Steam Generation and the "Rankine" Cycle.

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One of the standard power cycles for generating electricity or work in the form of propulsion[1] from a heat source (or energy stored in chemical bonds, or the nucleus of large atoms) is idealized as the "*Rankine*[2]" cycle. A photo taken in the boiler room of the *USS Missouri* shows the basic cycle for ship propulsion.
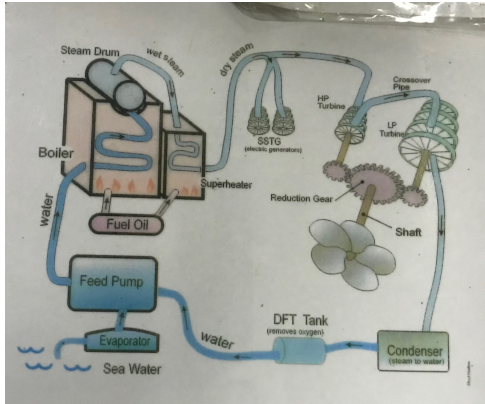

Figure 1. The diagram that is shown on tours of the USS Missouri

Figure 3, control valves for steam to a turbine.

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[1] For ocean going vessels, "steam" replaced sails and a Rankine cycle was used up until about 1950 when improved diesels and gas turbines became better choices. Nowadays, except for warships, even the largest vessels are usually powered by large marine diesels. You may wish to follow-up with this in the *Introduction* of your report.

[2] Named for William JM Rankine (1820-1872), a Scottish Engineer

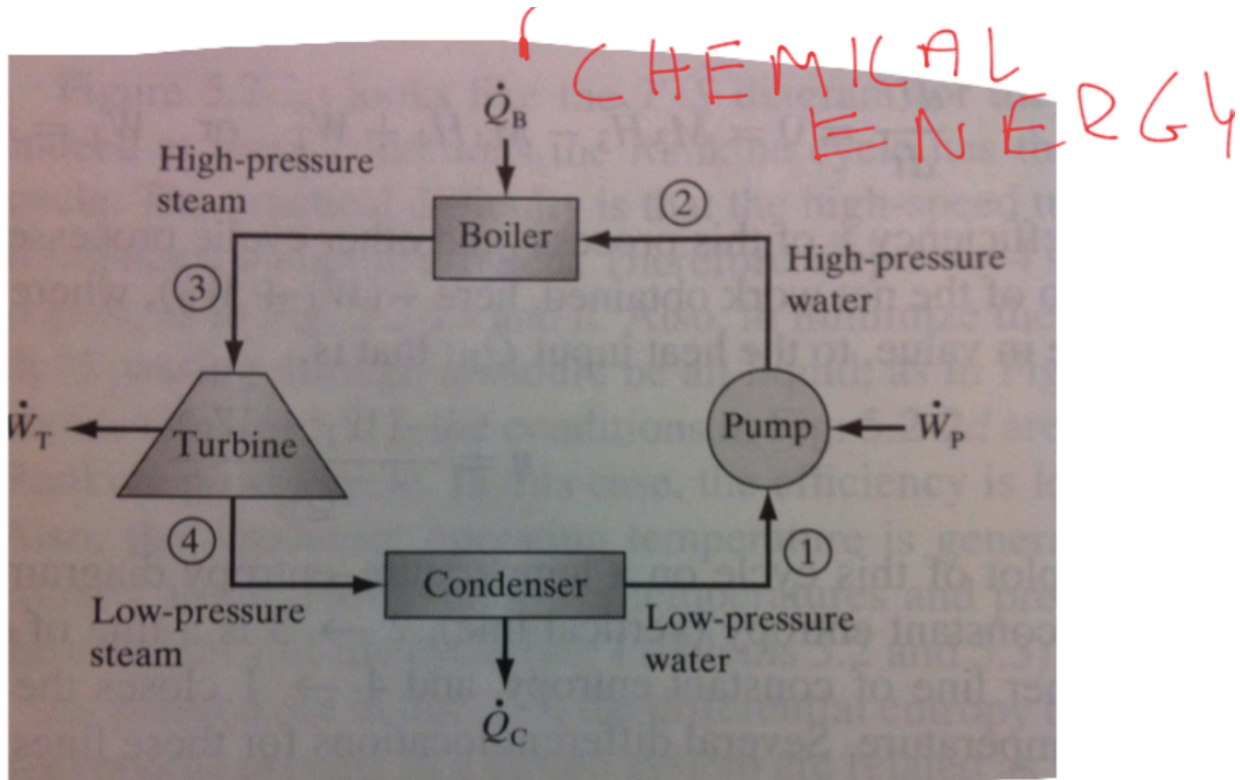The "simplest" version of this cycle is shown in figure 4.

