Meeting 16

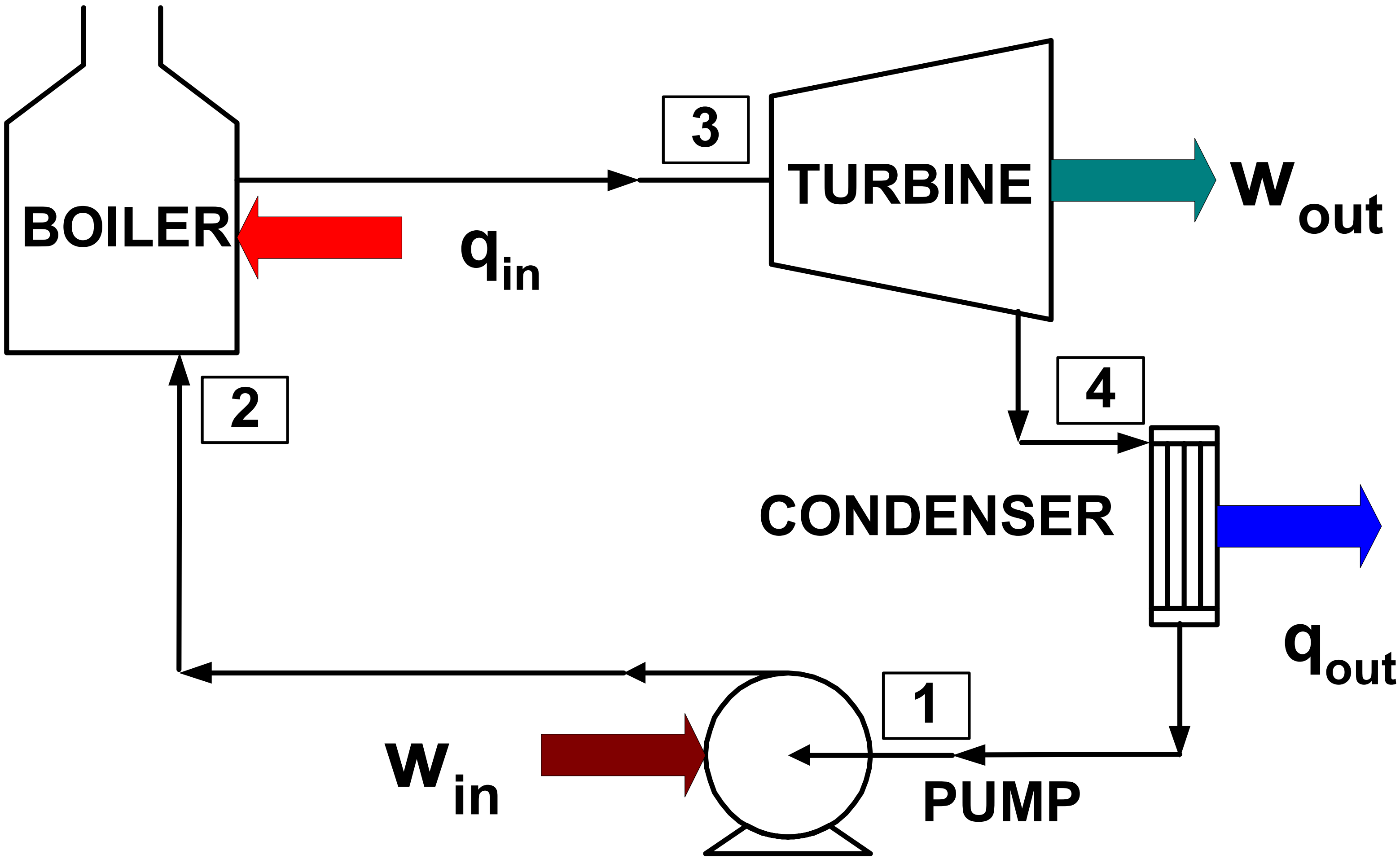
Section 5-8 & Exercises

Vapor Power Cycles

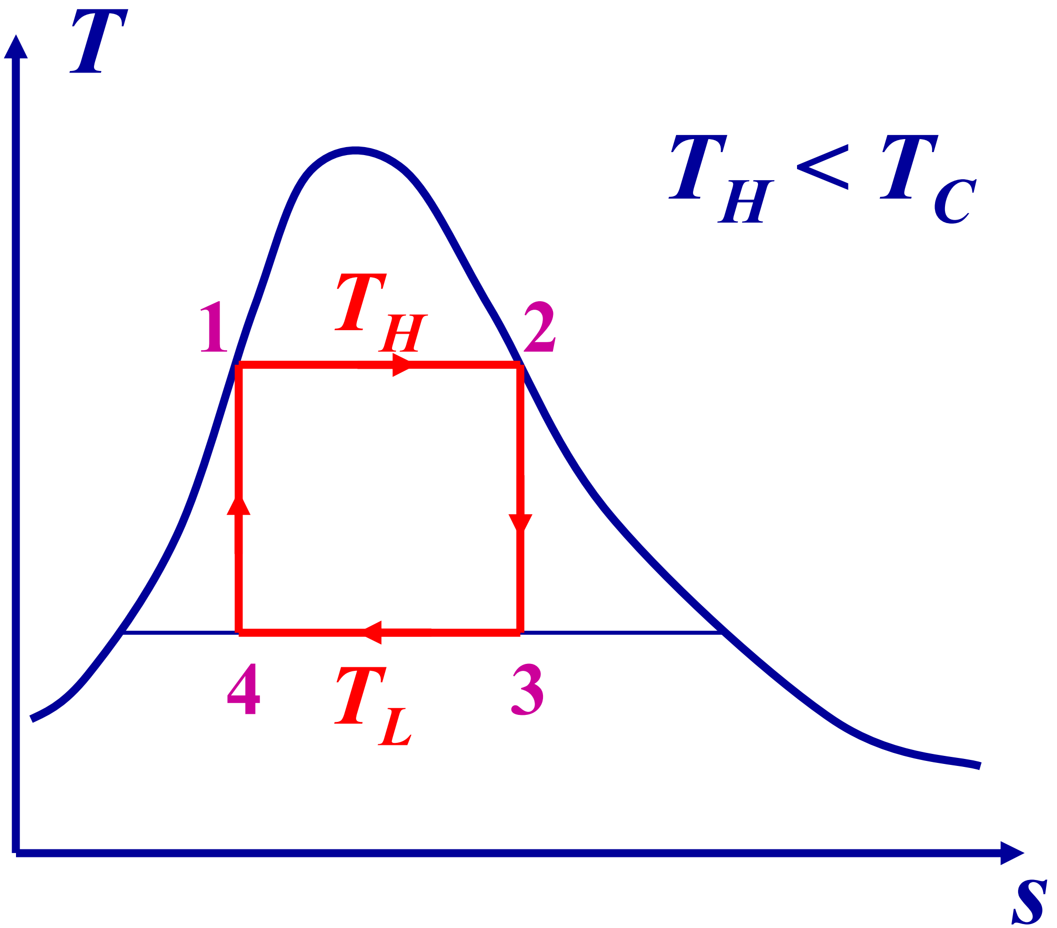
- We’ll look specifically at the Rankine cycle, which is a vapor power cycle.
- It is the primary electrical producing cycle in the world.
- The cycle can use a variety of fuels.

Overview of a coal fired steam power station.
(Courtesy of Carolina Power and Light Company)

We'll simplify the power plant



Carnot Vapor Cycle



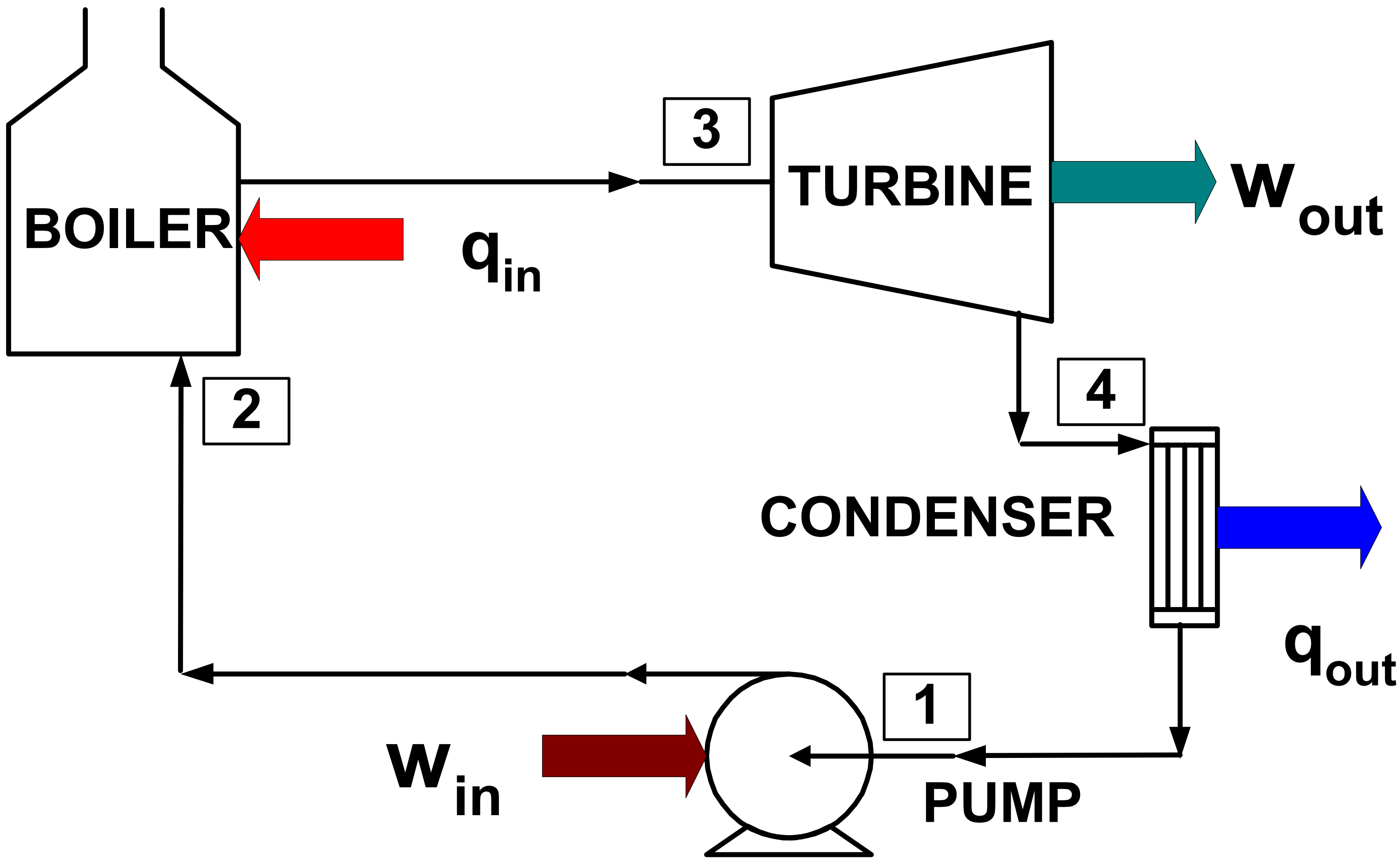
compressor and turbine must handle two phase flows!

