results in efficient heat transfer from the flame tube to the boiler's water.

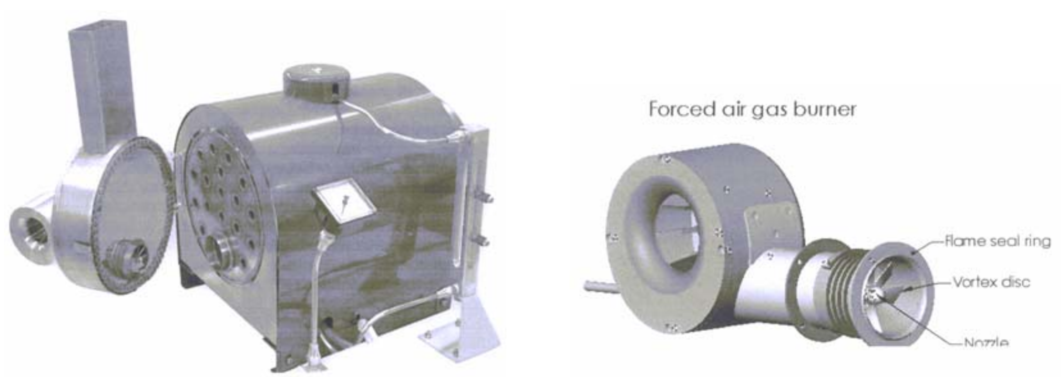

Figure 2: Picture and CAD model of Boiler –
Boiler's Inlet/Exhaust Header Door (left) and Blower and Swirl Generator (right)

The burner unit is flange mounted to the hinged front boiler door. This allows for ready viewing of internal boiler construction. Opening the front boiler door will reveal the burner nozzle and boiler flame tubes. NEVER ATTEMPT TO OPEN EITHER OF THE BOILER DOORS DURING OPERATION. THEY ARE VERY HOT. ALWAYS WAIT UNTIL COOL DOWN IS ASSURED.

Electromechanical and electronic burner and boiler controls are located within the front operator panel enclosure. An A.G.A. certified electronic ignition gas valve and microprocessor-based gas ignition module automates flame control.

A transducer assists in regulating boiler pressure by cycling the burner on and off. A poppet valve, located on top of the boiler, serves as a safety valve. In the event of control malfunction, the poppet valve will open and relieve boiler pressure.

A boiler over temperature bi-metallic switch is fitted to the boiler and will interrupt the burner operation in the event of extreme boiler over temperature conditions. This condition can be reached in the event of low boiler water operation, or in the event of automatic control failure. BOILER PRESSURE AND TEMPERATURE MUST BE CONSTANTLY MONITORED DURING OPERATION.

The boiler rear door is opened in the same manner as previously described for the front door. REMEMBER – DO NOT TOUCH THE POWER PLANT COMPONENTS WHEN HOT! The only safe items to touch are labeled operator controls, which are insulated.

The rear door is fitted with the igniter. Opening of the rear door will allow for a clear view of the boiler flame tubes and high temperature door insulation. DO NOT SLAM THE DOOR. DO NOT TOUCH THE IGNITER. The igniter is a "hot surface" unit. Its material is brittle, fragile, and sensitive to oily contamination that could be introduced by touching the igniter's surface.

Four threaded bosses are also integral to the boilers construction. They include the following:

1. A sight-glass supply boss.
2. The steam dome discharge fitting is threaded to the boiler's top boss.
3. The boiler water temperature thermocouple is threaded into a third boss called the thermocouple well.
4. The fourth boss consists of a sight-glass breather tube vent / poppet valve. It occupies a position on top of the boiler.

The entire boiler is insulated with a blanket of ceramic insulation and is protected by an external sheet metal mantle.

Steam Turbine / Generator Set

The steam turbine, shown in the left of Fig. 3, consists of the following major components:

1. A precision machined, stainless steel front and rear housing.
2. Front and rear bronze bearings.
3. Front and rear bearing oilers.
4. A stainless steel shaft.
5. A nozzle ring and a single stage shrouded impulse turbine wheel.

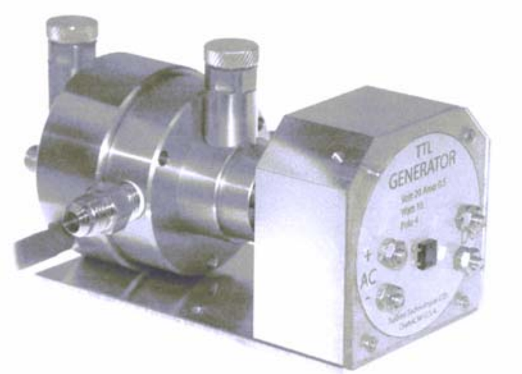

Figure 3: Steam Turbine and Generator

Impulse Steam Turbine

The turbine wheel, shown in Fig. 4, is mounted to the drive shaft by the flange of a taper lock bushing. Front and rear bronze bearing seal and support the rotating components, which are lubricated by back pressure sealed oilers. Mechanical power transmission to the generator is achieved through a "spring pin coupler." This coupling provides for smooth and relatively quiet operation.

