KU LEUVEN

B-KUL-Z55337
Applied Thermodynamics

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Adapted from: Y.A. Cengel, M. A. Boles, Thermodynamics – An Engineering Approach (5th Edition)

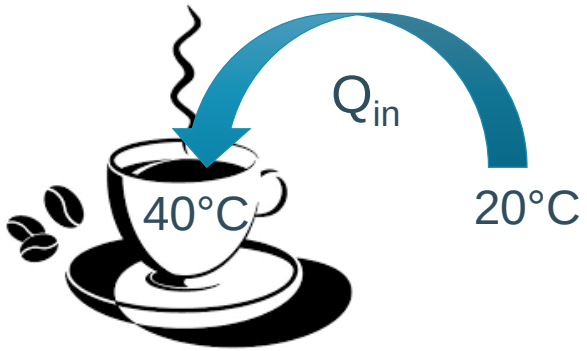
Chapter 6

The Second Law of Thermodynamics

Introduction

- The first law of thermodynamics deals with the energy conservation principle. We used to analyse open and closed systems.
- The first law does not involve any restrisction regarding the direction heat and work transfers. Examples:
  - A coffee cup canot be heated up by itself,
  - An electrical resistance does no pump heat in the surrounding to generate electricity

However, the first law of thermodynamics does not prohibit these evolutions!



Introduction

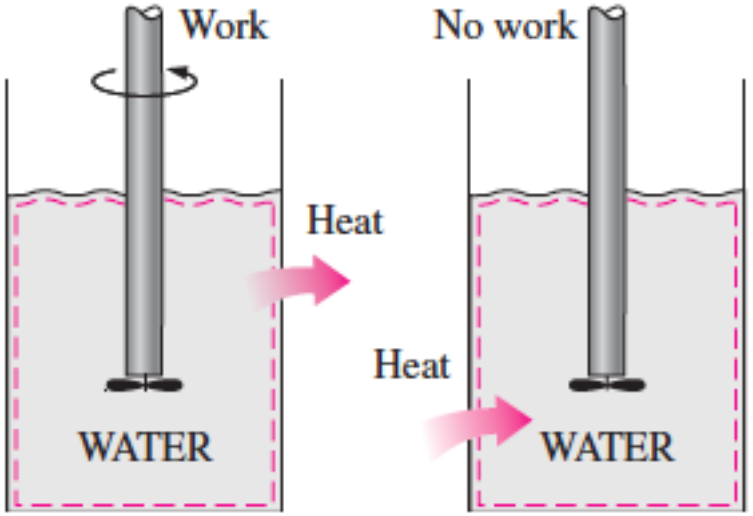
- We need an additional law (**The second law of thermodynamics**).
- This second law is not limited to the prediction of the direction of an evolution, it also asserts that energy has **quality** as well as quantity

Thermal Energy Reservoirs

- A **Thermal Energy Reservoir** is a hypothetical body with a large thermal energy capacity that can supply or absorb finite amounts of heat without undergoing any change in temperature.
- A **heat source** is a thermal reservoir that provides heat to a system
- A **heat sink** is a thermal reservoir that absorbs heat emitted by a system

