Steam Turbine Experiment

RankineCycler™ *- An Educational, Micro-Electric Power-Generating* Station

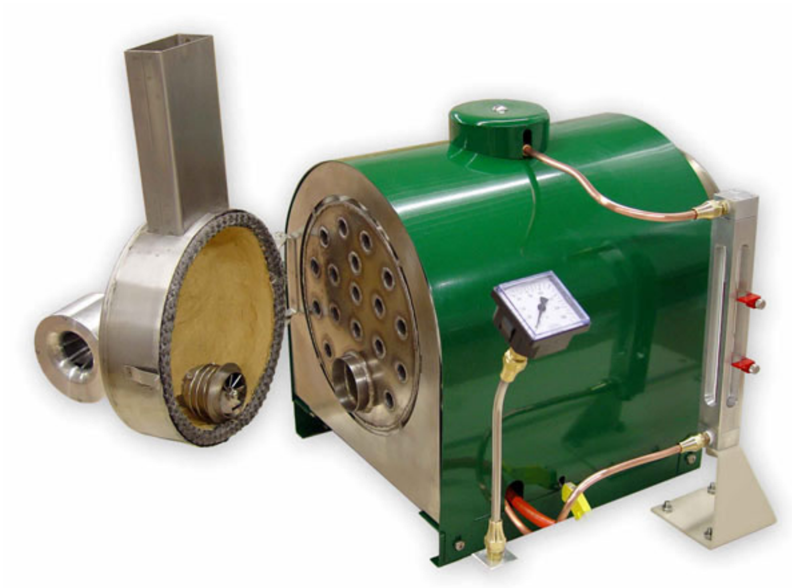
I. Objective

The objective of this laboratory is to offer students hands-on experience with the operation of a functional steam turbine power plant. A comparison of real world operating characteristics to that of the ideal Rankine power cycle will be made.

The apparatus is scaled for educational use and utilizes components and systems similar to full-scale industrial facilities. Students will be able to operate and analyze this system in detail, allowing them to determine the efficiency of the facility and suggest possible modifications for further improvement. The turnkey laboratory system carries the trade name of RankineCycler™.

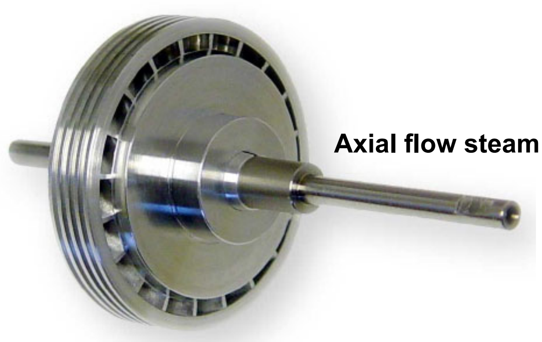
II. Theory

The Rankine cycle is the most common of all power generation cycles and is diagrammatically depicted via Figures 1 and 2. The Rankine cycle was devised to make use of the characteristics of water as the working fluid. The cycle begins in a boiler (State 2 in figure 1), where the water is heated until it reaches saturation- in a constant-pressure process.



Boiler

Once saturation is reached, further heat transfer takes place at a constant temperature, until the working fluid reaches a quality of 100% (State 3). At this point, the high-quality vapor is expanded isentropically through an axially bladed turbine stage to produce shaft work. The steam then exits the turbine at State 4. The working fluid, at State 4, is at a low-pressure, but has a fairly high quality, so it is routed through a condenser, where the steam is condensed into liquid (State 1).



Axial flow steam turbine wheel

Finally, the cycle is completed via the return of the liquid to the boiler, which is normally accomplished by a mechanical pump* (See notation under Figure 3).

Figure 1 below shows a P-v diagram for a simple ideal Rankine cycle (refer to your thermodynamics text for additional details)