- The *Carnot cycle* is not a suitable model for vapor power cycles because it cannot be approximated in practice.

Ideal power plant cycle is called the Rankine Cycle

- **The model cycle for vapor power cycles is the *Rankine cycle* which is composed of four internally reversible processes:**
- **1-2 reversible adiabatic (isentropic) compression in the pump**
- **2-3 constant pressure heat addition in the boiler.**
- **3-4 reversible adiabatic (isentropic) expansion through turbine**
- **4-1 constant pressure heat rejection in the condenser**

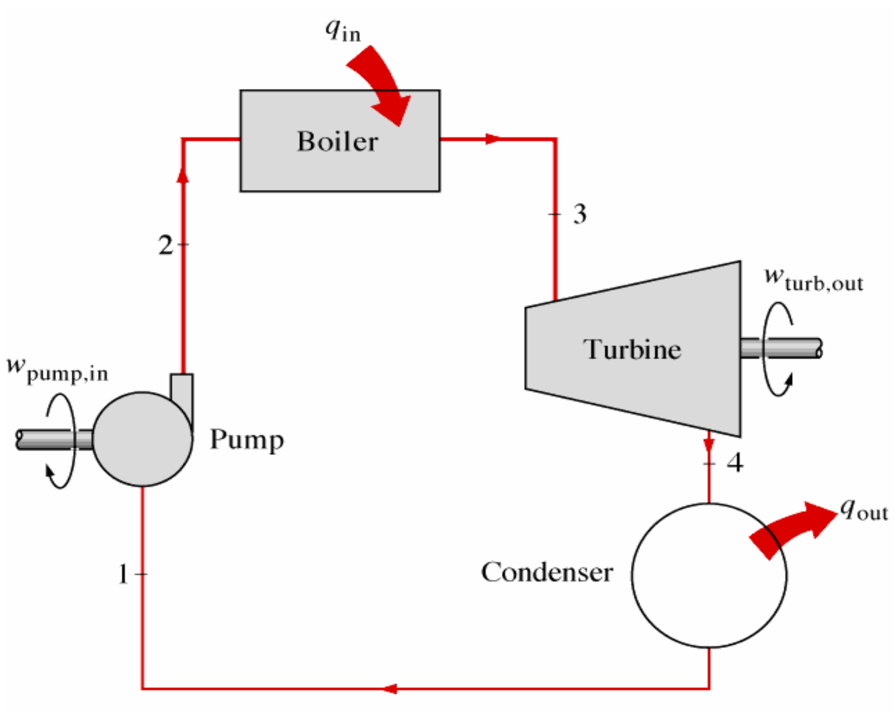
Basic vapor (Rankine) cycle power plant

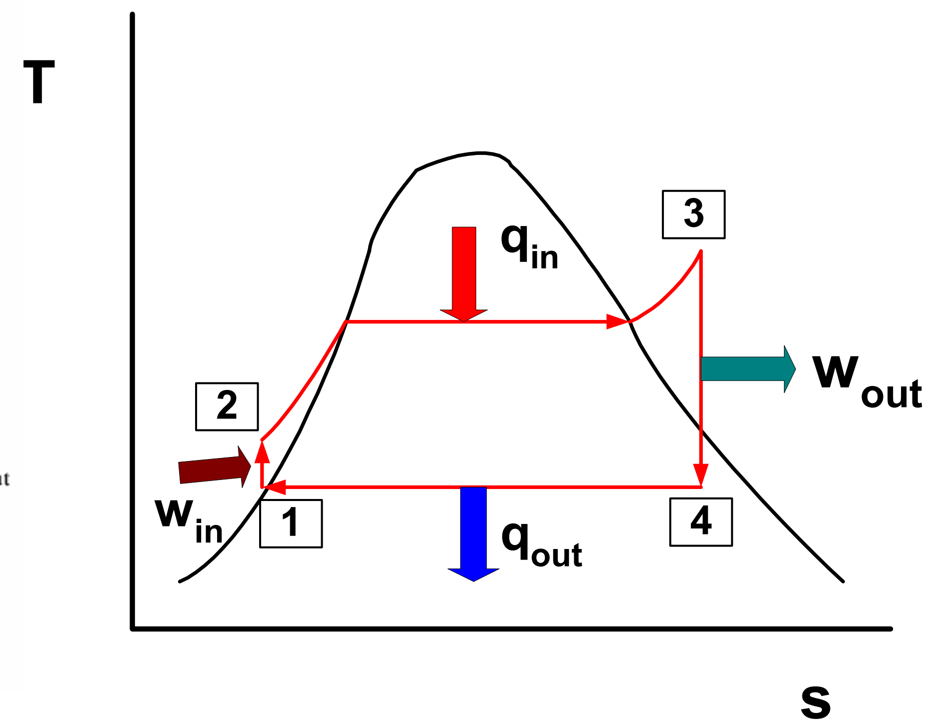


Rankine cycle power plants

- **The steady-state first law is applied to the four major machines of the power plant**
  - **Pump (1 to 2)**
  - **Boiler [heat exchanger] (2 to 3)**
  - **Turbine (3 to 4)**
  - **Condenser [heat-exchanger] (4 to 1)**

Vapor-cycle power plants





What are the main parameters we want to describe the cycle?

=> Net power or work output

Power

$$\dot{W}_{out} = \dot{W}_{tur} - \dot{W}_{pump}$$

Specific Work

$$w_{out} = w_{tur} - w_{pump}$$

Main parameters….

=> **Efficiency**

$$\eta = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

or

$$\eta = \frac{w_{net}}{q_{in}}$$

General comments about analysis

- Typical assumptions…
  - Steady flow in all components
  - Steady state in all components
  - Usually ignore kinetic and potential energy changes in all components
  - Pressure losses are considered negligible in boiler and condenser
  - Pumps/turbines are isentropic for ideal cycle

Start our analysis with the pump

$$\dot{Q}_{pump} - \dot{W}_{Pump} = \dot{m}\left[h_2 - h_1 + \Delta KE + \Delta PE\right]$$

The pump is adiabatic, with no kinetic or potential energy changes. The work per unit mass is:

$$w_{pump} = h_1 - h_2 = v(P_1 - P_2)$$

Pump Analysis

This expression gives us <u>negative</u> value for w_p. It is standard practice in dealing with cycles to express works as positive values, then add or subtract depending on whether they're in or out.

$$w_{Pump} = \left| h_1 - h_2 \right|$$

This gives us a <u>*positive*</u> value for work.