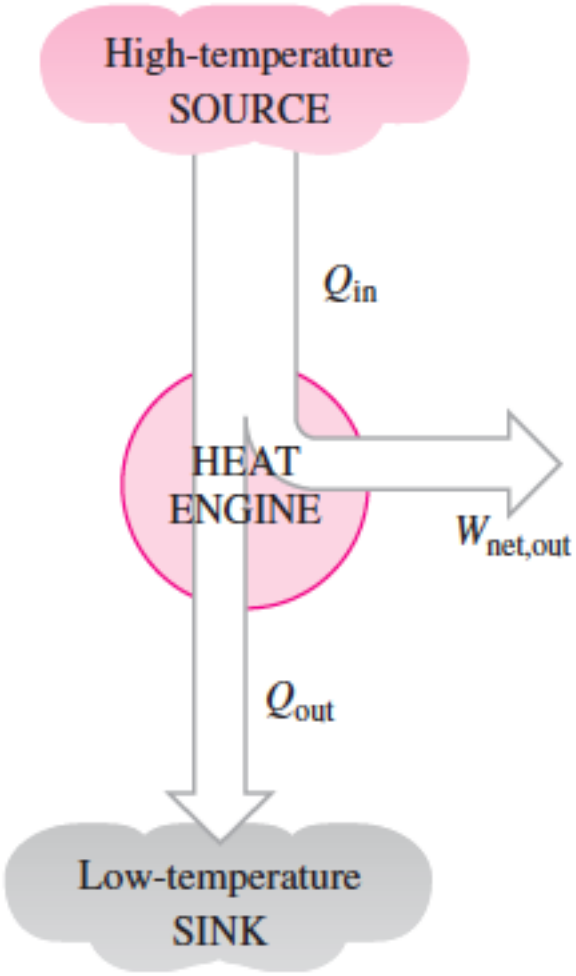
Heat engines

- Work can easily be converted into heat (e.g. through friction). However, the contrary is not straigthforward and requires the use of a **heat engine**



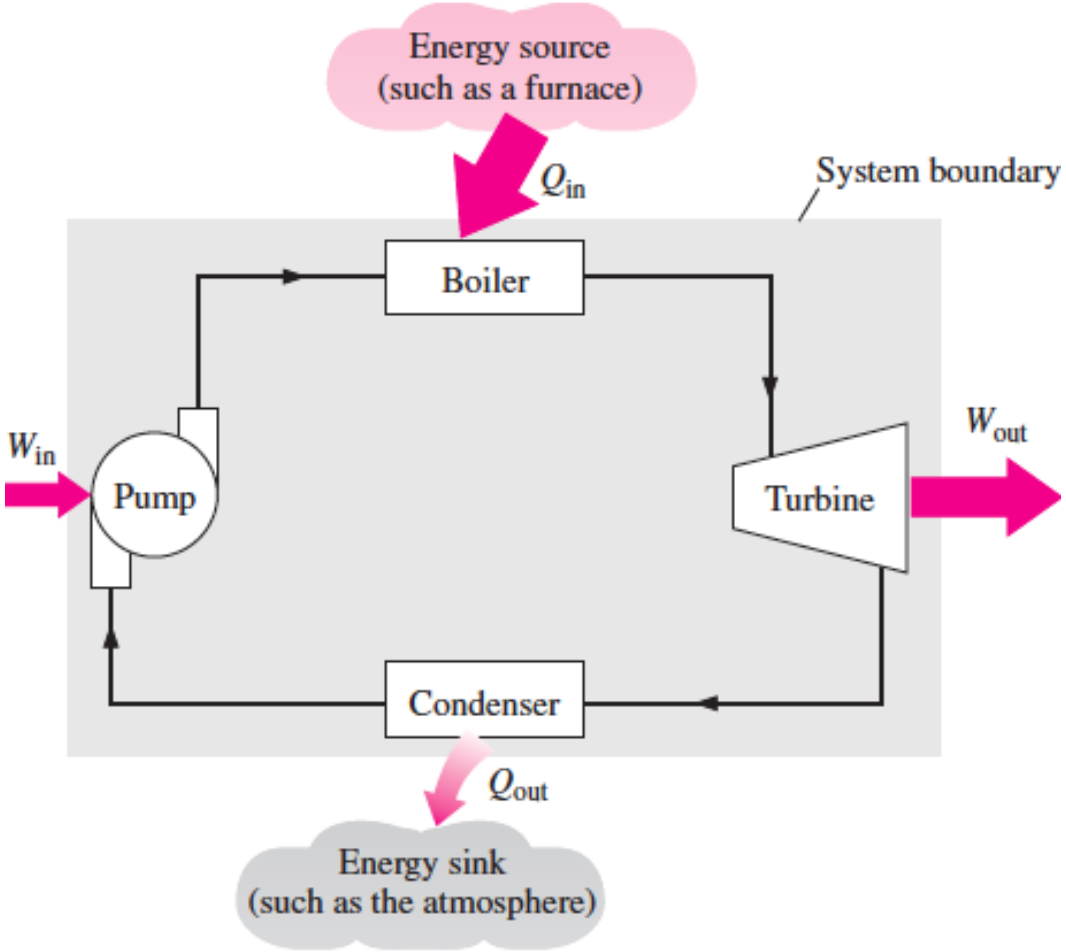
Heat engines

- Heat engines are characterized by:
  - They receive heat from a high-temperature heat source
  - They convert a part of the heat into work
  - They reject the remaining part of the heat into a low-temperature sink
- The heat engines we will consider in this class use a working fluid describing a cycle



Heat engines

Steam power plant



- The net power output is given by:

$$W_{net,out} = W_{out} - W_{in}\ (kJ)$$

- Since the closed system describes a cycle, its variation of internal energy is null, and thus:

$$W_{net,out} = Q_{in} - Q_{out}\ (kJ)$$

« The net power output is equal to the net heat transmitted to the system ».