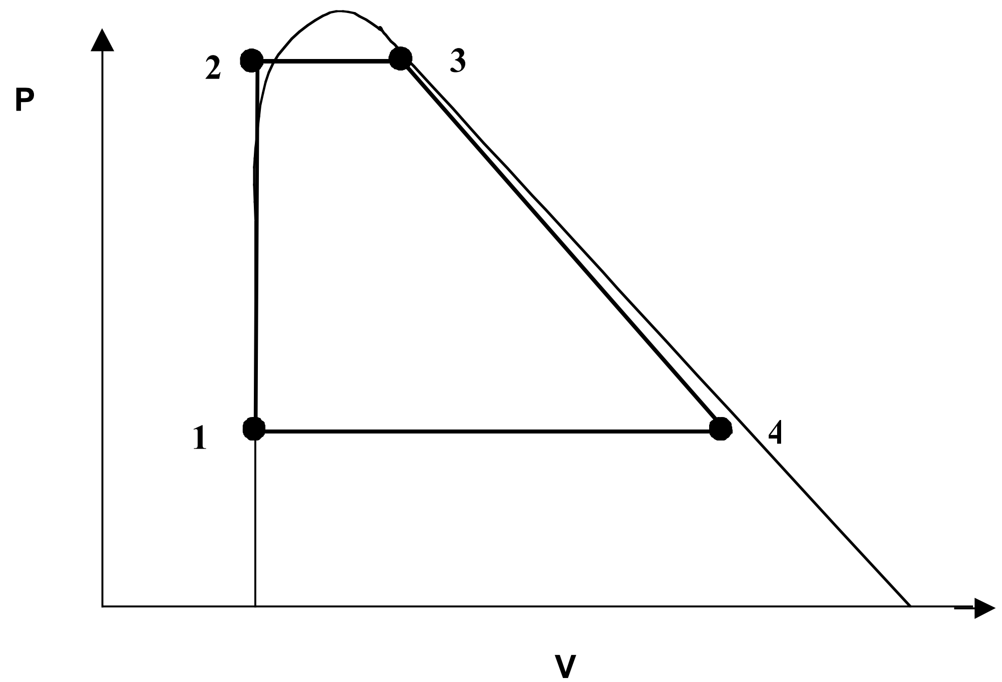


Figure 1. P-v diagram for simple ideal Rankine

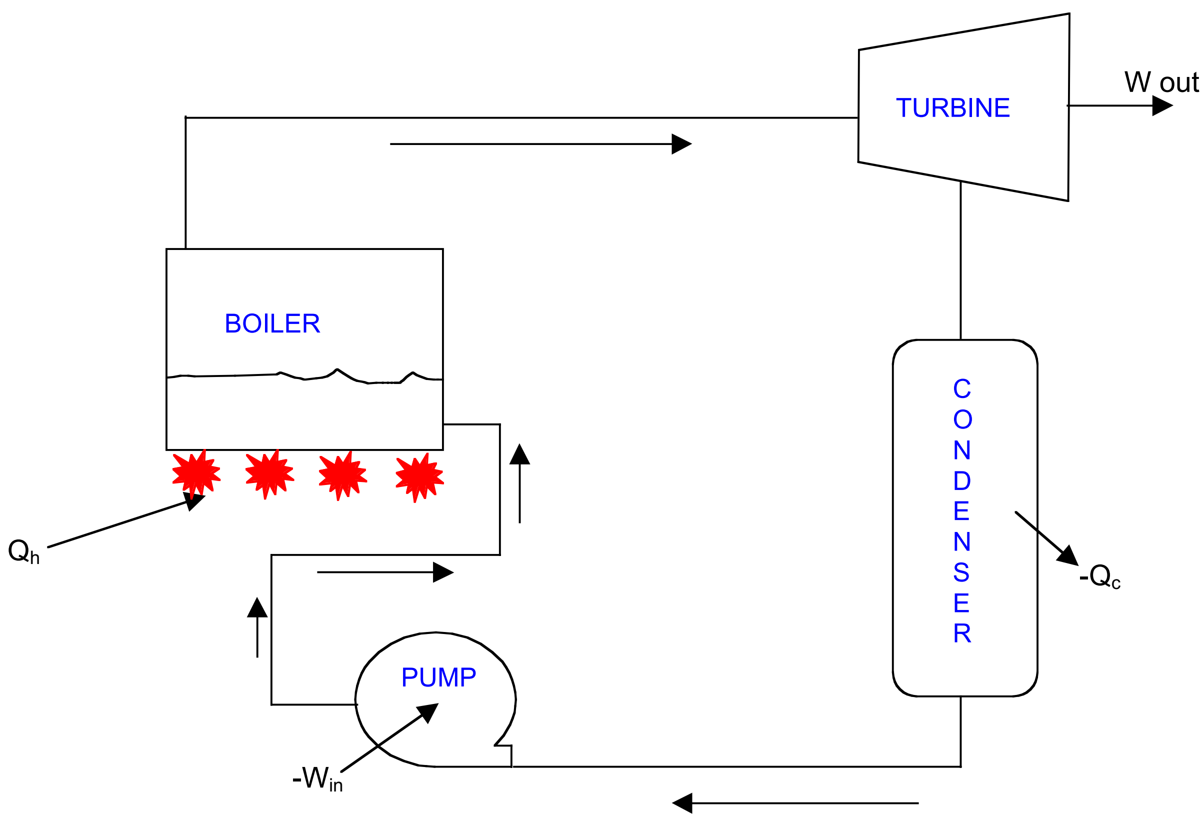


Figure 2. Schematic of simple ideal Rankine cycle

III. Experimental Apparatus

The experimental hardware (RankineCycler™) consists of multiple components that make up the necessary components for electrical power generation (utilizing water as the working fluid). These components include:

BOILER
A stainless steel constructed, dual pass, flame-through tube type boiler, with super heat dome, that includes front and rear doors. Both doors are insulated and open easily to reveal the gas fired burner, flame tubes, hot surface igniter and general boiler construction. The boiler walls are insulated to minimize heat loss. A side mounted sight glass indicates water level.

COMBUSTION BURNER / BLOWER
The custom manufactured burner is designed to operate on either LP or natural gas. A solid-state controller automatically regulates boiler pressure via the initiation and termination of burner operation. This U.L. approved system controls electronic ignition, gas flow control and flame sensing.

TURBINE
The axial flow steam turbine is mounted on a precision-machined stainless steel shaft, which is supported by custom manufactured bronze bearings. Two oiler ports supply lubrication to the bearings. The turbine includes a taper lock for precise mounting and is driven by steam that is directed by an axial flow, bladed nozzle ring. The turbine output shaft is coupled to an AC/DC generator.

ELECTRIC GENERATOR
An electric generator, driven by the axial flow steam turbine, is of the brushless type. It is a custom wound, 4-pole type and exhibits a safe/low voltage and amperage output. Both AC and DC output poles are readily available for analysis (rpm output, waveform study, relationship between amperage, voltage and power). A variable resistor load is operator adjustable and allows for power output adjustments.

CONDENSER TOWER
The seamless, metal-spun condenser tower features 4 stainless steel baffles and facilitates the collection of water vapor. The condensed steam (water) is collected in the bottom of the tower and can be easily drained for measurement/flow rate calculations.

The experimental apparatus is also equipped with an integral computer data acquisition station, which utilizes National Instruments™ data acquisition software.

The fully integrated data acquisition system includes 9 sensors. The sensor outputs are conditioned and displayed in "real time"- on screen. Data can be stored and replayed. Run data can be copied off to floppy for follow-on, individual student analysis. Data can be viewed in Notepad, Excel and MSWord (all included).

The system is test run at the factory prior to delivery and the "factory test run" is stored on the hard drive under the "My documents" folder. This file should be reviewed prior to operation, as it gives the participant an overview of typical operating parameters and acquisition capability.

SENSORS

Nine (9) sensors are installed at key system locations. Each sensor output lead is routed to a centrally located terminal board. A shielded 64-pin cable routes all data to the installed data acquisition card. This card is responsible for signal conditioning and analog to digital conversion. Software and sensor calibration is accomplished at the factory prior to shipment.