Boiler is the next component

$$\dot{Q}_{boiler} - \dot{W}_{boiler} = \dot{m}\left[h_3 - h_2 + \Delta KE + \Delta PE\right]$$

- Boilers do no work. In boilers, heat is added to the working fluid, so the heat transfer term is already positive.
- So $$\frac{\dot{Q}_{boiler}}{\dot{m}} = q_{boiler} = h_3 - h_2$$

Proceeding to the Turbine

$$\dot{Q}_{turbine} - \dot{W}_{turbine} = \dot{m}\left[h_4 - h_3 + \Delta KE + \Delta PE\right]$$

Turbines are almost always adiabatic. In addition, we'll usually ignore kinetic and potential energy changes:

$$\frac{\dot{W}_{turbine}}{\dot{m}} = w_{turb} = h_3 - h_4$$

Last component is the Condenser

$$\dot{Q}_{cond} - \dot{W}_{cond} = \dot{m}\left[h_1 - h_4 + \Delta KE + \Delta PE\right]$$

Condensers do no work (they are heat exchangers), and if there is no ΔKE and ΔPE,

$$\frac{\dot{Q}_{cond}}{\dot{m}} = q_{cond} = h_1 - h_4$$

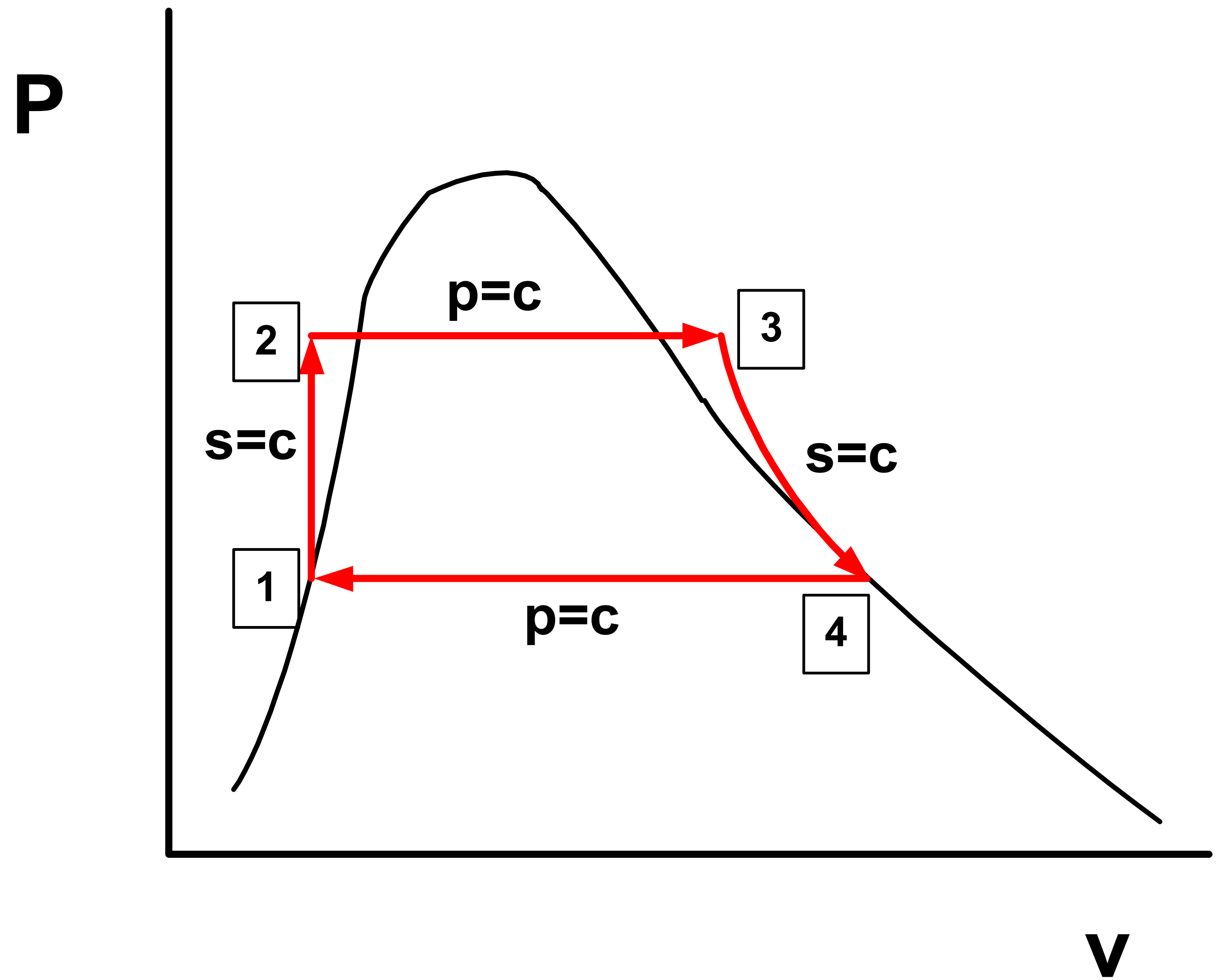
More condenser...

What is the sign of q_{cond} ?

As with work, we're going to want the sign of all the heat transfer terms positive.

$$\frac{\dot{Q}_{cond}}{\dot{m}} = q_{cond} = \left| h_1 - h_4 \right|$$

Ideal Rankine Cycle on a P-v diagram



Efficiency

$$\eta = \frac{w_{out}}{q_{in}}$$

$$\eta = \frac{h_3 - h_4 - v(P_2 - P_1)}{h_3 - h_2}$$

Example Problem

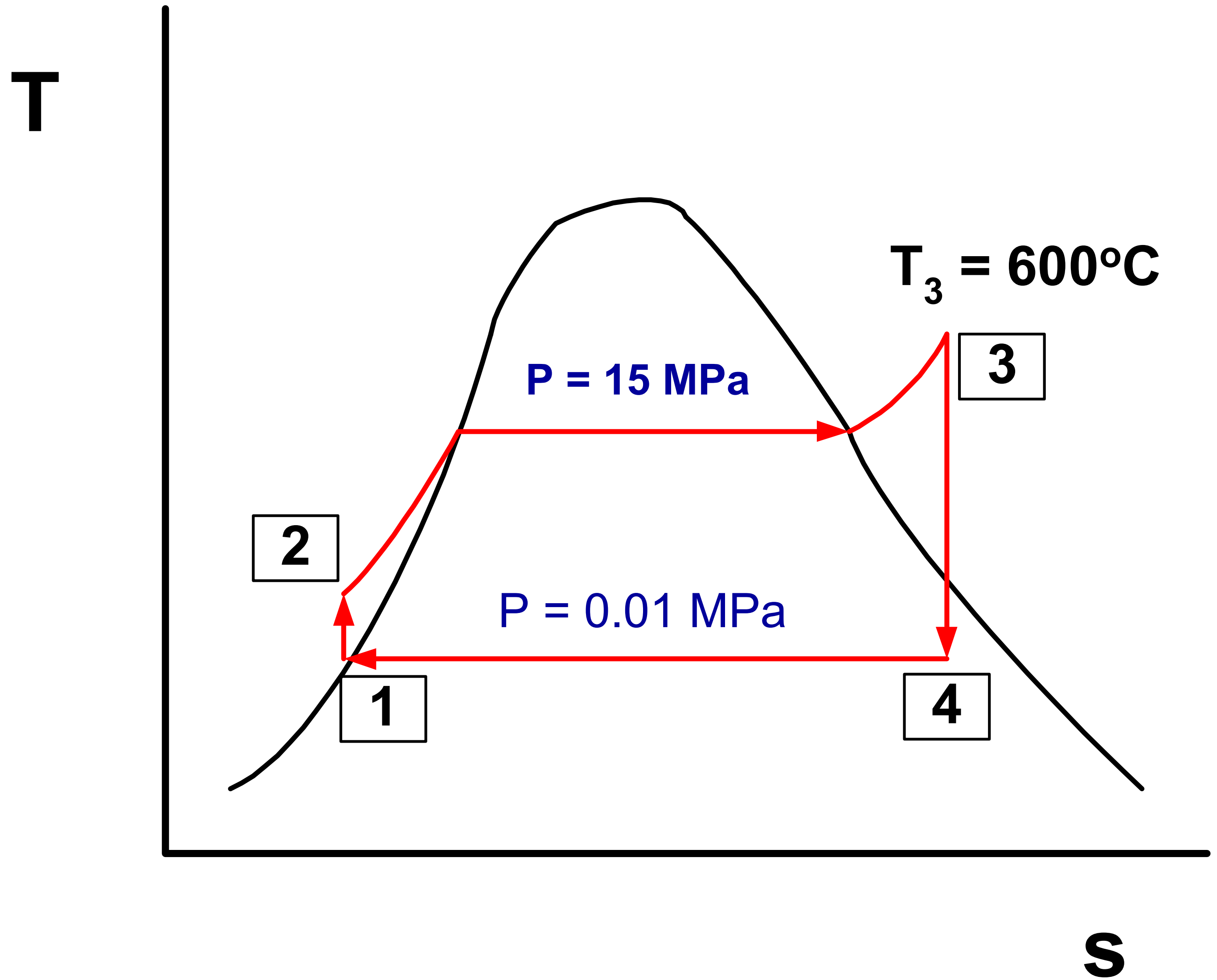
A Rankine cycle has an exhaust pressure from the turbine of 0.1 bars. Determine the quality of the steam leaving the turbine and the thermal efficiency of the cycle which has turbine inlet pressure of 150 bars and 600°C.

Start an analysis:

Assumptions:

- pump and turbine are isentropic
- $P_2 = P_3 = 150$ bars $= 15$ MPa
- $T_3 = 600°C$
- $P_4 = P_1 = 0.1$ bars $= 0.01$ MPa
- Kinetic and potential energy changes are negligible

Draw diagram or cycle



Some comments about working cycle problems

- **Get the BIG picture first - where's the work, where's the heat transfer, etc.**
- **Tables can be real useful - they help you put all the data you will need in one place…*It also makes it easier for me to grade!***
- **You will need to know how to look up properties in the steam & air tables!**

Put together property data

State	T (°C)	P(MPa)	v(m^3/kg)	h(kJ/kg)	s(kJ/kgK)	x
1		0.01				0
2		15				n.a.
3	600	15	----			
4		0.01	----			

Pump (1 to 2) -> isoentropic (const. volume)

Boiler [heat exchanger] (2 to 3) -> const. pressure

Turbine (3 to 4) -> isoentropic

Condenser [heat-exchanger] (4 to 1) -> const. pressure

Property Data

State	T (°C)	P(MPa)	v(m^3/kg)	h(kJ/kg)	s(kJ/kgK)	x
1	45.81	0.01	0.00101	191.83		0
2	49.42	15	0.00101	206.93		Liq. comp
3	600	15	0.02491	3582.3	6.6776	Super aquec
4	45.81	0.01	12.266	2114.9	6.6776	0.8037

We've got the leaving quality, now we need efficiency

Cycle efficiency:

$$\eta = \frac{w_{out}}{q_{in}}$$

Substituting for net work:

$$\eta = \frac{w_{turbine} - w_{pump}}{q_{in}}$$

Let start with pump work

Pump work:

$$w_{pump} = \left| v(P_1 - P_2) \right| = \left| h_1 - h_2 \right|$$

$$w_{pump} = \left| (0.00101)\frac{m^3}{kg}(0.01 - 15)MPa \right|$$

$$w_{pump} = 15.1\ \frac{kJ}{kg}$$

More calculations...