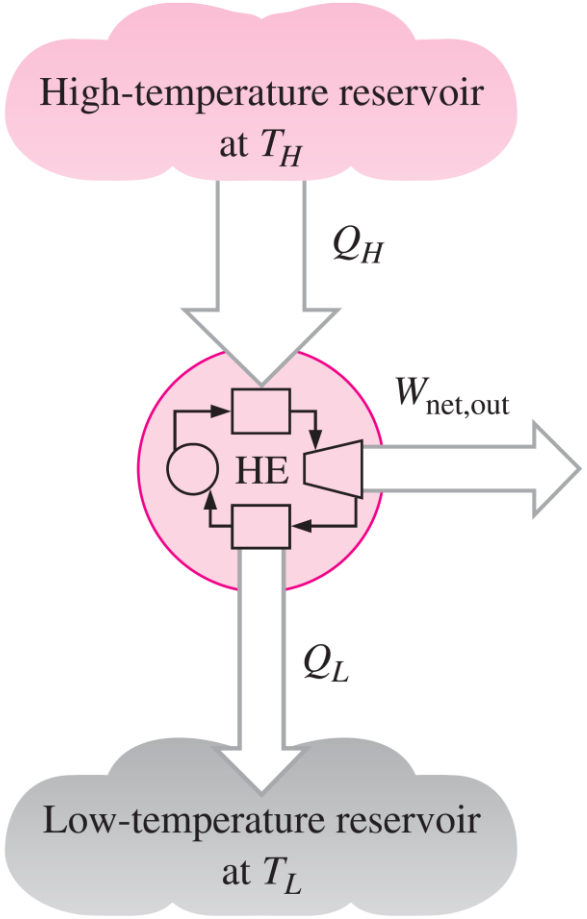
Heat engines

Thermal efficiency

- Only a fraction of the heat transmitted to the system is converted into work. The remaining part is transmitted to low temperature reservoir
- The thermal efficiency is defined by:

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} = 1 - \frac{Q_L}{Q_H}$$

- Examples:
  - Internal combustion engine: 25%
  - Large diesel engines: 40%
  - Nuclear power plant: 33%



Heat engines

Kelvin–Planck Statement

- Observation: heat engines rejects heat.

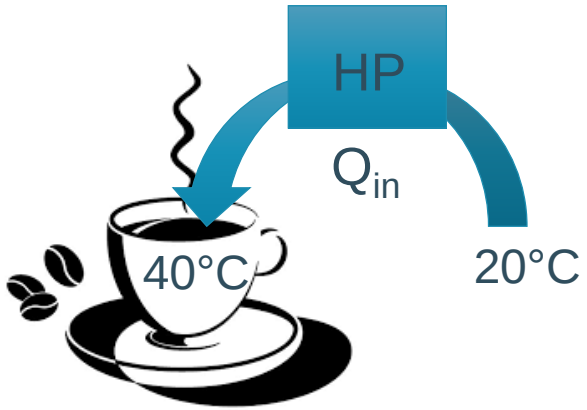
- <u>Kelvin–Planck Statement (second law of thermodynamics)</u>:

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work. A heat engines always rejects heat.