Installed sensor list includes:

1. Boiler pressure
2. Boiler temperature
3. Turbine inlet pressure
4. Turbine inlet temperature
5. Turbine exit pressure
6. Turbine exit temperature
7. Fuel flow
8. Generator voltage output
9. Generator amperage output

OVER ALL SYSTEM DIMENSIONS

Length:	48.0 inches (122 cm)
Width:	30.0 inches (77 cm)
Height:	58.0 inches (148 cm)

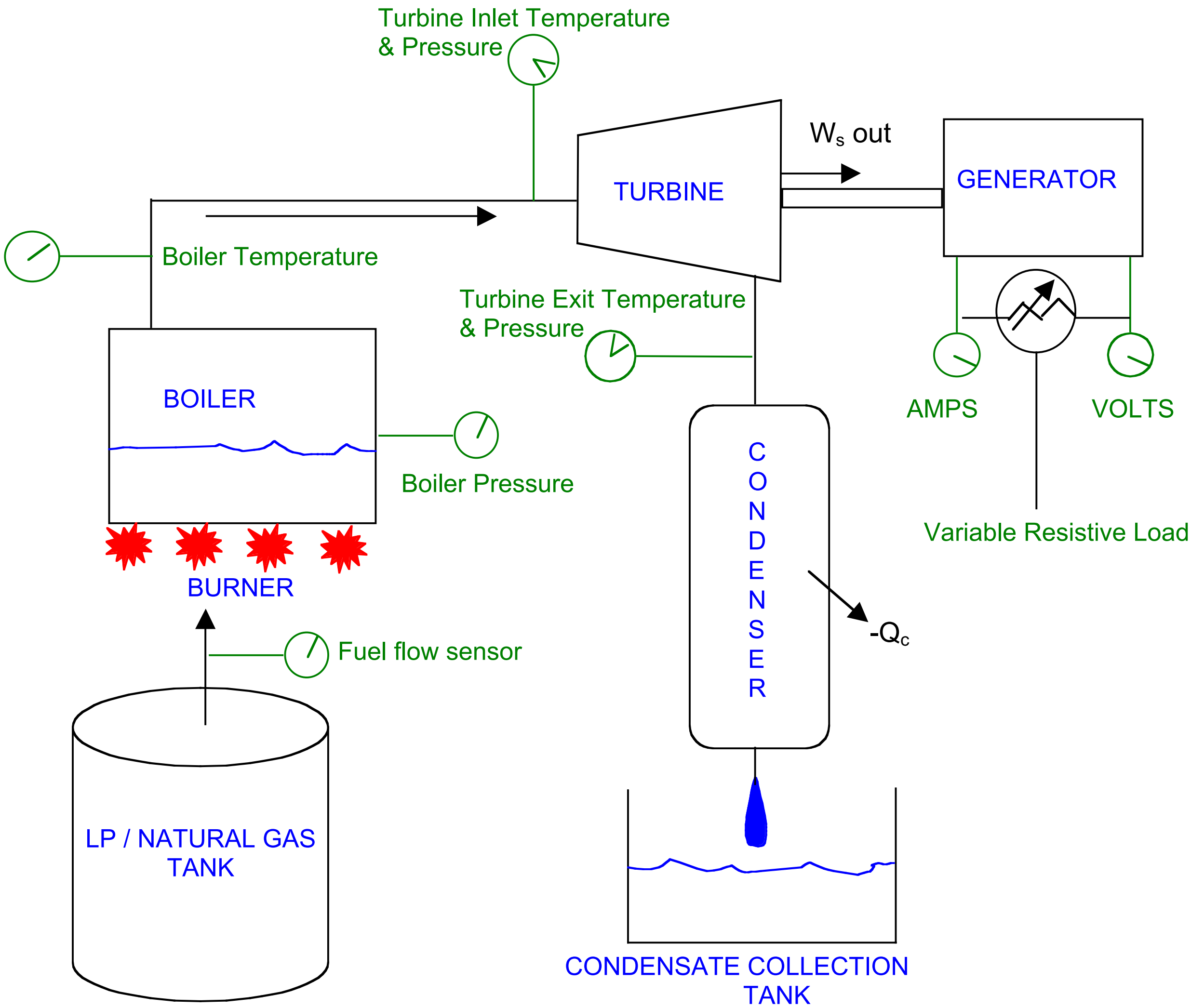


Figure 3. Schematic of RankineCycler™ Steam Turbine Apparatus

***Note:** When compared to figure 2 (simple ideal Rankine cycle), the steam ejected from the RankineCycler™ turbine condenses into liquid via the condenser tower and then exits the condenser into a collecting volume at the condensers base, rather than being pumped back to the boiler. The condensate can subsequently be weighed. This allows for measurement of the mass flow rate of the working fluid, by means of collection of a certain amount of condensate and recording the length of time required for that collection. This represents the main difference between the simple Rankine cycle described in figure 2, since the liquid exiting the condenser is dispensed, rather than pumped back to the boiler.

The RankineCycler™ apparatus schematic depicted on the previous page allows students to monitor the power plant system and obtain data from the 9 installed sensors (depicted in green, Figure 3).

Thermocouples and pressure transducers located at various locations in the steam loop allow for monitoring of pressures and temperatures, which can be used to determine the state of the working fluid at appropriate locations.

IV. General Safety

The RankineCycler™ apparatus exhibits hot surfaces during operation. Equipment familiarization is particularly important in order to prevent injury. Under no circumstance should anyone attempt to open boiler doors during operation, or at anytime that the boiler exhibits a positive pressure reading. The boiler has been low cycle fatigue pressure tested. Ultimate operating pressures that exceed normal operating pressures by 50% have been tested. NEVER ATTEMPT TO EXCEED MAXIMUM OPERATING PRESSURE. DO NOT ATTEMPT TO MAKE ANY ADJUSTMENTS TO SAFETY DEVICES AND OR CONTROLS TO ATTEMPT OPERATIONS OUTSIDE OF ESTABLISHED LIMITS. The boiler is not ASME rated, nor is it approved by any other test facility. IMPROPER USE MAY CAUSE DEATH OR SERIOUS INJURY. Should any questions arise regarding the safe operation of this equipment, please speak to your laboratory supervisor.

