# **Chapter 8**

#### **Vapor Power Systems**

# **Introducing Power Generation**

To meet our national power needs there are challenges related to

 Declining economically recoverable supplies of *nonrenewable* energy resources.
 Effects of global climate change and other environmental and human health and safety issues.
 Rapidly increasing demand for power owing to increasing population.

Current	<b>U.S</b> .	Elect	ricity
Generat	ion b	ο δοι	irce

Coal	48.5%
Natural gas	21.6%
Nuclear	19.4%
Hydroelectric	5.8%
Other renewables	2.5%
Oil	1.6%
Others	0.6%

► Today we are heavily dependent on coal, natural gas, and nuclear, all of which are nonrenewable.

# **Introducing Power Generation**

While coal, natural gas, and nuclear will continue to play important roles in years ahead, contributions from wind power, solar power, and other renewable sources are expected to be increasingly significant up to mid-century at least.
Table 8.2

Large-Scale Electric Power Generation through 2050 from Renewable and Nonrenewable Sources

Power Plant Type	Nonrenewable Source	Renewable Source	Thermodynamic Cycle
Coal-fueled	Yes		Rankine
Natural gas-fueled	Yes		Brayton
Nuclear-fueled	Yes		Rankine
Oil-fueled	Yes		Rankine
Biomass-fueled		Yes	Rankine
Geothermal		Yes	Rankine
Solar-concentrating		Yes	Rankine
Hydroelectric		Yes	None
Wind		Yes	None
Solar-photovoltaic		Yes	None
Fuel cells	Yes		None
Currents, tides, and waves		Yes	None

The components of four alternative vapor power plant configurations.

They are

Fossil-fueled vapor power plants.

Pressurized-water reactor nuclear vapor power plants.

- Concentrating solar thermal vapor power plants.
- Geothermal vapor power plants.

In each of the four types of vapor power plant, a working fluid is alternately vaporized and condensed. A key difference among the plants is the origin of the energy required to vaporize the working fluid.

► In fossil-fueled plants, the energy required for vaporization originates in combustion of the fuel.



In nuclear plants, the energy required for vaporization originates in a controlled nuclear reaction.



(b) Pressurized-water reactor nuclear vapor power plant.

In solar plants, the energy required for vaporization originates in collected and concentrated solar radiation.



(c) Concentrating solar thermal vapor power plant.

In geothermal plants, the energy required for vaporization originates in hot water and/or steam drawn from below the earth's surface.



► The fossil-fueled vapor power plant is considered as representative. The overall plant is broken into four major subsystems identified by A, B, C, and D. Water is the working fluid.



Subsystem A provides the heat transfer of energy needed to vaporize water circulating in subsystem B. In fossil-fueled plants this heat transfer has its origin in the combustion of the fuel.



► In subsystem B, the water vapor expands through the turbine, developing power. The water then condenses and returns to the boiler.



► In subsystem C, power developed by the turbine drives an electric generator.



Subsystem D removes energy by heat transfer arising from steam condensing in subsystem B.



Each unit of mass of water periodically undergoes a thermodynamic cycle as it circulates through the components of subsystem B. This cycle is the *Rankine cycle*.



# **Power Cycle Review**

► The first law of thermodynamics requires the net work developed by a system undergoing a power cycle to equal the net energy added by heat transfer to the system:

$$\dot{W}_{\text{cycle}} = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}}$$

► The thermal efficiency of a power cycle is





# **Power Cycle Review**

► The second law of thermodynamics requires the thermal efficiency to be less than 100%. Most of today's vapor power plants have thermal efficiencies ranging up to about 40%.

► Thermal efficiency tends to increase as the average temperature at which energy is added by heat transfer increases and/or the average temperature at which energy is rejected by heat transfer decreases.

Improved thermodynamic performance of power cycles, as measured by increased thermal efficiency, for example, also accompanies the reduction of irreversibilities and losses.

The extent of improved power cycle performance is limited, however, by constraints imposed by thermodynamics and economics.