Figure 4. Schematic of a standard Ranking Cycle.

A cyclical process allows for continuous transformation of the input heat into the output work. The best possible efficiency for the process can be attained when the heat flow matches what is needed for the required power. This process can, in principle, operate transiently or at steady state. You will want to read more about the Rankine cycle and the basic thermodynamics that is governing its operation (in either your Thermo book or elsewhere.).

Since uncorrelated energy (heat) is being transformed into precisely controllable and directable *work*, we expect to pay an efficiency penalty. For the internal cycle efficiency, $\dot{W}_T/(\dot{W}_P +/\dot{Q}_B)$, the Carnot formula will set an upper limit, $\eta= 1- T_2/T_1$, where T_2 is the temperature of the steam in the condenser and T_1 is the temperature of the steam leaving the boiler. Of course not all of the heat going to the boiler finds its way into the steam and most of the heat removed from the condenser is not useful. So a real efficiency of could be as low as 35% if the cycle were operated just as drawn here.

The apparatus for this laboratory experiment consists of two components. There is a burner/ boiler that produces steam from a propane combustion flame and a heat exchanger that functions as a condenser to remove heat and condense the water to complete the cycle. For this you can measure the combustion product composition, use an energy balance to quantify the efficiency of the burner/boiler is at making steam and check for heat losses associated with condensation. You also can measure the temperature-pressure relation for saturated steam.

The second component uses the steam to drive a turbine and measure the power that is being produced. The turbine spins a disk that has a controllable load. From the rotation rate and torque you can get the power produced — hence the mechanical work from the steam input. There is some operational range to allow you to find the best conditions to produce the most power. Further you will be able to get an overall (Rankine) cycle efficiency.

As this device requires several steps to get it to operate correctly, the first task for this experiment is for you write a "startup" procedure that includes appropriate safety. As such the first week session of lab will entail tracing the various tubes and cables, verifying all readouts and then formulating an appropriate procedure to first run the boiler/condenser unit and verify its operation. The second procedure is needed to run the power generation device and obtain data from it. Note that most of the other experiment devices are considerably simpler to operate and so don't need an operating procedure. However, don't worry, once you have the apparatus fully figured-out, you can get all of the necessary data in an hour or so.

Experimental device.

The "Rankine Cycle" lab consists of a Gunt ET850 "Steam Generator Module" shown here.

Directly to the right of this is the Gunt ET 851 "Steam Turbine Module"

There is an experiment manual for each of these devices on *Sakai*. These give all details of the device configuration and operation. At the end of these manuals there are sample calculations that should help you do your calculations.