Enthalpy at pump outlet:

$$h_2 = h_1 + w_{pump}$$

Plugging in some numbers:

$$h_2 = (191.83 + 15.1)\ \frac{kJ}{kg}$$

$$h_2 = 206.93\ \frac{kJ}{kg}$$

How Can I Get The Pump Outlet Temp?

If the Enthalpy at pump outlet is 206.93 KJ/kg, then consider the *compressed liquid* a the same temperature of the *saturated liquid* which has h = 206.93 KJ/kg

Interpolating from the saturated steam table one finds: 49^{o}C

Calculate heat input and turbine work..

Boiler heat input:

$$q_{boiler} = h_3 - h_2 = (3582.3 - 206.93)\frac{kJ}{kg}$$

$$q_{boiler} = 3375.4\ \frac{kJ}{kg}$$

Turbine work

Isentropic: $s_4 = s_3 = 6.6776\,kJ/kg \cdot K$

$$\Rightarrow x_4 = 0.8037; \qquad h_4 = 2114.9\,kJ/kg$$

Turbine work:

$$w_{turbine} = h_3 - h_4 = (3582.3 - 2114.9)\frac{kJ}{kg}$$

$$w_{turbine} = 1467.4\ kJ/kg$$

Overall thermal efficiency

$$\eta = \frac{w_{turbine} - w_{pump}}{q_{in}}$$

$$\eta = \frac{(1467.4 - 15.1)\frac{kJ}{kg}}{3375.4\ \frac{kJ}{kg}} = 0.430$$

Some general characteristics of the Rankine cycle

- Low condensing pressure (below atmospheric pressure)
- High vapor temperature entering the turbine (600 to 1000°C)
- Small backwork ratio (bwr)

$$BWR \equiv \frac{w_{pump}}{w_{turbine}} = \frac{|h_1 - h_2|}{h_3 - h_4} \approx 0.01$$

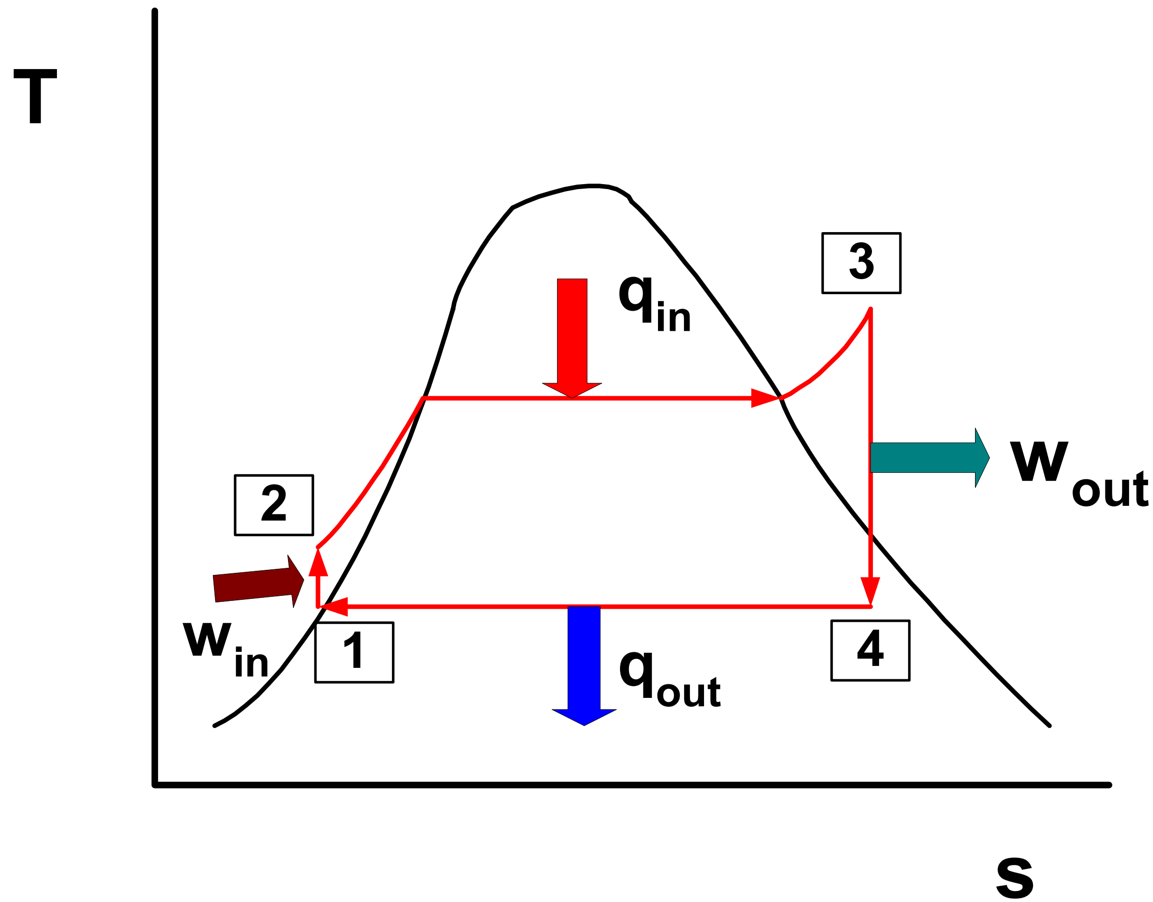
Questions …

- Consider the ideal Rankine cycle from 1-2-3-4:

•How would you increase its thermal efficiency η?

•What determines the upper T limit?

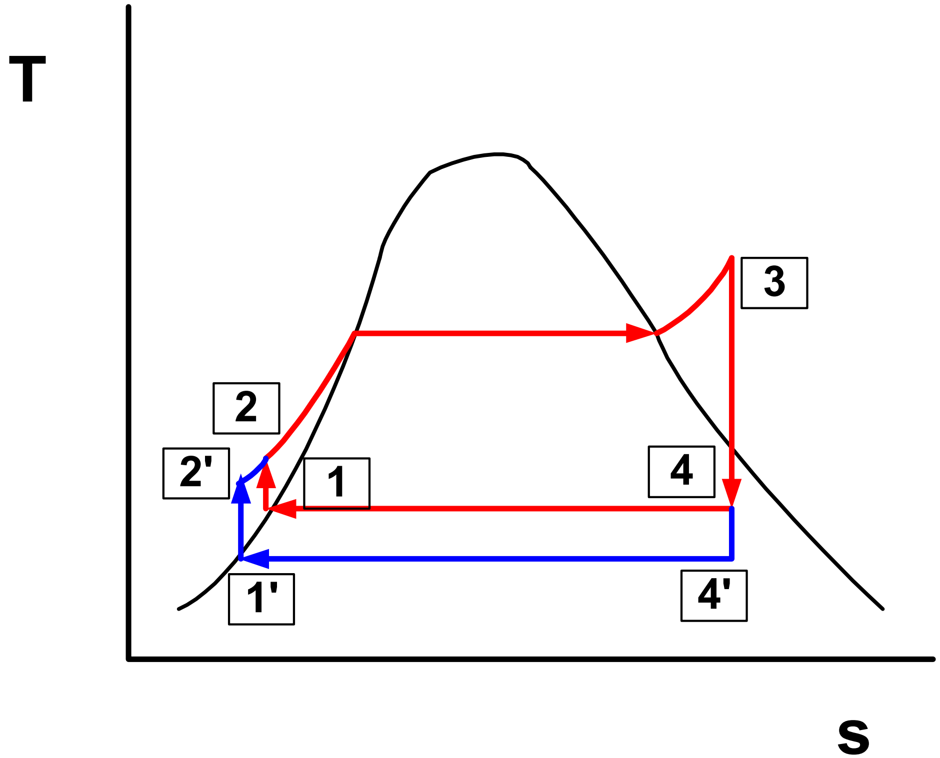
•What determines the lower T limit?



