Description of the Rankine Cycle

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Introduction

The Rankine cycle is a thermodynamic process by which a fluid is converted into mechanical work using an external heat source. This four step cycle is the fundamental operating process that runs every thermal power plant in the United States. One of the main reasons this cycle is so commonly used is because the materials used throughout the cycle are completely reused, which increases efficiency while lowering cost. The cycle also demonstrates crucial thermodynamic activity that every future engineer should be familiar with and which will be explained throughout this description.

Water is Heated in the Boiler

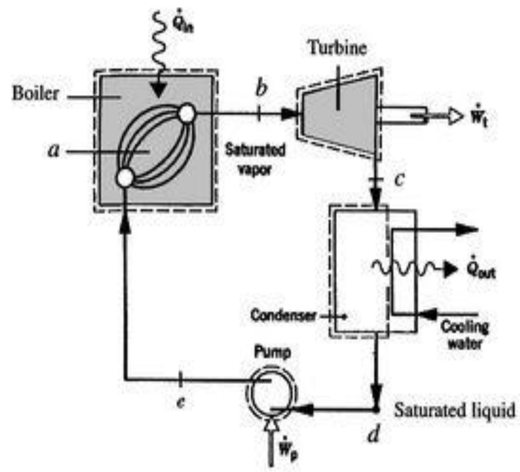

Figure 1: Cycle Schematic

The process starts with the entrance of a high pressure working fluid, usually water, entering the boiler after being fed by a pump. As the name suggests, the water is then heated in the boiler by adding an external heat source. The most commonly used heat sources come from the burning of fossil fuels such as oil, natural gas, and coal. This added heat is represented by the squiggly line "q" entering the boiler in Figure 1. The fluid is heated until it is entirely in a gaseous state. Thermodynamically, it is important to note that the heating that occurs in this stage is done so under constant pressure, which can be seen by the horizontal line moving from Point 2 to Point 3 on the Temperature-Entropy diagram in Figure 2.

Steam Turns the Turbine

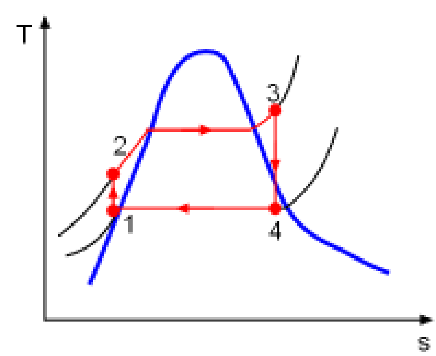

Figure 2: Temperature-Entropy Diagram

As the steam exits the boiler from step 1, it is immediately forced through a turbine connected to an electrical generator. The pressure gradient between the still high pressure steam and the low pressure atmosphere on the other side of the turbine acts as the driving force that moves the steam through the turbine. As the steam moves through the turbine, it turns several blades which consequently creates a turning moment on the turbine's rotor. It is this rotary motion in the turbine that ultimately creates the electricity in the power plant.

This mechanical work is depicted as the “w” arrow coming out of the turbine in Figure 1. When the steam has completed traveling through the turbine, it has cooled down naturally to become a liquid-vapor mixture, which corresponds to Point 4 in Figure 2.

Mixture Cools in the Condenser

Figure 3: Power Plant Built Near Water Source

Upon leaving the turbine, the mixture enters a condenser in its new low pressure state. Here, water is added to the system from an external source to cool down the mixture so that it once again becomes completely liquid. This removal of heat is represented by the line “q” leaving the pump in Figure 1. Oftentimes, power plants are built by large water sources such as oceans or reservoirs so the cooling water added into the condenser can be immediately released back where it came from. This not only saves resources and money, but is also completely safe for the environment as no pollutants are added throughout the entire cycle. Figure 3 shows an example of a power plant where cooling water can be used to cool down the mixture, and then be released back into the sea. Similarly to the water being heated in the boiler, the cooling process occurs at constant pressure, as shown as Point 4 to Point 1 in Figure 2. The advantage of constant pressure cooling, like heating, allows increased control over the physical end state of the mixture.

Water Pressurizes in the Pump

After the liquid water leaves the condenser, it enters again enters the feed pump. In the pump, external work is required to return the water to its high pressure state, which can be seen in Figure 2 as the movement from Point 1 to Point 2. The work that is required to run the pump is most commonly electrical and is relatively small compared to the work produced by the turbine. The “w” arrow pointing into the pump in Figure 2 depicts this work entering the system. After the pressure has been increased, the water is then pumped to the boiler where the water is again heated and the process repeats itself, thus completing the closed loop.

Cycle Summary

In thermodynamics, the overall effectiveness of any cycle is measured by the cumulative sum of the amount of work (w) that enters and leaves the system. In the Rankine cycle, there are two steps where work enters and leaves the system. The first comes in step 2, mechanical work leaves the cycle in the form of the spinning turbine rotor which produces the electricity for the power plant. Then in step 4, electrical work into the system is required to pressurize the water in the pump. As mentioned before, it is important to note that the amount of work leaving through the turbine is much greater than the amount of work required to run the cycle. Therefore, the net amount of work generated by the system is positive which enables the plant to produce power.

The theoretical efficiency of the Rankine cycle is about 63%, which does not sound spectacular, but it is actually quite good for a closed thermodynamic process. However, the average actual thermal efficiency for a United States coal-fired power plant is closer to 42%. While still a relatively good efficiency, factors such as the high amount of heat required for vaporization of the working fluid and a relatively low steam turbine entry temperature push down the rating. Because of these limitations, several variations of the Rankine cycle have been implemented in power plants to improve thermal efficiency throughout the years, such as the reheat method and the use of supercritical fluids. Though the basic Rankine cycle as described above has evolved, its fundamental concept has been providing electricity to the United States for over a century and looks to do so for the foreseeable future.