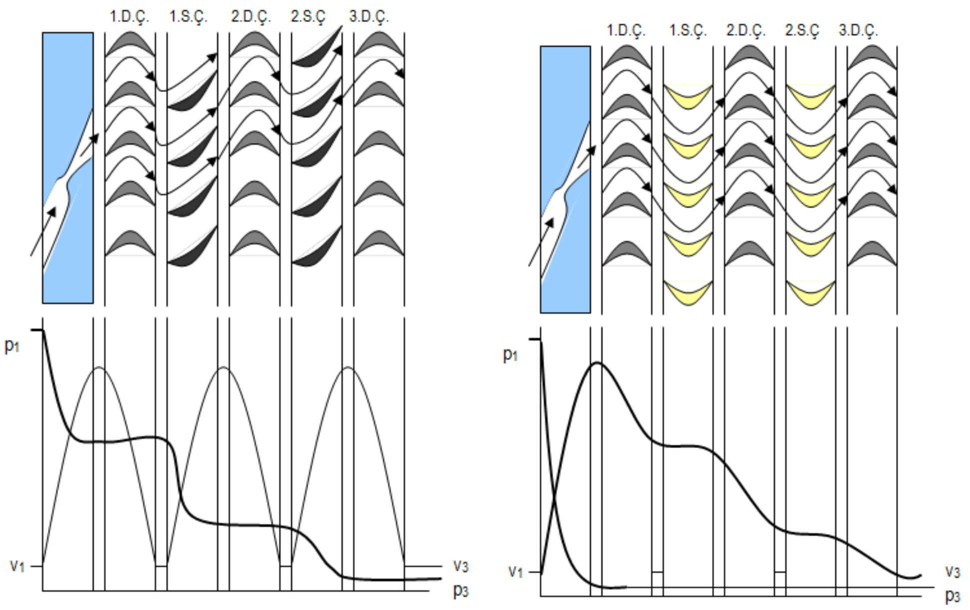
ENE 411 - ENGINEERING LAB II
RANKINE CYCLE
EXPERIMENT MANUAL

OBJECTIVE
The aim of the experiment is to understand how Rankine cycle operates and calculate the efficiencies of the steam generator, turbine and condenser of the system.

THEORY
Steam Turbines
Steam turbine is a system that converts the thermal energy of steam under high pressure into mechanical rotational energy. Usually electricity is produced as a result of this. Steam is sent at a high velocity through the blades of the turbine. With this, a rotational motion occurs. To convert the pressure energy of the steam into energy in the most efficient way (convergent-divergent) nozzles are used. The nozzle first narrows abruptly, then gradually widens. Due to the feature of the nozzle, the pressure of the passing steam is converted into kinetic energy, that is, velocity. As the velocity of the steam increases, the pressure that the steam jet will apply to the obstacle it encounters also increases. This also depends on the separation of the steam from its initial orbit. If the blades on a shaft turn the incoming steam almost in the direction of the periphery, the steam will apply a force in the direction of the circumference to rotate the shaft.
There are multi-stage ones in the form of successive stages in order to take the energy in the steam in the most efficient way. The bladed parts of each stage are placed on the same spindle. That's why they rotate at the same speed. This rotating arrangement is called the rotor as a whole. Theoretically, the entire pressure of the steam can be reduced to atmospheric pressure with a single mouth and converted to velocity. However, in this case the shaft must rotate at a very high speed to achieve reasonable efficiency. This brings some technical difficulties and can destroy the machine due to the large centrifugal forces. Turbines that use energy in successive stages are built according to several principles:
<u>1. Fast-stage</u>: In this system, the exact pressure of the steam is converted to a single speed. The obtained high-speed steam jet is sprayed to a certain part of the blades in the rotor stage, and its energy is utilized. Curtis turbine is this type of turbine.
<u>2. Pressure cascade</u>: The steam expands in the blast pipe and the resulting high velocity steam hits the cascading blades and turns the rotor. The steam then passes between the guide vanes. Here the steam expands a little and the speed turns another level. The steam passing between the blades in the fixed and rotating stages in this way expands a little at each stage and continues this process until all the pressure in the stages is used. Each time the steam, which is the same in weight, passes through the circuit, its pressure is gradually reduced with the increase in volume. For this reason, the diameter of the blades of the stage at the exit end of the turbine is larger than those at the inlet. These are called action turbines.
<u>3. Stage of reaction</u>: In this system, the pressure is converted to speed not only in the spray lance and the fixed guide stages, but also in the rotor stages. These are called reaction turbines. Steam turbines



(a) (b)