Let's try to improve the efficiency of the basic cycle

- **Decrease exhaust pressure of turbine**
  - **decreases condensing temperature**
  - **increases work output**
  - **increases heat input**
  - **decreases quality at turbine outlet**

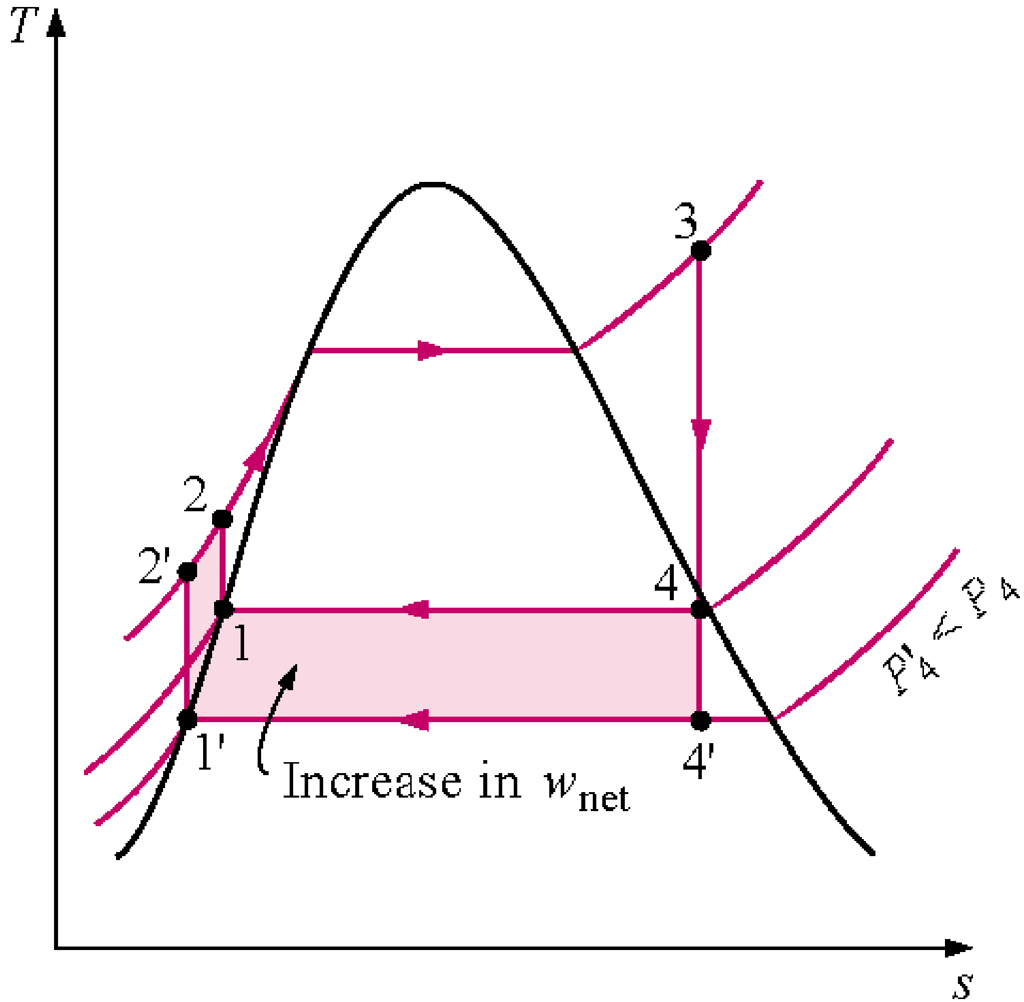
Lower Exhaust Pressure



Work output increases faster than heat input, so the cycle efficiency increases.

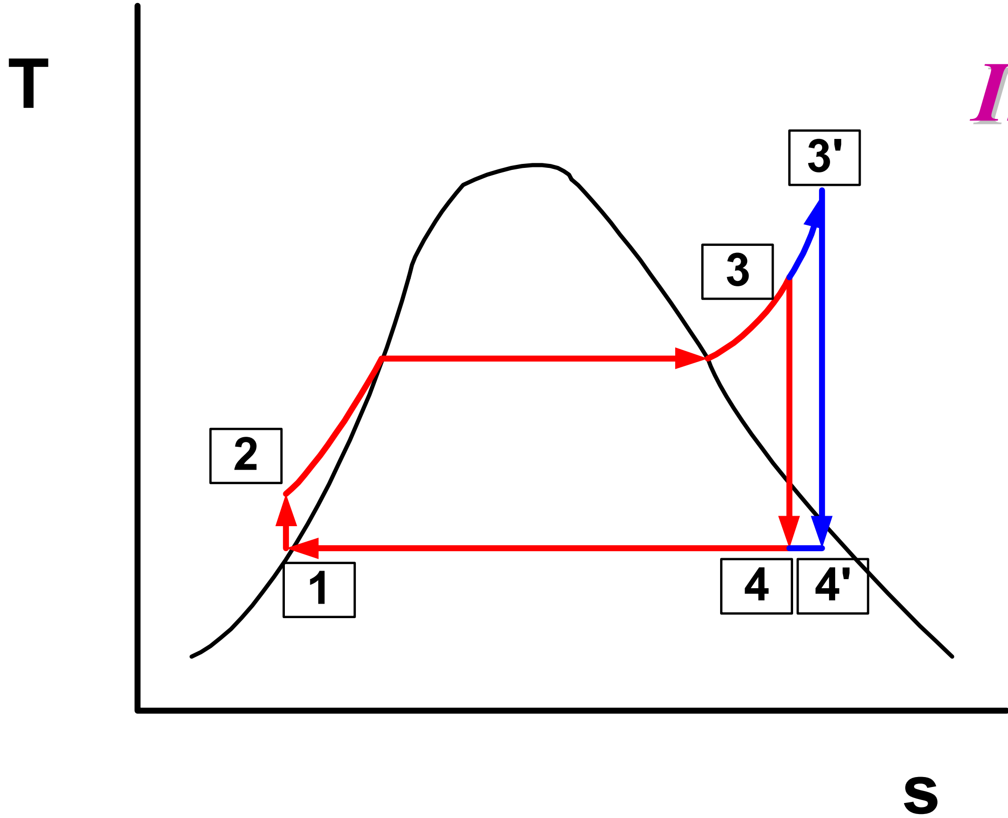
- **The average temperature during heat rejection can be decreased by lowering the turbine exit pressure.**
- **Consequently the condenser pressure, of most vapor power plants, is well below the atmospheric pressure.**

Effect of Lowering Condenser Pressure on the Ideal Rankine cycle



Superheat and reheat

- Notice that reducing the condenser pressure (which will lower the temperature of heat rejection and again increase the efficiency) will also reduce the quality of the steam exiting the turbine.
- Turbines do not like to see water coming out the exhaust.
- Lower qualities mean water droplets are forming before the steam leaves the turbine.
- Water droplets lead to turbine blade erosion.
- Efforts are made to keep the quality > 90%.



Increase Superheat

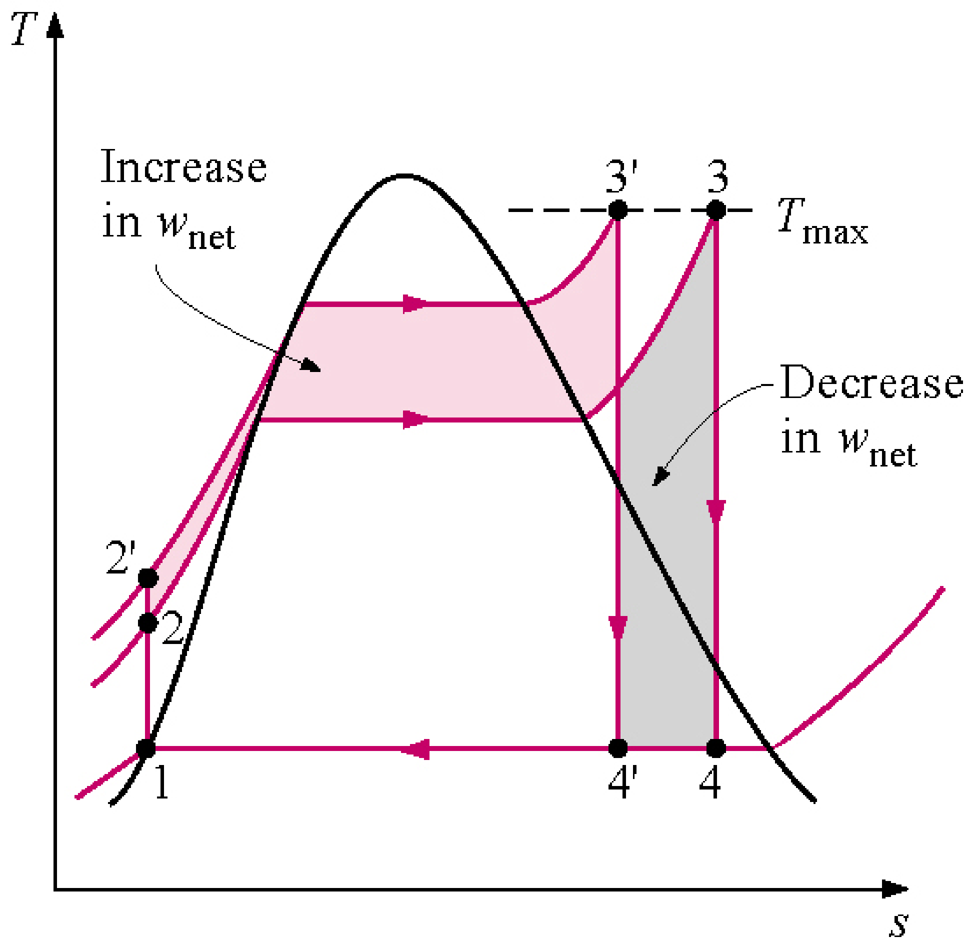
Work output increases faster than heat input, so the cycle efficiency increases.

higher quality

Increasing Superheat

* increases heat input
* increases work output
* increases quality at turbine outlet
* may produce material problems if temperature gets too high

Effect of Increasing Boiler Pressure on the Ideal Rankine cycle keeping constant the Boiler Outlet Temperature Tmax



TEAMPLAY

- **Consider a simple ideal Rankine cycle with fixed turbine inlet temperature and condenser pressure. What is the effect of increasing the boiler pressure on**