Figure 4: Steam Turbine

Generator

The generator, shown in the right of Fig. 3, is a 4-pole, permanent magnet, brushless unit. The rotor is supported by pre-loaded precision ball bearings. The generator includes a full wave, integral rectifier bridge that delivers direct current to the generator's DC terminals. The generator's terminal board also carries a set of AC output terminals for experimental procedures that may entail the use of a transformer, or deal with frequency related topics, RPM measurement, and other AC related experiments.

Condensing Tower

The condenser tower's outer mantle is formed from a single piece of aluminum. The tower's large surface area affects heat transfer to ambient air and provides a realistic appearance. Turbine exhaust steam is piped into the bottom of the tower. The steam is kept in close contact with the outside mantle by means of 4 baffles. A drain hose and clamp are located at the left rear of the system. Following an experiment, the condensate can be drained into a beaker and measured.

Figure 5: Cutaway View of Condensing Tower

Sight Glass

A sight glass is provided to indicate boiler water level. Two level indicators, set by thumbscrew bezels, can be adjusted at the beginning and end of each experiment to determine steam rate (water volume divided by start and stop times).

Potential Experiments:

Some of the thermodynamic experiments of which the equipment is capable of performing are listed below.

1. Computation of mass flow rate through the turbine.

2. Determination of the adiabatic efficiency of the turbine at two operating points.

3. Comprehensive use of steam tables and charts.

4. Comparing theoretical results with actual practical results and understanding the limitations of a practical cycle.

Safety:

NEVER ATTEMPT TO OPEN EITHER OF THE BOILER DOORS DURING OPERATION. THEY ARE VERY HOT. ALWAYS WAIT UNTIL COOL DOWN IS ASSURED.

BOILER PRESSURE AND TEMPERATURE MUST BE CONSTANTLY MONITORED DURING OPERATION. PRESSURE SHOULD NOT RISE ABOVE 125 PSIG.

REMEMBER – DO NOT TOUCH THE POWER PLANT COMPONENTS WHEN HOT!

DO NOT SLAM EITHER OF THE BOILER DOORS. DO NOT TOUCH THE IGNITER.

DO NOT SCRATCH THE SIGHT GLASS.

Set Up and Operating Instructions:

The apparatus is delivered complete, ready to operate with the minimum of preparatory work. A single phase electricity supply, a fume hood, a water supply and water drain are the only external facilities required. The following order of instructions should be followed:

1. Fill the oil reservoirs with specified oil.

2. The large graduated cylinder will be used only for backfilling the boiler, while the smaller one will be used for measuring the amount of liquid in the condensing unit. Use of separate graduated cylinders for each operation prevents the entry of oil from the bearings into the boiler.

3. Make sure the boiler is filled to about ¾ its capacity – try to do this one day before the experiment in order to achieve temperature equilibrium with the surroundings. Open the steam admission valve for 5 seconds in order to equalize tank pressure to atmospheric pressure.

4. Turn on the main power.

5. Start the data acquisition code and examine the different readings. Under Edit … and File Settings … set the filename to be saved to the current group number and day one or day two. Press START to run the code, turn Logging On to write to the data file.

6. Make sure the propane tank is connected, that the tank valve open, and the valve on the control panel is turned counterclockwise to the ON position (3 o'clock position).

7. Turn the burner on and wait until the pressure in the boiler reaches 130 psig. At this point the boiler should turn off.

8. With the load switch off, open the steam admission valve and let the system run for around 20 seconds. The voltage will speed up quickly – try to keep it near the maximum voltage but not over.

9. Close the steam admission valve.

10. Get one person to set the upper sight glass to denote the fluid's level.

11. Open the steam admission valve, and turn on the load and get one person to set the current to 0.4 A and the voltage to 9 V. This must be done by adjusting both the steam admission valve and the load knob.

12. Once these conditions are established, reset the top sight glass to the liquid level and note the time from the data acquisition code.

13. Run the system for 5 minutes under these settings making sure to maintain the operating point voltage and current.

14. After 5 minutes, close the steam admission valve and turn off the boiler. Close the valve on the propane tank and the gas valve at the top of the control panel (turn clockwise to the 6 o'clock position). Turn the burner fan back on and let the fan cool the boiler. The flame will not ignite as the fuel is turned off.