# The Rankine Cycle

Each unit of mass of water circulating through the interconnected components of Subsystem B of Fig. 8.1(a) undergoes a thermodynamic cycle known as the Rankine cycle.

There are four principal control volumes involving these components:

- Turbine
- Condenser
- Pump
- Boiler



All energy transfers by work and heat are taken as positive in the directions of the arrows on the schematic and energy balances are written accordingly.

The ideal Rankine cycle provides a simple setting to study aspects of vapor power plant performance. The ideal cycle adheres to additional modeling assumptions:

Frictional pressure drops are absent during flows through the boiler and condenser. Thus, these processes occur at constant pressure.

Flows through the turbine and pump occur adiabatically and without irreversibility. Thus, these processes are isentropic.

The ideal Rankine cycle consists of four internally reversible processes:

Process1-2: Isentropic expansion through the turbine

Process 2-3: Heat transfer *from* the working fluid passing through the condenser at constant pressure



Process 3-4: Isentropic compression in the pump Process 4-1: Heat transfer *to* the working fluid passing through the boiler at constant pressure

Possible variations of this cycle include: turbine inlet state is **superheated vapor**, **State 1'**; pump inlet, **State 3**, falls in the liquid region.

The ideal Rankine cycle involves internally reversible processes.

Hence, the pump work input per unit of mass flowing can be evaluated as follows

$$\left(\frac{\dot{W_p}}{\dot{m}}\right)_{\rm s} \approx v_3(p_4 - p_3) \quad \text{(Eq. 8.7b)}$$

where  $v_3$  is the specific volume at the pump inlet and the subscript s signals the isentropic process of the liquid flowing through the pump.

Applying Eq. 6.49, areas under process lines on the *T*-s diagram can be interpreted as heat transfers, each per unit of mass flowing:

Area 1-b-c-4-a-1 represents heat transfer to the water flowing through the boiler

Area 2-b-c-3-2 represents heat transfer from the water flowing through the condenser.

Enclosed area 1-2-3-4-a-1 represents the net heat input or equivalently the net work developed by the cycle.



► The figure shows two cycles having the same boiler pressure but different condenser pressures:

- one is at atmospheric pressure and
- ► the other is at less than atmospheric pressure.



# <u>Using the Ideal Rankine Cycle to Study</u> <u>the Effects on Performance of Varying</u> <u>Condenser Pressure</u>

► Power plant condensers normally operate with steam condensing at a pressure well below atmospheric. For heat rejection to the surroundings the lowest feasible condenser pressure is the saturation pressure corresponding to the ambient temperature.

► A primary reason for including condensers in vapor power plants is the increase in thermal efficiency realized when the condenser operates at a pressure less than atmospheric pressure. Another is that the condenser allows the working fluid to flow in a closed loop and so demineralized water that is less corrosive than tap water can be used economically.

# <u>Using the Ideal Rankine Cycle to Study</u> <u>the Effects on Performance of Varying</u> <u>Condenser Pressure</u>

► As steam condenses, energy is discharged by heat transfer to cooling water flowing separately through the condenser. Although the cooling water carries away considerable energy, its utility is extremely limited because cooling water temperature is increased only by a few degrees above the ambient. Such warm cooling water has little thermodynamic or economic value.

► The figure shows two cycles having the same condenser pressure but different boiler pressures:

one is at a given pressure and

The other is at higher than the given pressure.



Since the average temperature of heat addition for cycle 1'-2'-3-4'-1' is greater than for cycle 1-2-3-4-1, the higher pressure cycle has the greater thermal efficiency.
Increasing the boiler pressure tends to increase thermal efficiency.



► However, an increase in boiler pressure also results in a reduction of steam quality for the expansion through the turbine – compare the lower quality state 2' with state 2.

► If the quality of the expanding steam becomes too low, the impact of liquid droplets in the steam can erode the turbine blades and possibly diminish performance.