Pump work input:	(a) increases, (b) decreases, (c) remains the same
Turbine work output:	(a) increases, (b) decreases, (c) remains the same
Heat supplied:	(a) increases, (b) decreases, (c) remains the same
Heat rejected:	(a) increases, (b) decreases, (c) remains the same
Cycle efficiency:	(a) increases, (b) decreases, (c) remains the same
Moisture content at turbine exit:	(a) increases, (b) decreases, (c) remains the same

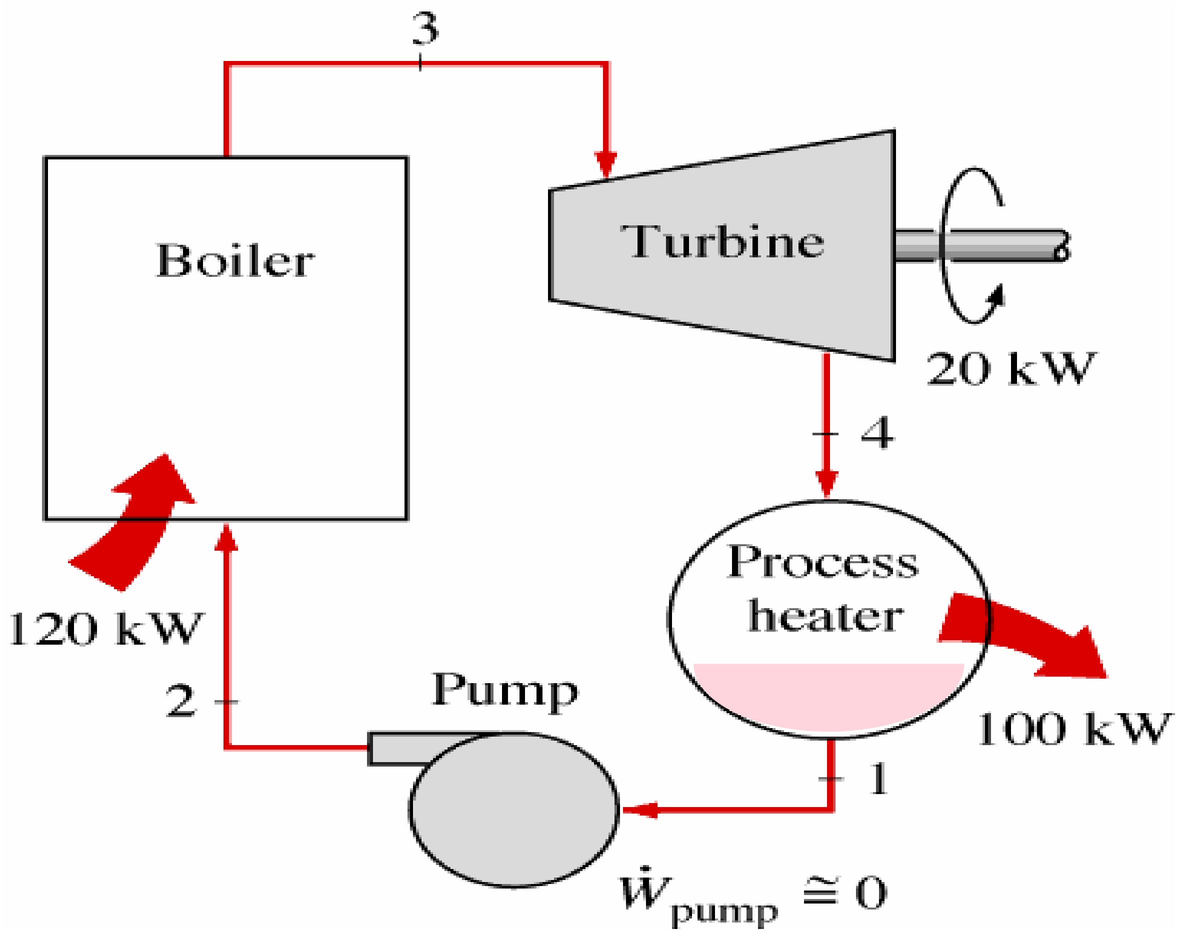
Cogeneration

- **The production of more than one useful form of energy (such as process heat and electric power) from the same energy source is called *cogeneration*.**

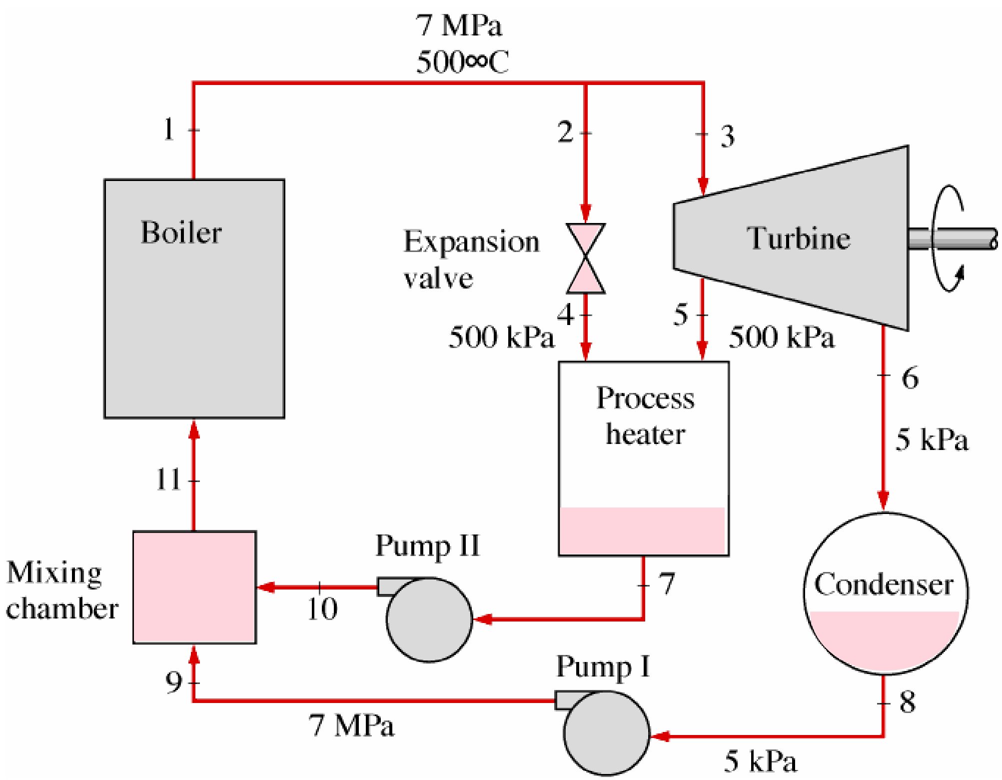
- **Cogeneration plants produce electric power while meeting the process heat requirements of certain industrial processes. This way, more of the energy transferred to the fluid in the boiler is utilized for a useful purpose.**

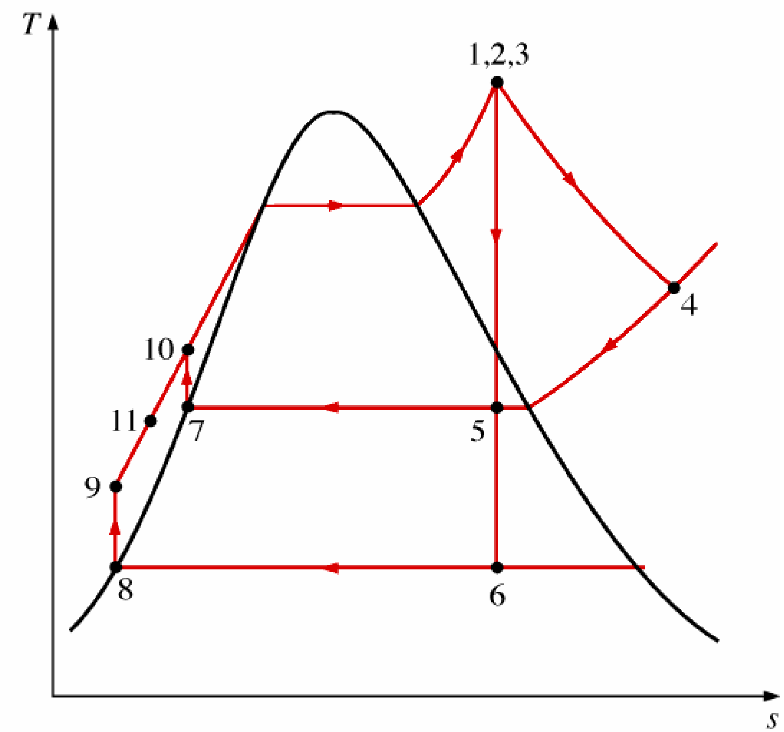
- **The fraction of energy that is used for either process heat or power generation is called the *utilization factor* of the cogeneration plant.**