Personal protection
This plan is a sample plan of precautionary measures that should be considered to prevent injury during the use of the RankineCycler™ and may or may not be more stringent than your current lab safety plan. It should be used as a guide only. Safety measures must be taken during all use of laboratory equipment. ***Consult your lab safety specialist for a detailed, site-specific plan.***

Suggested Protection Devices:

Gloves
Eye Protection
Splash Protection
Fire Extinguisher
Posted Emergency Exit
Posted Emergency Numbers

Before developing your own personal protection plan, you first need to read and review the RankineCycler™ owner's manual, as well as your facility's general lab safety plan and procedures.

Combustion is taking place and results in hot surfaces. Do not touch any surface unless familiar with the system.

Before use, the boiler should be checked to verify component integrity. DO NOT USE the RankineCycler™ unless given explicit permission to do so.

During use, the following should be worn at all times: gloves, safety goggles and a splash apron. Jeans and a long sleeved shirt are much better than shorts and a t-shirt. The heavier clothing will provide some protection in the event hot surface or vapor contact.

Familiarize yourself with the location of the nearest fire extinguisher. If the RankineCycler™ is running and you notice the smell of natural gas or LP (dependent upon fuel type used), quickly turn off the gas and exit the room. Notify your supervisor that a potential gas leak exists.

Assure that emergency contact number are posted and that you are aware of the nearest exit and phone locations. Also, be sure you know where the laboratory first aid kit is located and that it is properly stocked.

V. RankineCycler™ Operation

Do not begin operation without proper supervision. Prior to beginning any operation, assure that a trained lab technician, TA, or faculty member is present.

RankineCycler entails the following operator controls:

GAS VALVE
The gas valve is a simple two-position valve (On or Off). It is located on the far right side of the slanted operator control panel. It will prevent gas flow to the burner when in the off position-regardless of any other control positions/settings.

KEYED MASTER SWITCH
The systems electronic master switch is key operated and is located on the left side of the operator control panel. This key switch supplies power to all electronic and electrically operated components. A green indicator light, located directly above the keyed master switch, will light when the master switch is selected to the on position and power is available to the switch

BURNER SWITCH
The burner switch is labeled as such and is located next to the keyed master switch. The burner switch powers the automatic gas valve and ignition controls. A green indicator light, located directly above the burner switch, will light when the burner switch is selected to the on position and power is available to the switch.

LOAD SWITCH
The load switch functions as a generator load disconnect switch

LOAD RHEOSTAT CONTROL KNOB
The load rheostat control knob is connected in series with the load toggle switch and generator DC output terminals. It provides a source of variable generator load.

AMP METER
The amp meter indicates generator load conditions.

VOLTMETER
The voltmeter indicates the generator voltage output.

STEAM ADMISSION VALVE
The steam admission valve controls the steam flow rate to the steam turbine.

Sensors

Pressure, Temperature and Flow Sensors facilitate collection, storage and retrieval of "real time" data.

GAS FLOW
The gas flow sensor is a turbine-based flow-metering unit. It is installed inside of the operator panel and interfaced with the computer data collection station. Gas flow rates are depicted on the PC's monitor via a graphical and numerical presentation.

BOILER PRESSURE AND TEMPERATURE
Boiler pressure and temperature data is collected via transducer and thermocouple sensors, respectively. The sensor output is calibrated to read in engineering units via the PC data acquisition presentation.

STEAM TURBINE INLET & OUTLET PRESSURE & TEMPERATURE
Inlet and outlet pressure and temperature sensors for the steam turbine are installed in the steam turbines front and rear housings. Pressure transducers are located within the front operator panel enclosure. Temperature sensing thermocouples are plug connected and routed to the data acquisition terminal board. The terminal board features on board cold junction compensation.

OPERATIONAL CHECKLISTS
PRE-START

1. Determine suitability of operational location (i.e. adequate ventilation, access to 110V power)
2. Lock caster wheels
3. Perform visual inspection to check for general system condition (sight glass, piping, boiler, overall system integrity).
4. Assure front and rear boiler doors are latched
5. Open steam admission valve. *Do not attempt to fill boiler while hot or under pressure.*
6. Insert supplied fill/drain fitting (hose attached) into filler port located at the rear of the boiler (opposite side of instrument panel). Attach a funnel to end of hose and hold funnel above boiler height.
7. Fill boiler with clean tap water (if the boiler doesn't appear to be accepting water, pull filler fitting out slightly until water starts to flow into boiler. If fitting is pulled out too far, water will spill onto the base cabinet).

The actual boiler diameter is equal to the door diameter. Do not fill the boiler to a higher level than to 3/4ths the height of the door height.

8. Remove filler hose.
9. Close the steam admission valve
10. Turn load switch to "off" position
11. Turn burner switch to "off" position
12. Turn load rheostat knob fully counter clockwise (minimum load).
13. Insert multi pin computer plug into terminal board on left side of RankineCycler cabinet.
14. Plug computer power cord into 115 VAC outlet
15. Plug RankineCycler power cord into 115 VAC outlet
16. Connect gas pressure regulator to LP gas tank
17. Connect low pressure gas hose from regulator exit to barbed RankineCycler gas inlet fitting (located on the right side of the operator control panel) Assure *leak free connection* Allow any remaining condensate to drain from the tower by locating attached condenser drain hose and squeezing hose fitting to "un-pinch" the drain hose. Hold hose below condensate tower and drain tower water into any available container.
18. Remove knurled screw caps from steam turbine front and rear oilers.

19. Fill oilers to within 1/8th inch from the top of the oiler with turbine oil that meets Mil-L-23699C specifications.

NOTE: OIL MUST BE ADDED TO THE OILERS AFTER EACH RUN. DO NOT ATTEMPT START WITHOUT CHECKING OIL LEVEL. TURBINE BEARING DAMAGE WILL OCCUR WITHOUT PROPER LUBRICATION.