Figure-1 (a) Speed steps in a Curtis turbine (D.Ç: rotary wheel, S.Ç: Fixed wheel),
(b) Pressure steps in the iso-pressure Zoelly turbine (D.Ç: rotary wheel, S.Ç: Fixed impeller)

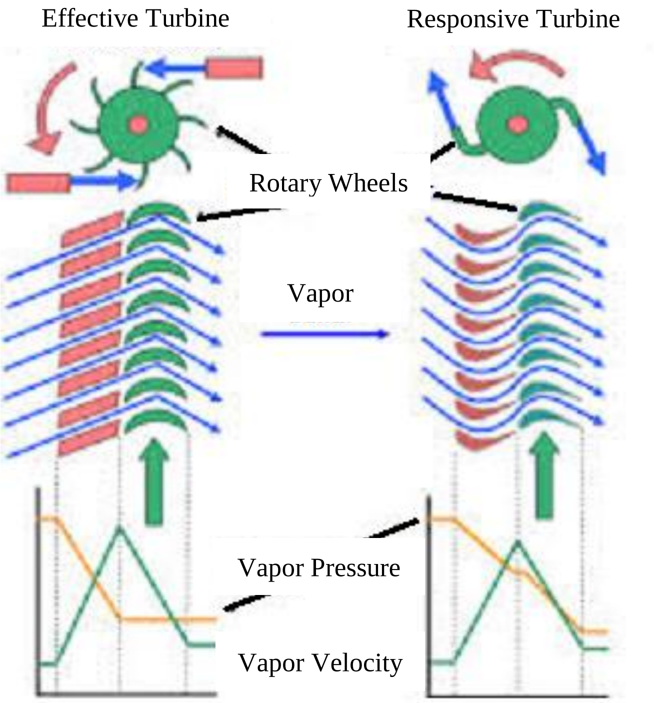


Figure-2 Effective and responsive turbine concepts

also leave the turbine. It is also classified as with or without a condenser, depending on where the low pressure steam enters. Since turbines with condensers reduce the temperature and pressure of the outlet steam, the efficiency of the turbine increases due to the drop rate of the pressure in the turbine. In systems without a condenser, the spent steam, whose work is finished in the turbine, is sent to the atmosphere or to a heating system or any place of use. Different names are given to the turbines according to the places where the steam enters after the exit.

Efficiencies of Cycle Components

Cauldron efficiency: The capacity of the steam generator is the energy it can absorb. The efficiency of the steam generator can be written as;

$$\eta = \frac{\dot{Q}_k}{P_{el}}$$

$$\dot{Q}_k = \dot{m}_v(h_{v,in} - h_w)$$

where $\dot{m}_v$: Mass flow rate of steam coming out of the cauldron

$h_{v,in}$: Enthalpy of superheated steam leaving the cauldron

h_w : Enthalpy of water entering the cauldron

P_{el} : Cauldron electrical input, fixed

Turbine-generator efficiency:

$$\eta = \frac{P_T}{\dot{Q}_T}$$

$$\dot{Q}_T = \dot{m}_v(h_{v,in} - h_{v,out})$$

where $\dot{m}_v$: Mass flow rate of steam entering the turbine

$h_{v,in}$: Steam enthalpy at the turbine input

$h_{v,out}$: enthalpy of waste steam

P_T : Turbine power output

Condenser capacity and efficiency:

$$\dot{Q}_{c1} = \dot{m}_v(h_{v,out} - h_{cw})$$

$$\dot{Q}_{c2} = \dot{m}_w C_w(T_{out} - T_{in})$$

$$\eta = \frac{\dot{Q}_{c2}}{\dot{Q}_{c1}}$$

where $\dot{m}_v$: Mass flow rate of steam entering the turbine

h_{cw} : Enthalpy of condensed water

$h_{v,out}$: Enthalpy of waste steam

$\dot{m}_w$: Mass flow rate of cooling water

C_w : Specific heat of cooling water

T_{out} : Outlet temperature of cooling water

T_{in} : Inlet temperature of cooling water

<u>Cycle efficiency</u>:

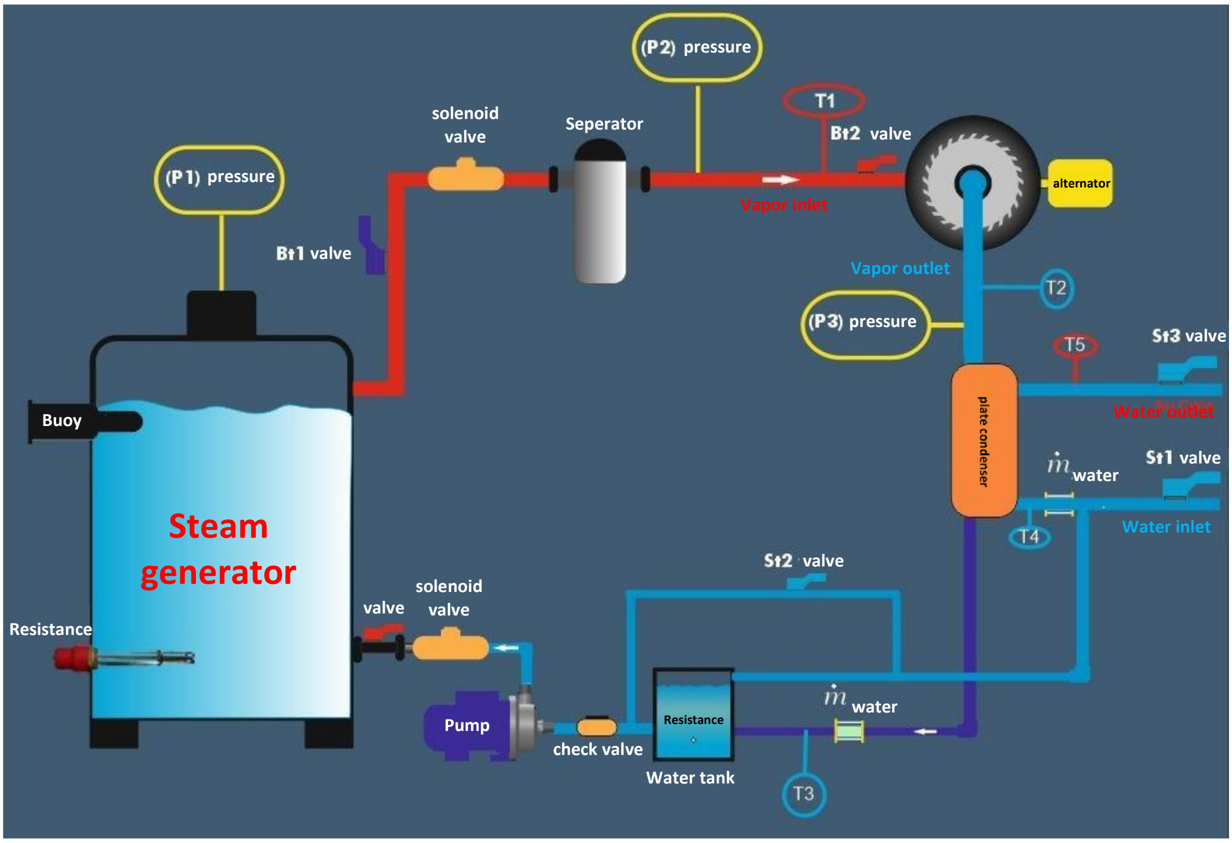
$$\eta = \frac{P_{turbine} - P_{pump}}{P_{el}}$$