Rankine cycle modifications known as superheat and reheat permit advantageous operating pressures in the boiler and condenser while avoiding low-quality steam in the turbine expansion. Another such modification is the supercritical cycle. All three are considered next.

#### **Ideal Rankine Cycle with Superheat**

► The figure shows a Rankine cycle with superheated vapor at the turbine inlet: cycle 1'-2'-3-4-1'.

► The cycle with superheat has a higher average temperature of heat addition than cycle 1-2-3-4-1 without superheat, and thus has a higher thermal efficiency.



► Moreover, with superheat the quality at the turbine exit, state 2', is greater than at state 2, the turbine exit without superheat.

A combined boiler-superheater is called a steam generator.

#### **Ideal Reheat Cycle**

► The reheat cycle is another Rankine cycle modification that takes advantage of the increased thermal efficiency resulting from a high average temperature of heat addition and yet avoids lowquality steam during expansion through the turbine.

► With reheat, the steam quality at the turbine exit, state 4, is greater than at state 4', the turbine exit without reheat.



### **Ideal Reheat Cycle**

Departures of the reheat cycle from the simple vapor power cycle considered thus far include

> Process 1-2. Steam expands through the highpressure turbine stage.

Process 2-3. Steam is reheated in the steam generator.

Process 3-4. Steam expands through the lowpressure turbine stage.



#### **Ideal Reheat Cycle**

When computing the thermal efficiency of a reheat cycle it is necessary to account for the

► Total work developed in the two turbine stages: processes 1-2 and 3-4.

► Total heat added during vaporization/superheating and reheating: processes 6-1 and 2-3.



$$\eta = \frac{\dot{W_{t_{\rm HP}}} + \dot{W_{t_{\rm LP}}} - \dot{W_{\rm p}}}{\dot{Q_{6-1}} + \dot{Q_{2-3}}}$$

### **Supercritical Ideal Reheat Cycle**

Steady improvements over many decades in materials and fabrication methods have permitted significant increases in maximum allowed temperatures and steam generator pressures.

These efforts are embodied in the supercritical reheat cycle.

# **Supercritical Ideal Reheat Cycle**

Steam generation occurs at a pressure greater than the critical pressure of water: Process 6-1.

► No phase change occurs during process 6-1. Instead, water flowing through tubes is heated from liquid to vapor without the bubbling associated with boiling.

► Today's supercritical plants achieve thermal efficiencies up to 47%. *Ultrasupercritical* plants capable of operating at still higher temperatures and steam generator pressures will have thermal efficiencies exceeding 50%.



Irreversibilities are associated with each of the four subsystems designated by A, B, C, and D on the figure.



For a fossil-fueled vapor power plant the most significant site of irreversibility by far is subsystem A. There, irreversibility is associated with combustion of the fuel and subsequent heat transfer from hot combustion gases to vaporize water flowing through



the closed loop of subsystem  $\mathbf{B}$ , which is the focus of discussion.

► As such irreversibilities occur in the surroundings of subsystem B, they are classified as *external* irreversibilities for that subsystem.

Irreversibilities in subsystems C and D are also external irreversibilities of subsystem B but they are minor relative to the combustion and heat transfer irreversibilities occurring in the boiler.

Combustion irreversibility is studied in Chapter 13.

Irreversibilities associated with subsystem B are called internal. They include the expansion of steam through the turbine and the effects of friction in flow through the pump, boiler, and condenser.

► The most significant internal irreversibility associated with subsystem B is expansion through the turbine.



► Isentropic turbine efficiency, introduced in Sec. 6.12.1, accounts for the effects of irreversibilities within the turbine in terms of actual and isentropic turbine work, each per unit of mass flowing through the turbine.



► While pump work input is much less than turbine work output, irreversibilities in the pump affect net power output of the vapor plant.