START

1. Open LP bottle gas valve
2. Turn gas valve knob CCW to "on" position
3. Turn master switch on (observe green indicator light on)
4. Turn burner switch on (observe green indicator light on)

NOTE: Combustion blower starts automatically. Wait for 30 seconds. This will allow the lines to purge. Then turn the burner switch to the "off" position and immediately back on (this step can be eliminated from the start procedure if the system has previously been operated using the currently attached LP source). This resets the starting cycle and assures that the lines are purged. After approximately 20 seconds, the automatic gas valve will open and the burner will light.

5. Boiler pressure indication should be observed within 3 minutes of ignition.

NOTE: SHUT OFF BURNER SWITCH IF THE BOILER PRESSURE EXCEEDES 130 PSIG. Automatic regulation should assure shutoff at approximately 120 psig. In the even of over pressure (exceeding 125 psig), contact Turbine Technologies Ltd.

6. Power up data acquisition station and open "Virtual Bench" on desktop
7. Observe voltmeter and open steam admission valve. Regulate turbine speed to indicate 7-10 volts. This will pre-heat turbine components and pipes. Close valve after 20 seconds and wait for boiler pressure to rise. Very small leaks may be visible due to condensation and cold turbine bearing clearances. This is normal and will stop after normal operating temperatures are attained.
8. Open steam admission valve to read close to maximum voltage.
9. Turn load switch to "on" position.
10. Adjust load rheostat knob and steam admission valve to obtain a steady state power output. 9 volts and 0.4 amps are good values for steady state operation.
11. Mark time and set upper sight glass bezel to current water level. Fine adjust steam admission valve for steady state operation

SHUT DOWN

1. Close steam admission valve when sight glass water level reaches the pre-selected lower bezel setting
2. Move burner switch to "off" position
3. Turn gas valve off
4. Turn LP gas bottle valve off
5. Hold heat resistant measuring beaker under condenser tower drain. Drain condensate by squeezing hose pinch. Measure condensate. *CAUTION: Water may be hot*
6. Wait until boiler cools and pressure is below 10 PSIG. Then open steam admission valve. When boiler pressure equals atmospheric, fill a measuring beaker with clean tap water and re-fill boiler via the boiler's drain/fill port- to the exact sightglass upper bezel level. The measured or weighted re-fill mass represents the boilers total steam production and can be correlated as steam rate by dividing the water weight by the duration of the run (found be looking at the start and stop time of the run as measured by the data acquisition station.

EMERGENCY SHUTDOWN

1. Unplug RankineCycler power cord
2. Move to a safe distance
3. If safety is not compromised: Turn burner switch off, turn load rheostat to maximum, open steam admission valve to obtain maximum voltage.

OPERATIONAL DO'S DON'TS

DO'S

Read, remember and follow operator's manual
Watch gage readings at all times
Check oil levels on turbine oilers often
Remember the working fluid is pressurized, hot steam
Develop your own protection plan
See through operator shielding, personal protective gear, etc.
Lock caster wheels
Provide good ventilation

DONT'S

Do not tap sight glass, scratch or mark
Do not tighten or adjust fittings while boiler is under pressure
Do not touch parts that are not labeled (hot components)
Do not operate boiler with water level below 4 inches or above 6.5 inches
Do not move unit with the boiler under pressure
Do not attempt to open fill/drain valve when boiler is hot
Do not exceed scale readings on volt or amp meter
Do not allow anyone to operate the unit that is not familiar with the Operating Manual and the systems practical usage
Do not operate unattended

VI. Data Acquisition, General Discussion

The Rankine*Cycler*^{Tm} comes equipped with a turnkey data acquisition system. The PC hardware is located on a wheeled cart as depicted on the front cover of this manual. A 64-pin interface cable is routed from this station to the Rankine*Cycler*^{Tm} terminal board. Nine (9) data points (pressures, temperatures, fuel flow, voltage and amperage) are collected via installed sensors.

The Sensor Parameter Chart (Table A) indicates the function, manufacturer/type, range and output value of the installed sensors. Table B depicts the physical location of the sensor output leads on the terminal board.

TABLE A
Sensor List

Function	Manufacturer/type	Range (PSIG)	Output (V)
Boiler Pressure	Setra Model 209	0-200	0.5 - 5.5
Turbine Inlet Pressure	Setra Model 209	0-200	0.5 - 5.5
Turbine Exit Pressure	Setra Model 209	0-25	0.5 - 5.5
Boiler Temperature	K-Type Thermocouple		
Turbine Inlet Temperature	K-Type Thermocouple		
Turbine Exit Temperature	K-Type Thermocouple		
Fuel flow sensor	Dwyer TF2110	2-10 liters/min	
Generator Voltage			
Generator Amperage			

TABLE B
Data Acquisition Port Illustration

Channel 8 Fuel Flow -
Channel 8 Fuel Flow +
Channel 7 Turbine Exit Temperature -
Channel 7 Turbine Exit Temperature +
Channel 6 Turbine Inlet Temperature -
Channel 6 Turbine Inlet Temperature +
Channel 5 Boiler Temperature -
Channel 5 Boiler Temperature +
Channel 4 Turbine Exit Pressure -
Channel 4 Turbine Exit Pressure +
Channel 3 Turbine Inlet Pressure -
Channel 3 Turbine Inlet Pressure +
Channel 2 Boiler Pressure -
Channel 2 Boiler Pressure +

Channel 15 open
Channel 15 open
Channel 14 open
Channel 14 open
Channel 13 open
Channel 13 open
Channel 12 open
Channel 12 open
Channel 11 open
Channel 11 open
Channel 10 Generator Amperage -
Channel 10 Generator Amperage +
Channel 9 Generator Voltage -
Channel 9 Generator Voltage +

VI. Possible Experimental Procedures

The following laboratory procedures should be used as a guide for possible student activities.