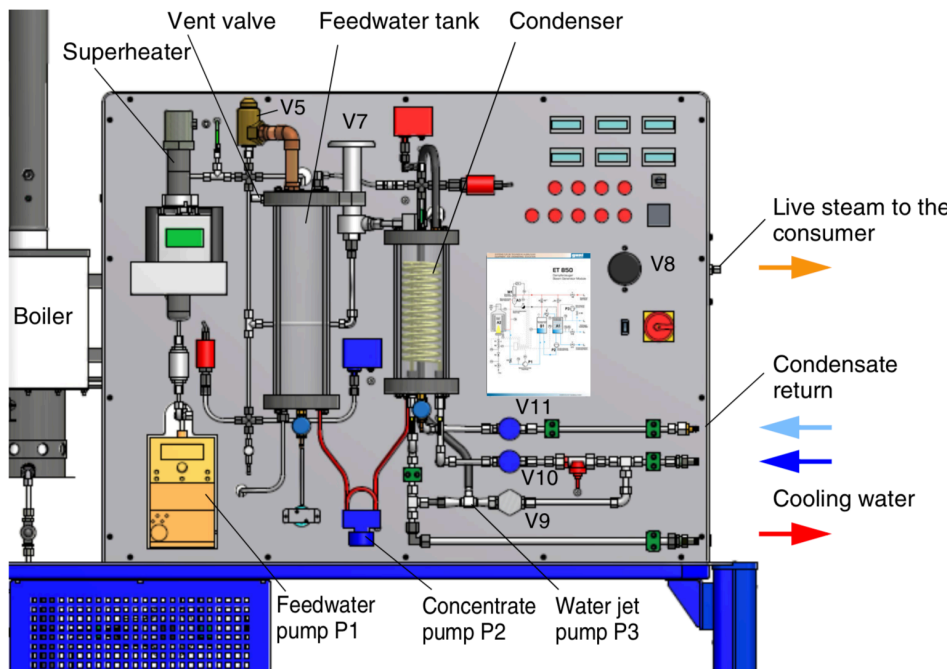The steam generator module "cartoon" is shown here:

Fig. 3.7   Condenser and feedwater supply

Water is fed by the pump to the boiler where the combustion process converts it to steam. The burner cannot be adjusted very much so that there is narrow range of water flow rates where the boiler can "just" produce fully-saturated steam. If the water flow is too low, the steam will be superheated in the boiler. If the water flow is too high, all of the water will not be converted to steam. You will be able to adjust the pump flow rate and observe this range of behavior.

After the boiler, the steam flows through the electric "superheater". This can be switched off or it can be on with a specific set point for the steam temperature. One possible experiment to try is to observe controller behavior by measuring the steam temperature that is produced as a function of time when you make a change to the "setpoint".

Unless steam is going to the turbine module it is condensed using "house" cooling water in the condenser. The condensed steam is pumped back to the feed water tank using the "condensate" (aka "*concentrate*") pump.

A process flow diagram for the steam generation module is given below.

ET 850   *STEAM GENERATOR MODULE*

3.2   Device function

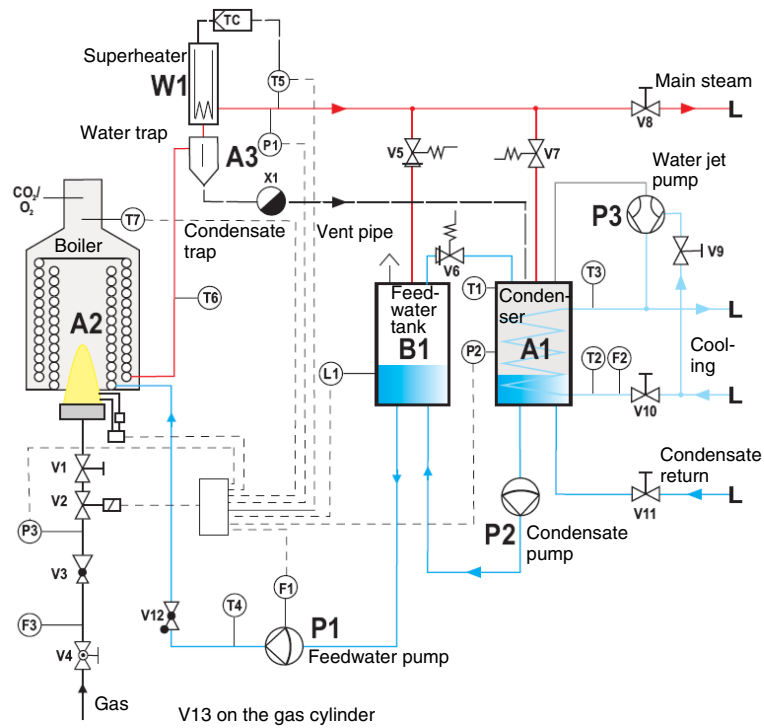### 3.2.1   Process schematic

Fig. 3.4   Process schematic

The steam turbine schematic is shown here:

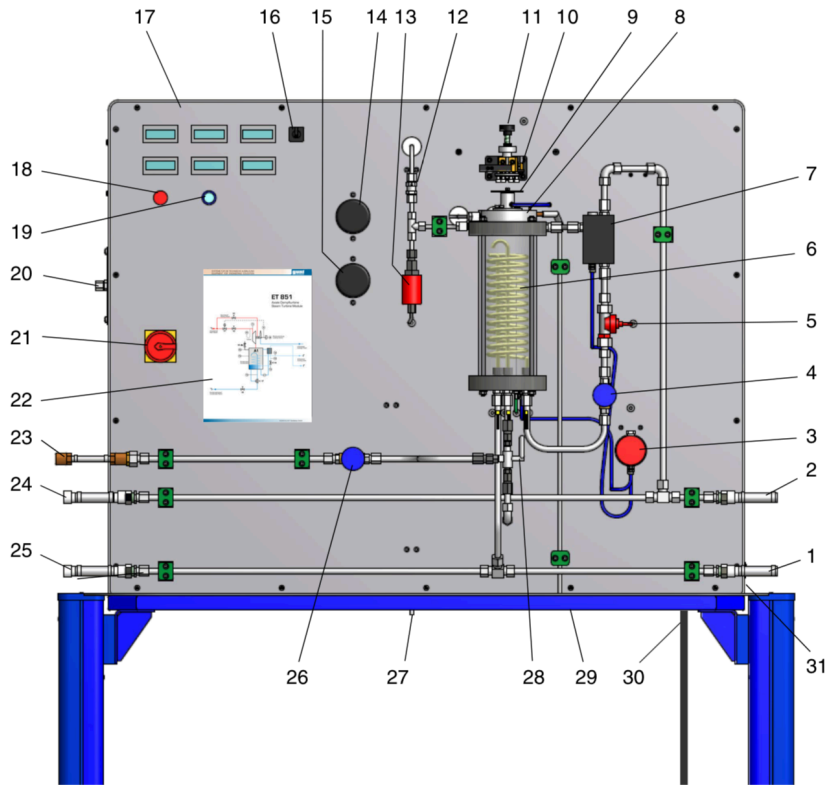**3.1   Device design**

Fig. 3.1   View

Steam from the generation module is fed through fitting 20. This connects directly to the turbine assembly, 8.   After passing by or causing the turbine to spin, the steam is condensed in the condenser 6. This water will return either by gravity or pressure differential using tubing 23 if valve 23 is the the proper position. Note that the inlet cooling water for both modules is connected to tube 2 and the cooling water drain for both modules is tube 1.

The turbine can be subjected to a variable load using the magnet assembly 11. The turbine speed is measured by (optical) sensor 10.

A process flow diagram of this device is shown below.
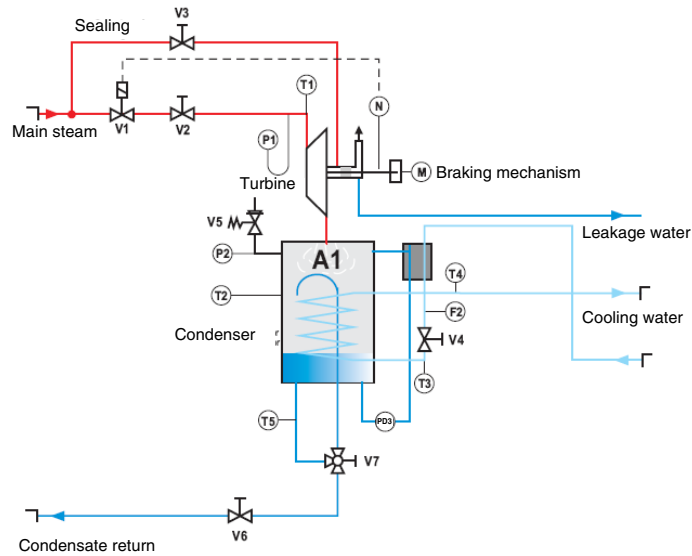
3.2 Device function