► Isentropic pump efficiency, introduced in Sec. 6.12.3, accounts for the effects of irreversibilities within the pump in terms of actual and isentropic pump work input, each per unit of mass flowing through the pump.  $T_{\parallel}$ 



► For simplicity, frictional effects resulting in pressure reductions from inlet to exit for the boiler and condenser are ignored in Chapter 8.

► Flow through these components is assumed to occur at constant pressure.



- Another method for increasing thermal efficiency of vapor power plants is by application of regenerative feedwater heaters.
- Regenerative feedwater heating increases the average temperature of heat addition, thereby increasing the thermal efficiency.
- In vapor power plants both open and closed feedwater heaters are typically used. Each feedwater heater type is considered in Sec. 8.4.

A vapor power cycle using a single open feedwater heater (a mixing chamber) is shown in the figure.



▶ In this cycle, water passes isentropically through each of two turbine stages, 1-2 and 2-3, and each of two pumps, 4-5 and 6-7.

Flow through the steam generator, 7-1, and condenser, 3-4, occur at constant pressure.

Mixing occurs within the feedwater heater, thereby introducing a source of irreversibility into an otherwise ideal cycle.

The feedwater heater is assumed to operate adiabatically.



Referring to the *T*-*s* diagram, heat transfer to the cycle takes place from state 7 to state 1, rather than from state a to state 1 as would be the case if there were no open feedwater heater.

Accordingly, when an open feedwater heater is included, the average temperature of heat addition to the cycle increases; thus, thermal efficiency increases.





► Referring to the schematic, let us follow a unit of mass as it moves through the cycle. The unit of mass is denoted in parentheses by (1).

► The unit of mass (1) enters the turbine at state 1 and expands to state 2 where a fraction (*y*) is diverted into the open feedwater heater.

► The remaining fraction (1-y) expands through the second turbine stage to state 3, is condensed to state 4, and then pumped to state 5 where it enters the open feedwater heater.



#### The fractions (y) and (1-y) entering the feedwater heater at states 2 and 5, respectively, mix within that component, giving a single stream at state 6 and recovering the unit of mass (1).

The unit of mass (1) at state 6 is pumped to state 7 where it enters the steam generator and returns to state 1 after heating.



Applying steady-state mass and energy rate balances to a control volume enclosing the feedwater heater, the fraction of the total flow y is

$$y = \frac{h_6 - h_5}{h_2 - h_5}$$
 (Eq. 8.12)

► With fraction *y* known, mass and energy rate balances applied to control volumes around the other components yield the following expressions, each on the basis of a unit of mass entering the first turbine stage.



For the pumps  $\frac{\dot{W}_{p}}{\dot{m}_{1}} = (h_{7} - h_{6}) + (1 - y)(h_{5} - h_{4})$ 

(Eq. 8.14)

For the steam generator  $\frac{\dot{Q}_{in}}{\dot{m}_1} = h_1 - h_7$  (Eq. 8.15)





$$\frac{\dot{Q}_{\text{out}}}{\dot{m}_1} = (1 - y)(h_3 - h_4)$$
 (Eq. 8.16)

# **Cogeneration Systems**

Are integrated systems that simultaneously yield two valuable products, electricity and steam (or hot water) from a single fuel input.

Typically provide cost savings relative to producing power and steam (or hot water) in separate systems.
 Are widely deployed in industrial plants, refineries, food processing plants, and other facilities requiring process steam, hot water, and electricity.

► Can be based on vapor power plants, gas turbine power plants, internal combustion engines, and fuel cells.

# **Cogeneration Systems**

► An application of cogeneration based on vapor power plants is district heating – providing steam or hot water for space heating together with electricity for domestic, commercial, and industrial use.



# **Cogeneration Systems**

Exporting useful steam to the community limits the electricity that also can be provided from a given fuel input, however.
 For instance, to produce saturated vapor at 100°C (1 atm) for export to the community water circulating through the power plant will condense at a higher temperature and thus at a higher pressure.

In such an operating mode thermal efficiency is less than when condensation occurs at a pressure below 1 atm, as in a plant fully dedicated to power production.