Sample labs:

The lab technician will start the facility and assist students in changing conditions. The students' primary function is to gather data at the appropriate time for each run condition. This is accomplished via the systems installed software. Lab prep should include a thorough understanding of the data acquisition modes/screens. Software help screens should be printed and distributed to participants prior to the lab session. Data will be taken at four different operating conditions:

1. *No load (i.e. the turbine is running free, and no power is being extracted from the generator)*
2. *_ of the maximum load applied on the turbine by the generator*
3. *_ of the maximum load, and*
4. *_ of the maximum load.*

Mass Flow Rate of a Rankine Cycle at four operating conditions.

Objective
The objective of this laboratory procedure is to perform an analysis on a steam turbine power plant. The mass flow rate of the system is to be determined at four different turbine loadings.

Background
Vapor power systems are a type of cycle that converts energy to a useful state. The main goal of these systems is to produce a useful power output from the potential energy stored in a fossil fuel (liquid petroleum or natural gas, in this case). In these cycles, a working fluid is vaporized and then condensed. This is done using many components; however, the main components include:

- Boiler
- Turbine
- Condenser
- Pump

Each of these components performs a key role in creating an output from the energy input. The heater, most often a burner/boiler (closed vessel) combination, uses the energy input from burning fossil fuels to heat and evaporate the working fluid (water). The working fluid, now a high-pressure vapor, expands through the turbine creating a work output.

Procedure

When you arrive at the lab, the steam turbine facility will be operational in the no load condition. You are to take data from the following sources:

The computer. Which records 9 separate data points, including:
1. Boiler temperature
2. Boiler pressure
3. Turbine inlet temperature
4. Turbine exit temperature
5. Turbine inlet pressure
6. Turbine exit pressure
7. Fuel flow
8. Generator amperage
9. Generator voltage

The condensate collection reservoir, when drained, will yield the mass flow rate (when divided by the testing interval time.

Equations to be Used

$$\frac{\dot{W}_t}{\dot{m}} = h_2 - h_3$$

A. Procedure

1. Calculate h_2 by using the temperature and pressure at the turbine inlet.
2. Calculate h_3 by using the temperature and pressure at the turbine exit.
3. Calculate W_{dot} by using the generator amperage and voltage.
4. Solve for m_{dot}.

Complete these steps at all 4 operating points

The mass flow rate can also be determined utilizing another method. This method would require a stable operating position with the steam admission valve being fixed at one position. A comparison of method A and B should be made. What factors might have influenced the difference in results?

B. Procedure

1. Establish steady state operation in no load condition
2. Operate system at one steam admission valve setting for 5 minutes
3. Collect condenser tower reservoir water
4. Weigh condensate.
5. Divide condensate amount by test time in order to arrive at the mass flow rate value

Repeat for all 4 operating load conditions

Discussion questions:

What factors might have influenced the variation in results when comparing method A versus method B?

Heat Transfer Rates to Surroundings

Objective

The purpose of this lab is to study the energy that is lost to the surroundings during the Rankine Cycle process. Each component is to be analyzed to determine the heat transfer rate to the surroundings.

Background

Vapor power systems are a type of cycle that converts energy to a useful state. The main goal of these systems is to produce a power output from a fossil fuel, nuclear, or solar energy input. In these cycles a working fluid is vaporized and then condensed. This is done using many components; however the general main components include the following:

-Heater (gas fired burner and boiler combination)
-Turbine
-Condenser
-Pump

Each of these components performs a key role in creating an output from the energy input. The heater, most often a boiler, uses the energy input from burning fossil fuels and evaporates the working fluid. The working fluid, now a vapor, then expands through the turbine creating a work output. The condenser transfers heat from the vapor working fluid to make it sub-cooled liquid. The pump uses a work input to move the liquid back through the cycle.

Equations to be Used

$$\dot{Q} = hA(T_s - T_\infty)$$

Use equations for Rayleigh Number and Nusselt Number for correlation, as given in your current thermodynamics text, to determine the heat transfer coefficient.

Procedure

1. Determine the pressure and temperature at each component of the system.
2. Use these values to calculate an enthalpy value at each component.
3. Apply these values (utilizing the governing equations contained herein) and solve for heat transfer rates.

EES Power Cycle Design for Best Efficiency

Objective

The purpose of this lab is to gain insight on vapor power systems and the effectiveness of their operation. For this experiment the overall efficiency of vapor power systems will be studied. With the use of Engineering Equations Solver a power cycle will be designed. The objective is to create a power system and alter it in different ways to achieve the greatest efficiency.

Background

Vapor power systems are a type of cycle that converts energy to a useful state. The main goal of these systems is to produce a power output from a fossil fuel, nuclear, or solar energy input. In these cycles a working fluid is vaporized and then condensed. This is done using many components; however the general main components include the following:

- -Heater (boiler)
- -Turbine
- -Condenser
- -Pump

Each of these components performs a key role in creating an output from the energy input. The heater, most often a boiler, uses the energy input from burning fossil fuels, nuclear, or solar energy to heat and evaporate the working fluid. The working fluid, now a vapor, then passes through the turbine creating a work output. The condenser transfers heat from the vapor working fluid to make it sub cooled liquid. The pump uses a work input to move the liquid back through the cycle.

Equations to be Used

Thermal efficiency of this system is defined by the following;

$$\eta = \frac{\frac{\dot{W}_t}{\dot{m}} - \frac{\dot{W}_p}{\dot{m}}}{\frac{\dot{Q}_{in}}{\dot{m}}} = \frac{(h_1 - h_2) - (h_4 - h_3)}{h_1 - h_4}$$

Procedure (a computer with EES software is required)

1. With EES define (within reasonable limits) the temperature and pressure at each of the stages in the cycle.
   T_1=
   P_1=
2. Next define that the h for each stage is the enthalpy for the working fluid at T and P.
3. Use a variable, such as _, which will be the efficiency of the cycle and enter the equation that defines thermal efficiency of the cycle.
4. Solve the equation in EES to find the efficiency of the cycle with the given stage temperatures and pressures.
5. Change the temperatures and pressures ant each state to get a better efficiency.
6. Repeat the procedure until an acceptable efficiency is achieved.
7. If necessary, such things as reheat or second turbine stages may be modeled in the system.