An Ideal Cogeneration Plant

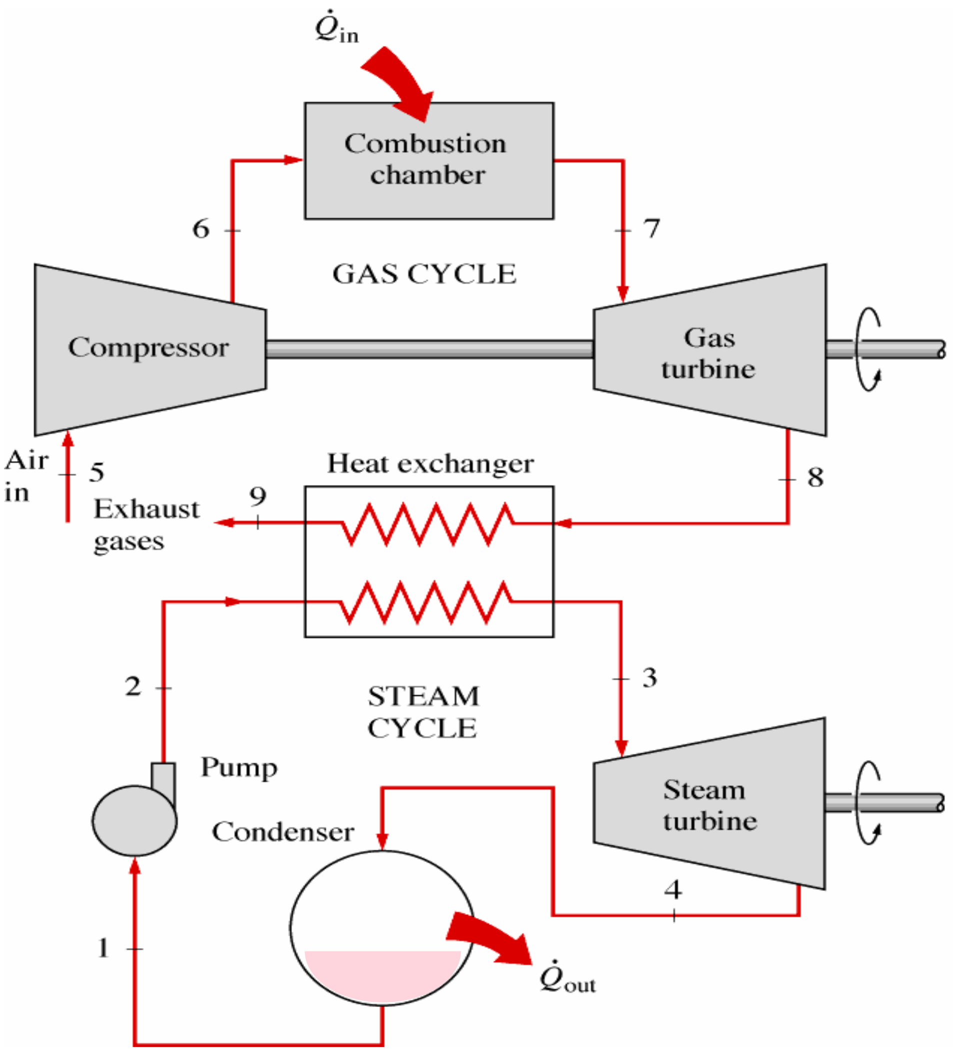


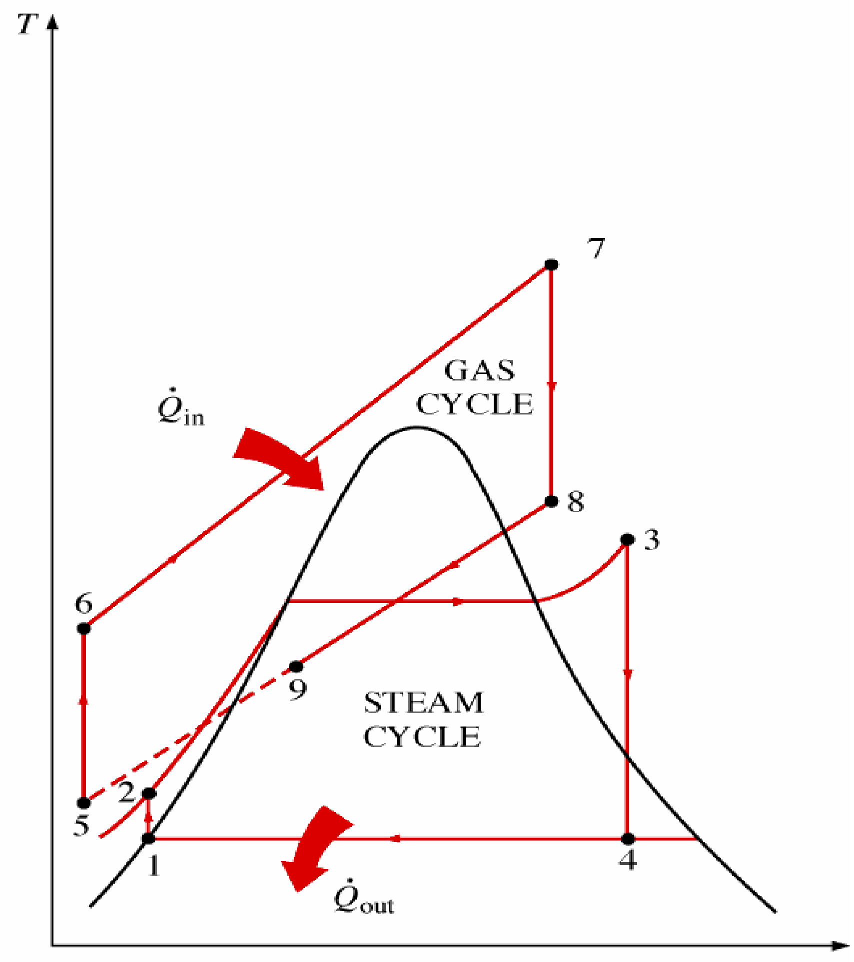
Schematic and T-s Diagram for Cogeneration





Combined Gas-Steam Power Plant

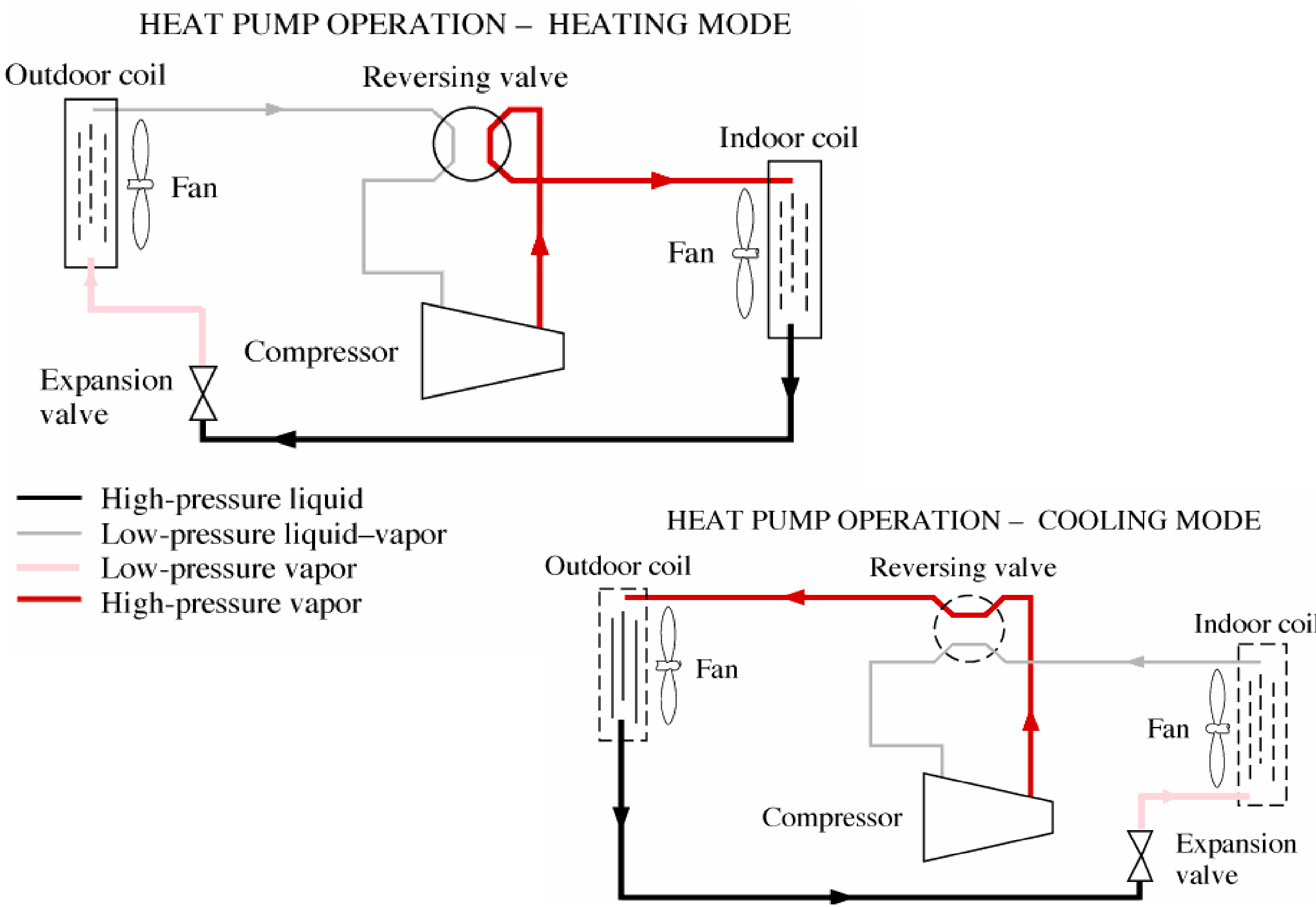




Refrigerators and Heat Pumps

- **The transfer of heat from lower temperature regions to higher temperature ones is called *refrigeration*.**
- **Devices that produce refrigeration are called *refrigerators*, and the cycles on which they operate are called *refrigeration cycles*.**
- **The working fluids used in refrigerators are called *refrigerants*.**
- **Refrigerators used for the purpose of heating a space by transferring heat from a cooler medium are called *heat pumps*.**