15. Wait until the pressure in the boiler drops below 10 psig. This may take up to 45 minutes.

16. Open the steam admission valve slightly to drop the boiler pressure to 0 psig. Close the steam admission valve. Turn logging off and STOP the data acquisition program. Make sure data was saved to the file. Turn the burner switch off.

17. Measure the amount of liquid in the condensing unit using the small 250 ml graduated cylinder. This will need to be done several times as there will most likely be more than 250 mL in the condensing unit.

18. Fill the large graduated to 6 L. Put the tank on top of the condensing tower, and plug the hose end into the boiler as shown in Fig. 6.

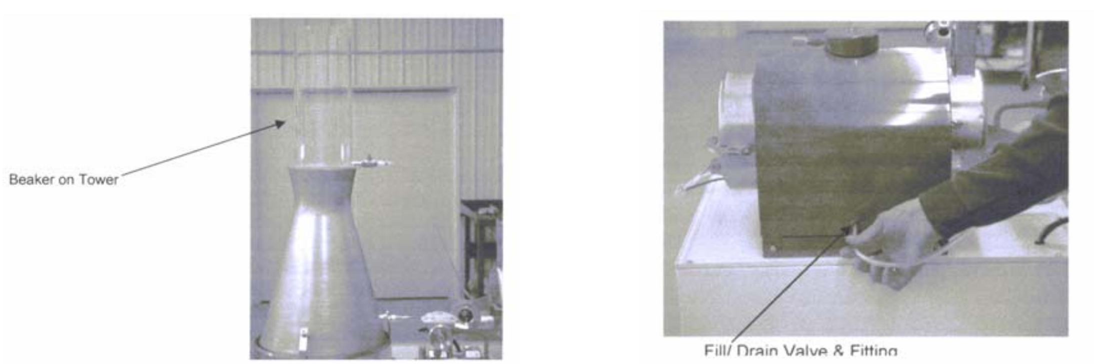

Figure 6: Picture of Backfilling the Boiler –
6 L Graduated Cylinder on Condensing Tower (left) and Connection to Boiler (right)

19. Backfill the boiler by opening the valve to the 6L tank. Hot liquid from the boiler will probably run back into the 6 L tank, and then it will slowly start to backfill the boiler. When the liquid level

in the boiler comes back to the point where the sight glass was set at the start of the 5 minute test, close the valve on the 6 L tank and stop backfilling.

20. Determine how much liquid was added to the boiler by draining the liquid in the 6 L tank down to 5 L using the small 250 mL graduated cylinder to accurately measure the amount of liquid that is removed. This will enable you to determine how much liquid was in the 6 L tank at the end of backfilling (5.xx L). You can determine the amount of liquid that went through the turbine in the 5 minute test by computing the difference between 6 L and 5.xx L.

21. Turn the computer off, disconnect the data acquisition cable.

22. Clean up the oil that may have dripped beneath the turbine bearings using a paper towel.

23. Turn the main power off on the control panel.

Procedure:

DAY ONE:

Experiment #1: Full-Load Performance Analysis (0.4 A, 9 V)

Follow the steps outlined under “Set Up and Operating Instructions.”

DAY TWO:

Experiment #2: Partial-Load Performance Analysis (0.2 A, 6 V)

Follow the steps outlined under “Set Up and Operating Instructions” with the exception of Step 11. Instead of 0.4 A and 9 V, operate the generator at 0.2 A and 6 V.

Calculations:

Experiment #1 and #2: Performance Analysis

Students are often introduced to the topic of vapor power cycles via a discussion of the Rankine Cycle and the Temperature-Entropy properties diagram. A T-s diagram can be found in Appendix 1 (Figs. A-9 and A-10) of the course texbook and analysis is conducted using both the T-s diagram and the steam tables. This exercise will demonstrate the use of thermodynamic charts and their respective advantages and disadvantages. It will also illustrate the challenges associated with using real-world data where small transducer errors can make it difficult to determine state information with the usual exactness and convenience associated with textbook problems.

Temperature-Entropy Diagram

The temperature-entropy diagram and process schematic for the Rankine cycle experiment are shown in Fig. 7. The pump (state 1 -> 2) has been drawn lightly as this part of the cycle does not exist in the RankineCycler experimental apparatus. Isentropic expansion to state 4s has also been shown in Fig. 7. In reality expansion takes place to state 4a to the right of state 4s on the T-s diagram.