RankineCycler™ Efficiency

Objective

The purpose of this lab is to obtain a better understanding of a steam turbine power plant. The efficiency of the RankineCycler™ is to be determined.

Background

Vapor power systems are a type of cycle that converts energy to a useful state. The main goal of these systems is to produce a power output from a fossil fuel, nuclear, or solar energy input. In these cycles a working fluid is vaporized and then condensed. This is done using many components; however the general main components include the following:

-Boiler
-Turbine
-Condenser
-Pump

Each of these components performs a key role in creating an output from the energy input. The heater, most often a boiler, uses the energy input from burning fossil fuels, nuclear, or solar energy to heat and evaporate the working fluid. The working fluid, now a vapor, then passes through the turbine creating a work output. The condenser transfers heat from the vapor working fluid to make it sub cooled liquid. The pump uses a work input to move the liquid back through the cycle.

Equations to be Used

The following efficiency equation will help determine the individual component efficiency.

$$\eta = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)} = \frac{\frac{\dot{W}_t}{\dot{m}} - \frac{\dot{W}_p}{\dot{m}}}{\frac{\dot{Q}_{in}}{\dot{m}}}$$

Procedure

4. Determine the pressure and temperature at each component of the system.
5. Use these values to calculate an enthalpy value at each component.
6. Plug these into the governing equation and solve for the efficiency of the system.

APPENDIX

The following section is a general description of the Rankine Cycle as it relates to Thermodynamics, Heat Transfer, and Fluid Mechanics.

Theoretical Background of Thermodynamics

One of the most important ways to convert energy from such things as fossil fuels, nuclear, and solar potential energy is through processes known as vapor power cycles. One example of the use of vapor power cycles is electrical power plants. As engineers it is important to become familiar with these types of systems. The first step in becoming familiar with these cycles is through studying the theoretical ideal of the processes.

The ideal cycle for vapor power cycles can be modeled using the Rankine Cycle. This cycle is composed of four components: heater (boiler), turbine, condenser, and pump. To complete the system there must be some type of fluid in the cycle, which is called working fluid. Most often the working fluid is water. As the working fluid passes through each of the components it undergoes a process and ends up at a new state. Keeping in mind that the ideal Rankine cycle is physically impossible, we define each process to involve no internal irreversibility's. For the following it is necessary to number each of the states. State 1 is the state that at the boiler exit. State 2 is the turbine exit. State 3 is the condenser exit and state 4 is the pump exit.

Now the processes that the working fluid undergoes as it completes the cycle will be defined. First is the heater, which in most cases is a boiler. As the fluid ends the cycle, at state four, it is pumped into the boiler. In the boiler, the working fluid is heated from sub-cooled liquid to saturated vapor. This occurs at a constant pressure and is described in the following equation:

$$\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4 \qquad \text{Equation 1}$$

Where $\frac{\dot{Q}_{in}}{\dot{m}}$ is the rate of heat addition per unit mass of working fluid passing through the boiler. The value ($h_1 - h_4$) is the difference in outlet and inlet enthalpies of the working fluid.

Second is the turbine. Through the turbine the vapor leaving the boiler expands to the condenser pressure. This is said to be isentropic expansion so that no heat transfer to the surroundings is present. The equation that is used to describe this process is as follows:

$$\frac{\dot{W}_{turbine}}{\dot{m}} = h_1 - h_2 \qquad \text{Equation 2}$$

$\frac{\dot{W}_{turbine}}{\dot{m}}$ is the rate at which work is developed per unit of mass passing through the turbine.

Again the difference in inlet and exit enthalpies of the working fluid is required.
Next the working fluid enters the condenser. At this stage heat is rejected from the vapor at a constant pressure. Ideally, this continues until all of the vapor condenses to leave nothing but saturated liquid. The equation for this is seen here:

$$\frac{\dot{Q}_{out}}{\dot{m}} = h_2 - h_3$$ Equation 3

$\frac{\dot{Q}_{out}}{\dot{m}}$ is the rate at which heat is transferred from the working fluid per unit of mass. The value ($h_2 - h_3$) is the difference between inlet and outlet enthalpies of the condenser.

Finally, the working fluid enters the pump. The fluid goes through an isentropic compression process to reach the boiler pressure. The equation describing this is as follows:

$$\frac{\dot{W}_{pump}}{\dot{m}} = h_4 - h_3$$ Equation 4

$\frac{\dot{W}_{pump}}{\dot{m}}$ rate of power input per unit of mass passing through the pump. Finally the difference in pump outlet enthalpy and inlet enthalpy is needed.

Theoretical Background of Heat Transfer

A heat exchanger is a device that facilitates the transfer of energy between two fluids at different temperatures while keeping them from mixing. Heat exchangers allow two types of heat transfer to occur. Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion. Conduction is the interaction of particles, which transfers energy from more energetic particles to the less energetic ones. The rate of energy transfer between two fluids depends on the temperature difference between the two fluids, which varies along the length of the heat exchanger.

A heat exchanger in which one fluid condenses as it flows and gives off heat is called a condenser. A heat exchanger that involves one fluid absorbing heat and vaporizing is known as a boiler.

Newton's law of cooling allows the rate of heat transfer to be expressed as:

$$\dot{Q} = U * A * \Delta T_{lm} \qquad \text{Equation 5}$$

A is the heat transfer area. U is the overall heat transfer coefficient. This can be determined from the equation:

$$\frac{1}{U} \approx \frac{1}{h_i} + \frac{1}{h_o} \qquad \text{Equation 6}$$

_T_{lm} is the logarithmic mean temperature difference:

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \qquad \text{Equation 7}$$

Theoretical Background of Fluid Mechanics

Fluid mechanics is concerned with the behavior of liquids and gases at rest and in motion. The RankineCycler™ applies two main topics of fluid mechanics: viscous pipe flow and turbo-machinery.