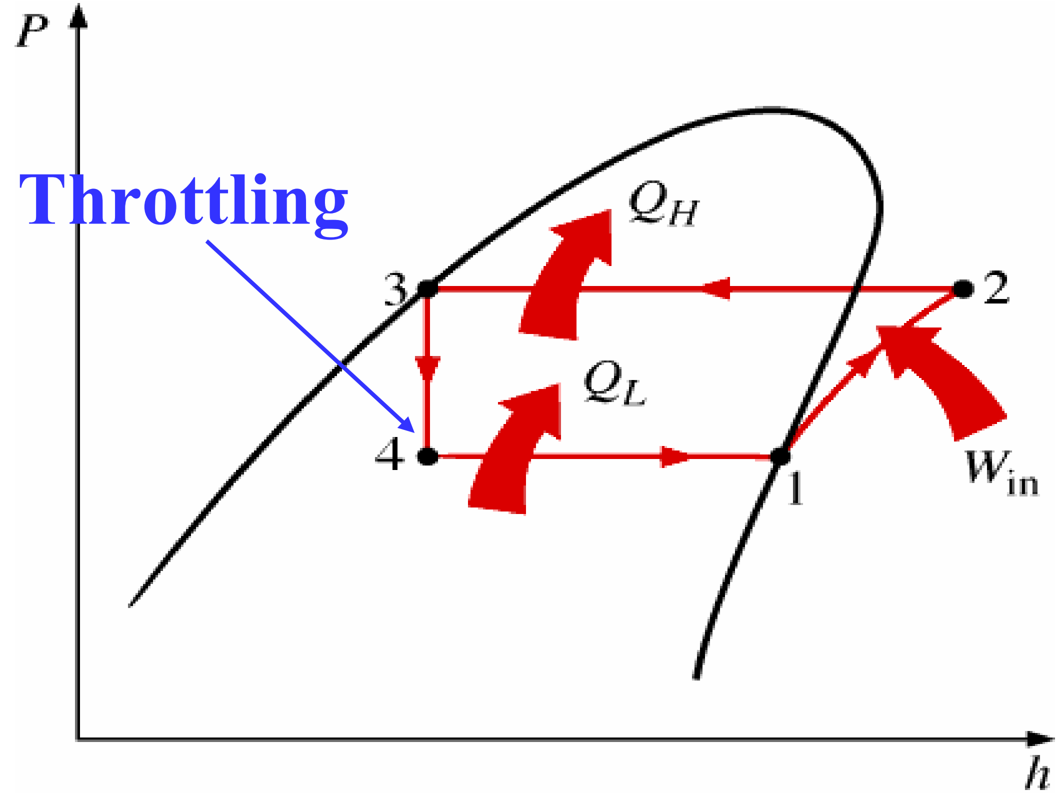
Heat Pump Heats a House in Winter and Cools it in Summer



Vapor-Compression Refrigeration Cycle

- **The most widely used refrigeration cycle is the *vapor-compression refrigeration cycle*.**

P-h Diagram of an Ideal Vapor-Compression Refrigeration Cycle



The refrigerant enters the compressor as a saturated vapor and is cooled to the saturated liquid state in the condenser. It is then throttled to the evaporator and vaporizes as it absorbs heat from the refrigerated space.

Four processes in cycle

- **Isentropic compression (1 to 2)**
- **Constant pressure condensation (2 to 3)**
- **Isenthalpic expansion (3 to 4)**
- **Constant pressure evaporation (4 to 1)**

Sample Problem

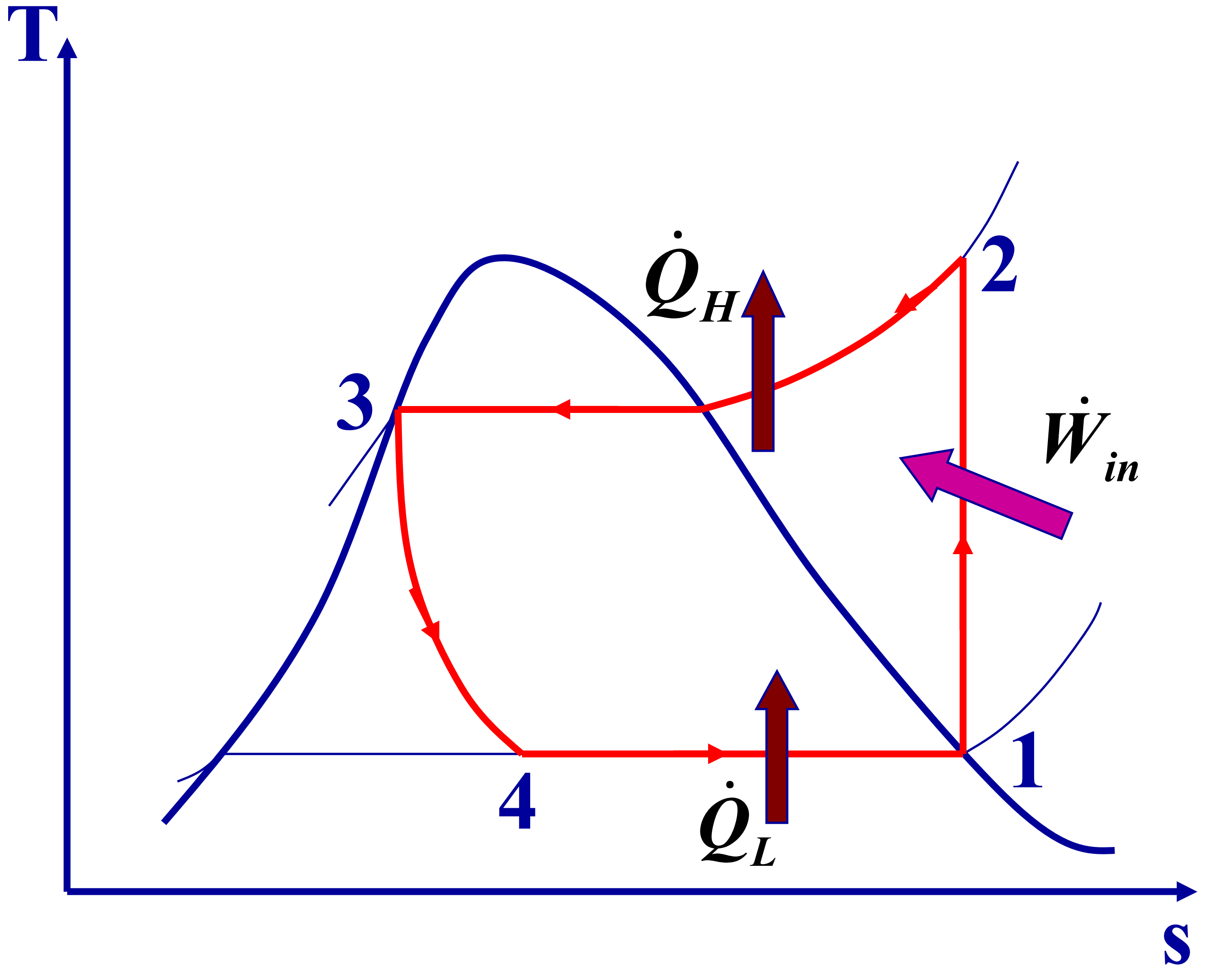
Consider a 300 kJ/min refrigeration system that operates on an ideal vapor-compression refrigeration cycle with refrigerant-134a as the working fluid. The refrigerant enters the compressor as saturated vapor at 140 kPa and is compressed to 800 kPa. Show the cycle on a T-s diagram with respect to saturation lines, and determine (a) the quality of the refrigerant at the end of the throttling process, (b) the coefficient of performance, and (c) the power input to the compressor.

List Assumptions:

- steady state steady flow
- isentropic compression in compressor
- kinetic and potential energy changes are zero

- $P_1 = 0.14$ MPa, $x_1 = 1.0$
- $P_2 = 0.8$ MPa, $s_2 = s_1$
- $P_3 = 0.8$ MPa, $x_3 = 0$
- $h_4 = h_3$ (throttling)

Draw cycle



Property Data (R-134a)

State	T (C)	P(MPa)	v(m^3/kg)	h(kJ/kg)	s(kJ/kgK)	x
1		0.14				1.0
2		0.8				
3		0.8				0.0
4						

Property Data (R-134a)

State	T (C)	P(MPa)	$v(m^3/kg)$	h(kJ/kg)	s(kJ/kgK)	x
1	-18.80	0.14		236.04	0.9322	1.0
2		0.8		272.05	0.9322	
3	31.33	0.8		93.42		0.0
4				93.42		

Isentropic compression: $s_2 = s_1$

Throttling: $h_4 = h_3$

Part (a): Refrigerant quality

The quality of the refrigerant at the end of the throttling process

$$x_4 = \frac{h_4 - h_f}{h_{fg}}$$

P_4 = 140 kPa

$$= \frac{93.42 - 25.77}{210.27} = 0.322$$

Part (b): Refrigerator COP

Coefficient of Performance

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{q_L}{w_{in}}$$

$$= \frac{h_1 - h_4}{h_2 - h_1} = \frac{236.04 - 93.42}{272.05 - 236.04}$$

$$COP_R = 3.96$$

Part (c): power input

$$COP_R = \frac{\text{cooling effect}}{\text{work input}} = \frac{\dot{Q}_L}{\dot{W}_{in}}$$

$$\dot{Q}_L = 300kJ/min = 5kJ/s = 5kW$$

Compressor Power Input

$$\dot{W}_{in} = \frac{\dot{Q}_L}{COP_R} = \frac{5kW}{3.96} = 1.26kW$$