3.2.1 Process schematic

Fig. 3.3   Process schematic

A1	Condenser	N	Turbine speed
V1	Main steam solenoid valve	M	Turbine torque
V2	Main steam valve	T1	Turbine inlet temperature
V3	Sealing steam valve	T2	Condenser temperature
V4	Cooling water valve	T3	Cooling water inlet temperature
V5	Safety valve	T4	Cooling water outlet temperature
V6	Condensate return valve	T5	Condensate return temperature
V7	Three-way valve	P1	Turbine inlet steam pressure
PD3	Differential pressure for fill level	P2	Condenser pressure
F2	Cooling water flow		

Fig. 3.4   Process schematic - components and measuring points of the system

Tasks for the Steam Generator module.

In comparison with other experiments in this laboratory, this device is more complicated in terms of number of different components and their interconnected function. Thus your first task is to make a sketch[3] of the connections between all of the main components using the labels given in the Gunt Manual (e.g., "P2", "V7"). Then you need to make a step by step procedure for starting up this device and acquiring the necessary data. Once this has been checked by the lab TA, you can operate this module.

We would like to verify the following performance variables and parameters for module.

1. Verify that the T and P of the steam from the boiler matches which is expected for saturated steam.

   After assuring safe operation and startup up, your first task will be to find the water flow rate that produces fully-saturated steam with the superheater off. You should then be able to trace out the saturated steam curve by restricting the exit flow of steam from the boiler, hence increasing the temperature and pressure. Note that you should not exceed 9 BAR as the pressure in the boiler.

2. Calculate the boiler efficiency, (heat gained by water)/heat of propane combustion).

   From the composition of the "stack" gases, you can calculate the total input air flow rate. Using this and the stack gas temperature you can tell how much heat is expelled up the stack. Then for water feed rates where you have achieved 100% quality, then you know how much heat has gone into the steam, how much has gone up the stack and from the propane flow and the assumption of complete combustion, you can calculate the boiler efficiency.

You will want to "model" the heat losses by radiation and natural convection[4]. Presumably most of these losses are from the exposed area of the combustion chamber.

3. Calculate the overall efficiency of the steam generation unit.

   An energy balance on the entire first unit has propane heat in, stack gas out, and heat removed by the condenser. Examine this energy balance and determine if the heat losses are about the same as for #2 or much larger.

Additional possible experiments:

Over a range of propane flow rates, you can check the composition of the combustion gases with the hand-held combustion analyzer.

Can you find an optimal water — propane pairing that is most efficient in terms of steam generation?

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[3] You can start with the schematic that is given but you will need to annotate it.

[4] Using a surface temperature of the "shiny metal" of about 70C, and an area of 0.4 m^2, you can estimate a natural convection heat transfer coefficient from a "Rayleigh" number correlation and also get a value for the radiative heat losses. (more later….)

Under conditions of ~100 quality steam, turn on the superheater and make a change to the temperature. How does the steam temperature change with time? Is this a first order change ?

Tasks for the steam turbine module

1. As with the steam generator module, your first task is to make a sketch[5] of the connections between all of the main components using the labels given in the Gunt Manual (e.g., "P2", "V7").
2. Then you need to make a step by step procedure for starting up this device and acquiring the necessary data. Once this has been checked by the lab TA, then you can operate this module.
3. Once you have completed all tasks for the steam generation module and have the device lined out at a nice steady state, warm up the turbine and then check its performance, as a function of the torque applied. You are ultimately interested in an overall efficiency of the power out versus heat rate in.
4. We are also interested in an efficiency based on the steam rate supplied to the turbine and the power produced. Ideally, you will collect the condensate over measured time periods and get an experimental value for the steam flow rate. How does this compare to the rate of steam generation?
5. As time (and noise) permits, find if these numbers change much for different propane flow rates.

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[5] You can start with the schematic that is given but you will need to annotate it.