Viscous pipe flow will either be completely filled or it will be partially filled open channel. It should be assumed that the steam moving through the pipe is completely filling the pipe. Determining how the flow is moving through the pipe is also important. Laminar, transitional, and turbulent flow could show up each of these cases has a different governing set of equations.

$$Q = V * A \qquad \text{Equation 8}$$

If the cross-sectional area, A, and the velocity, V, is known the volumetric flow rate, Q, can be found. It is also essential to find the Reynolds Number

$$\mathrm{Re} = \frac{\rho V D}{\mu} \qquad \text{Equation 9}$$

Where: r, is the density of the working fluid, V, is the average velocity in the pipe, D, is the pipe diameter, and m, and is the dynamic viscosity of the fluid. The Reynolds Number will help determine the type of flow. If the Reynolds Number in a round pipe is less than ~ 2100 the flow is laminar. If the Reynolds Number is greater than 4000 in a round pipe is determined to be turbulent. The transition region is between Reynolds Numbers of 2100 and 4000, respectively.

When a fluid enters a pipe with a near uniform velocity profile viscous effects cause the fluid to stick to the pipe wall. A boundary will form so the velocity profile changes with distance from the entrance region till the end of the entrance region, the boundary layer has completely filled the pipe. The entrance length is defined for laminar and turbulent flows as:

$$\frac{l_e}{D} = 0.06\ \mathrm{Re} \text{ for laminar flows} \qquad \text{Equation 10}$$

$$\frac{l_e}{D} = 4.4(\mathrm{Re})^{\frac{1}{6}} \text{ For turbulent flow} \qquad \text{Equation 11}$$

After the entrance region fully developed flow might be obtained depending upon the length of the pipe.

The pressure difference across a section of pipe:

$$\Delta p = p_1 - p_2 \qquad \text{Equation 12}$$

This is the force that moves the fluid through the pipe.

Fully developed laminar horizontal pipe flow can be described as the difference in pressure acting on the end of the pipe and the shear stress acting on the walls of the pipe. Thus:

$$p_1 \pi r^2 - (p_1 - \Delta p)\pi r^2 - \tau * 2\pi r l = 0$$

simplifies to:

$$\frac{\Delta p}{l} = \frac{2\tau}{r} \quad \text{Equation 13}$$

When r=0 there is no shear stress acting on the fluid. Although when r=D/2 the shear stress is at a maximum, where t_w, the wall shear stress, so:

$$\tau = \frac{2\tau_w r}{D} \quad \text{Equation 14}$$

The pressure drop if the viscosity was zero would be:

$$\Delta p = \frac{4l\tau_w}{D} \quad \text{Equation 15}$$

So a small shear stress can have a large pressure difference if the pipe is long ($l / D >> 1$).

The shear stress of a Newtonian fluid is proportional to the velocity gradient, so:

$$\tau = -\mu \frac{du}{dr} \quad \text{Equation 16}$$

The velocity profile can be written as:

$$u(r) = \frac{\Delta p D^2}{16\mu l}\left[1 - \left(\frac{2r}{D}\right)^2\right] = V_c\left[1 - \left(\frac{2r}{D}\right)^2\right] \quad \text{Equation 17}$$

where

$V_c = \frac{\Delta p D^2}{16\mu l}$ is the centerline velocity. Equation 18

Another expression is:

$$u(r) = \frac{\tau_w D}{4\mu}\left[1 - \left(\frac{r}{R}\right)^2\right] \quad \text{Equation 19}$$

The flow rate can also be expressed as:

$$Q = \frac{\pi D^4 \Delta p}{128\mu l} \quad \text{Equation 20}$$

The change in pressure is often written as:

$$\Delta p = f\frac{l}{D}\frac{\rho V^2}{2} \quad \text{Equation 21}$$

where f is the friction factor. For fully developed laminar pipe flow:

$$f = \frac{64}{\mathrm{Re}}$$ Equation 22

It is also essential to consider energy losses in the pipe:

$$\frac{p_1}{\gamma} + \alpha_1 \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \alpha_2 \frac{V_2^2}{2g} + z_2 + h_L$$ Equation 23

For uniform velocity profiles _=1 and for nonuniform velocity profiles _>1. The head loss, h_L, in a pipe is a result of the viscous shear stress on the wall.

$$h_L = \frac{2\tau l}{\gamma r} = \frac{4l\tau_w}{\gamma D}$$ Equation 24

When the pipe flow is considered to be turbulent, which probably will not occur, it is difficult to accurately predict the effects of the fluid being transported in the pipe. Consultation of the Moody chart is recommended.

The Rankine Cycler operates on the idea of using steam to drive a turbine turning a shaft connected to a generator; thus creating electrical energy from work energy. The Rankine Cycler operates using an axial flow turbine. When the flow over a turbine blade is broken down there are three components of velocity: absolute velocity, V, relative velocity, W, and blade velocity, U. The blade velocity, U, is in the direction of the moving blade. The relative velocity, W, is in the linear direction of the curve of the blade at a specified point on the blade. The absolute velocity can be expressed as:

$$V = W + U$$ Equation 18

When shaft torque and rotation are in the opposite direction a turbine is present. For steady flow:

$$\Sigma(r \otimes F) = \int_{cs} (r \otimes V)\rho V \cdot \hat{n}\, dA$$ Equation 19

and thus:

$$T_{shaft} = -\dot{m}_1\, r_1 V_{\theta 1} + \dot{m}_2\, r_2 V_{\theta 2}$$ Equation 20

The shaft power is related to the torque and the angular velocity by:

$$\dot{W}_{shaft} = T_{shaft}\omega$$ Equation 21

with U=wr:

$$\dot{W}_{shaft} = -\dot{m}_1\, U_1 V_{\theta 1} + \dot{m}_2\, U_2 V_{\theta 2}$$ Equation 22

and $w_{shaft} = \dot{W}_{shaft} / \dot{m}$:

$$w_{shaft} = -U_1 V_{\theta 1} + U_2 V_{\theta 2}$$ Equation 23

or:

$$w_{shaft} = \frac{V_2^2 - V_1^2 + U_2^2 - U_1^2 - (W_2^2 - W_1^2)}{2}$$ Equation 24

This is a simple overview of turbo machinery. Many different reference materials on axial flow turbines and turbo machinery are available for a more in-depth detail on these subjects.