where P_{tur} : Work derived from the turbine

P_{pump} : Work used by the pump, fixed

P_{el} : Cauldron electrical input, fixed

EXPERIMENTAL SETUP

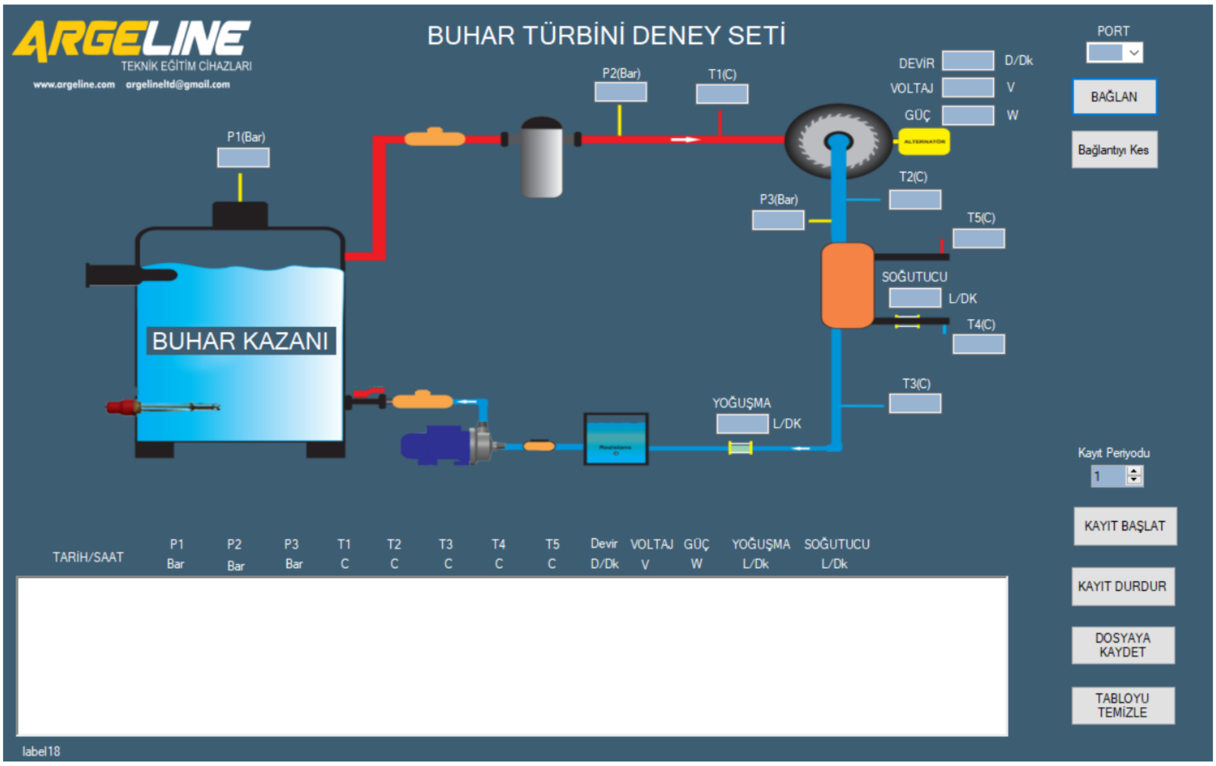


EXPERIMENTAL PROCEDURE

1. Plug the three-phase (380V) plug into the appropriate sockets.
2. Make sure the mains connection is connected to the device.
3. Emergency button and leakage current must be on and turn on the main switch.
4. Turn on the steam generator when the data is displayed on the LCD.
5. Press the resistor 1 and resistor 2 button.
6. Open the cold-water system sst1 valve and sst2 valve.
7. Close the sst2 valve after the lights turns on the resistor 1 and resistor 2 buttons.
8. Wait 15 minutes for the steam generator to generate steam.
9. When the pressure gauge shows 5 bar and above, the system is ready.
10. Open the bt1 valve on the steam installation and open the solenoid valve on the screen.
11. Inject steam to the turbine gradually with the bt2 valve on the steam installation.
12. Run the cycle clock on the LCD screen for 3 minutes until dry steam is formed.
13. After the system is in order, press the load switch on the LCD screen and open the bt2 valve completely.
14. Save the data on the LCD screen.

MEASUREMENTS

Data acquisition interface is shown in the figure below.



Measured properties		units
Cauldron pressure*	P_1	[bar]
Turbine input pressure*	P_2	[bar]
Turbine exit pressure*	P_3	[bar]
Steam inlet temperature	T_1	[°C]
Steam outlet temperature	T_2	[°C]
Condensation line temperature	T_3	[°C]
Coolant inlet temperature	T_4	[°C]
Coolant outlet temperature	T_5	[°C]
Turbine electrical output	P	[W]
Turbine rotation	n	[r/min]
Cooling water flow rate	$m_{cooling}$	[L/h]
Condensation flow rate	$m_{condenstaion}$	[L/h]

Given (fixed) properties		units	value
Electrical input power	P_{el}	[kW]	50
Pump inlet power	P_{pump}	[W]	100

* Please note that pressure values are given as relative pressure.

During your calculations assume that

- Pump outlet temperature is equal to T_3 and pressure is equal to P_2
- Turbine outlet state is saturated vapor
- Condenser outlet state is saturated liquid.

IN YOUR REPORT

1. Using your measurements, show
    a. P_1, P_2 and P_3 with respect to time in a single graph.
    b. T_1, T_2, $T_{3,}$ T_4 and T_5 with respect to time in a single graph
    c. $m_{cooling}$ and $m_{condenstaion}$ with respect to time in a single graph
    d. n and P with respect to time in a single graph

    and add trendlines (showing equations on the graph) for each series.
2. Choose three time points on the graphs (around the beginning, the middle and the end). Using the equations of the trend lines to determine the mass flow rates, work output and thermodynamic states (pressure and temperature values) at these three time points. Calculate efficiencies of steam generator, turbine-alternator, condenser and overall cycle.
3. Compare your results of three points with each other and efficiencies from literature, Discuss the differences and their possible sources.
4. Plot turbine electrical power with respect to number of turbine rotations and comment on the relationship between them.

* you can use your thermodynamic tables to look at the properties of the thermodynamic states.