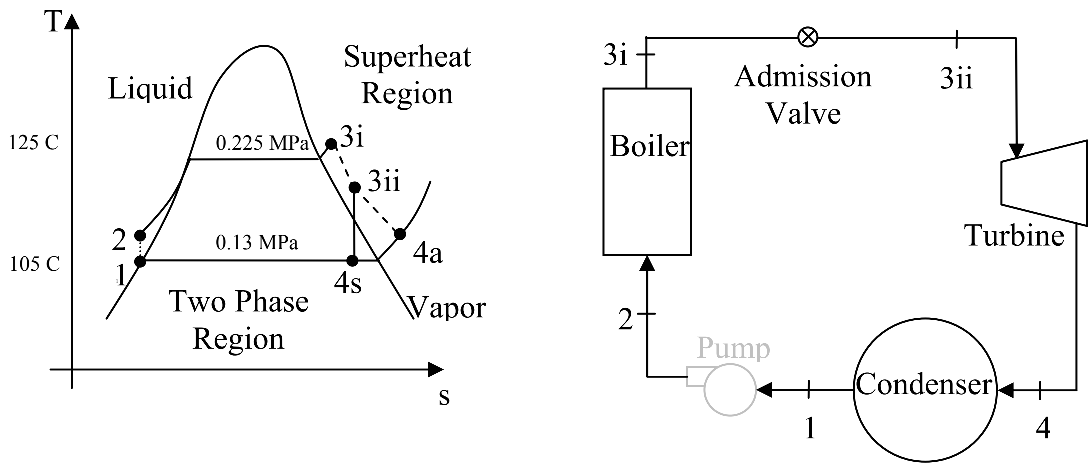

Figure 7: T-s Cycle Diagram, Idealized Straight-Line Expansion

The mass flow rate of steam passing through the turbine in the 5 minutes that steady-state data is collected can be determined using the amount of water that needs to be backfilled into the boiler. Compute the mass flow rate $\dot{m}$.

Correct all of the pressure and temperature data for offsets. This can be done by examining the pressure and temperature measurements at the start of the experiment. All of the pressures should read 0 psig while the temperatures should all read the same value.

Determine the properties (enthalpy, entropy) at state 3i from the temperature and pressure measurements. Is the steam superheated? Be careful as you will probably have to interpolate between several tables in order to get this result.

Determine the properties (enthalpy, entropy) at state 3ii from the temperature and pressure measurements. Is the steam superheated? Again, be careful as you will probably have to interpolate between several tables in order to get this result.

Is the throttling process through the steam admission valve a constant enthalpy process? Write out the first law for a single-input steady flow device and use it to try to understand what happens during the throttling process.

Knowing information at state 3ii, determine the properties at state 4s.

Determine the properties (enthalpy, entropy) at state 4a.

Compute the Work Output of the turbine:

$$\dot{W}_{turb} = I_{gen}V_{gen} = \dot{m}\left(h_{3ii} - h_{4s}\right)\eta_T$$

Try to compute the adiabatic efficiency of the turbine. Compute adiabatic efficiency using a second approach:

$$\eta_T = \frac{h_{3ii} - h_{4a}}{h_{3ii} - h_{4s}}$$

Discuss all of the results, explaining why they do or do not make sense.

TABLE 1 – Examples of Collected Data

Observed Experimental Data	Symbol	Units	Test 1
Boiler Pressure	P_{3i}	psig	75.0
Turbine Inlet Pressure	P_{3ii}	psig	16.4
Turbine Exit Pressure	P_{4a}	psig	4.6
Boiler Temperature	T_{3i}	°C	163.0
Turbine Inlet Temperature	T_{3ii}	°C	120.0
Turbine Exit Temperature	T_{4a}	°C	115.0
Fuel Flow Rate	$\dot{V}_{fuel}$	L/min	7.3
Generator Amperage	I_{gen}	C/s	0.4
Generator Voltage	V_{gen}	J/C	9.0
Backfilled Water	$V_{backfill}$	mL	470

TABLE 2 – System Transducers

Observed Experimental Data	Manufacturer	Range	Output
Boiler Pressure (P_{3i})	Setra Model 209	0-200 psig	0.5-5.5 V
Turbine Inlet Pressure (P_{3ii})	Setra Model 209	0-200 psig	0.5-5.5 V
Turbine Exit Pressure (P_{4a})	Setra Model 209	0-25 psig	0.5-5.5 V
Boiler Temperature (T_{3i})	K-type thermocouple		
Turbine Inlet Temperature (T_{3ii})	K-type thermocouple		
Turbine Exit Temperature (T_{4a})	K-type thermocouple		
Fuel Flow Rate ($\dot{V}_{fuel}$)	Dwyer TF2110	2-10 L/min	

References:

1. “RankineCycler Operator’s Manual,” Turbine Technologies Ltd., Rev. 3.2.

2. Cengel, Y.A., and Boles, M., *Thermodynamics: An Engineering Approach*, 4th Edition, McGraw Hill, 2002.