- Corollary: *no heat engine (even ideal) can have a thermal efficiency of 100%*

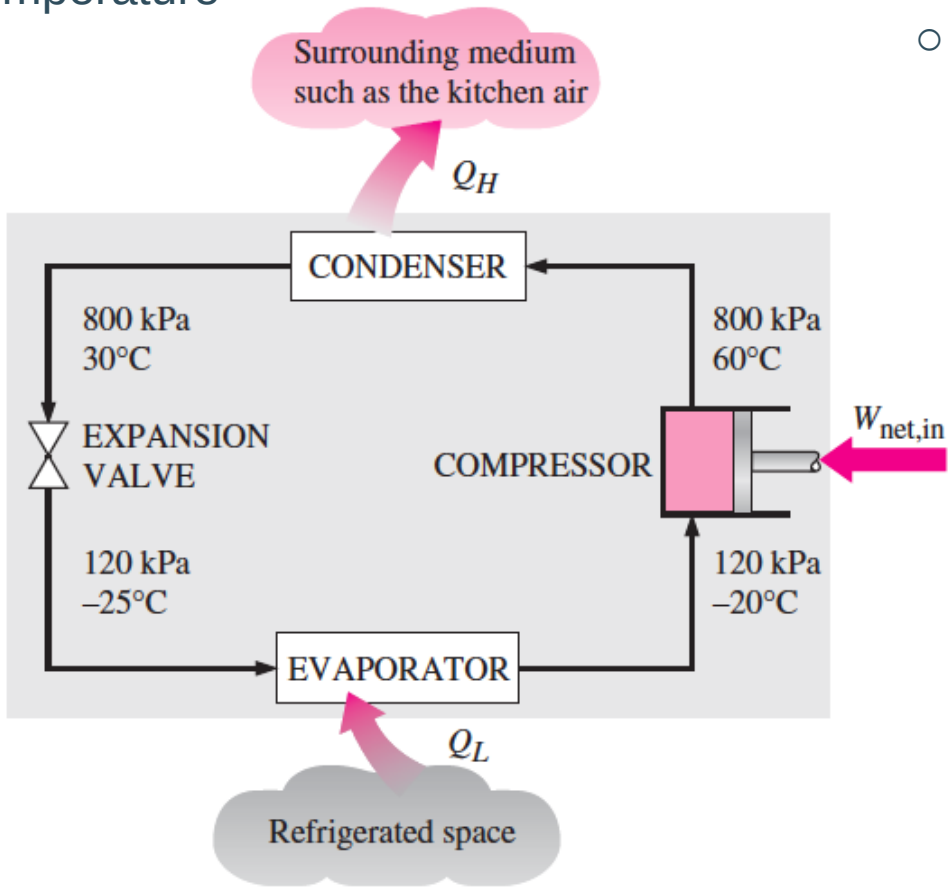
Refrigerators and heat pumps

- from experience: heat is transferred in the direction of decreasing temperature.
- The reverse process (heat transfer from a low temperature to a high temperature) is not spontaneous. A **heat pump** is neded
- The heat pump describes a thermodynamic cycle. The working fluid is call **refrigerant**.
- If the useful effect is cold production (instead of heat production), we will talk about a **refrigerator**.



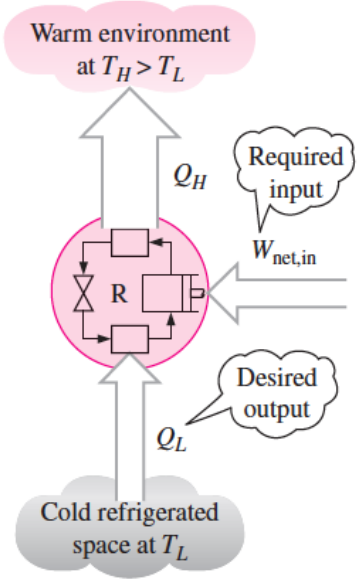
Refrigerators

- The most common heat pump/refrigerator type is the *vapor compression cycle*.
- In the case of a refrigerator, the desired effect is the heat transfer at low temperature



- The Coefficient of Performanc (COP) of a refrigeration machine is given by:

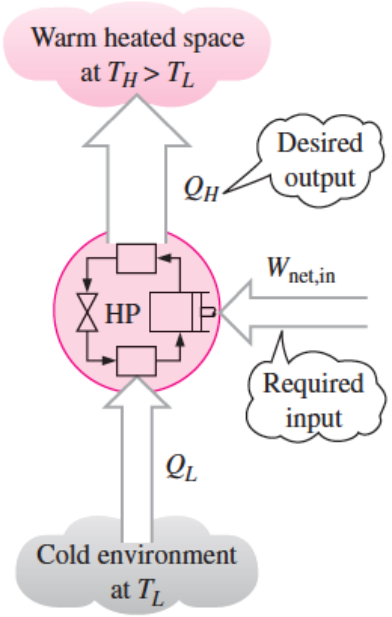
$$COP_L = \frac{Q_L}{W_{net,in}} = \frac{Q_L}{Q_H - Q_L}$$

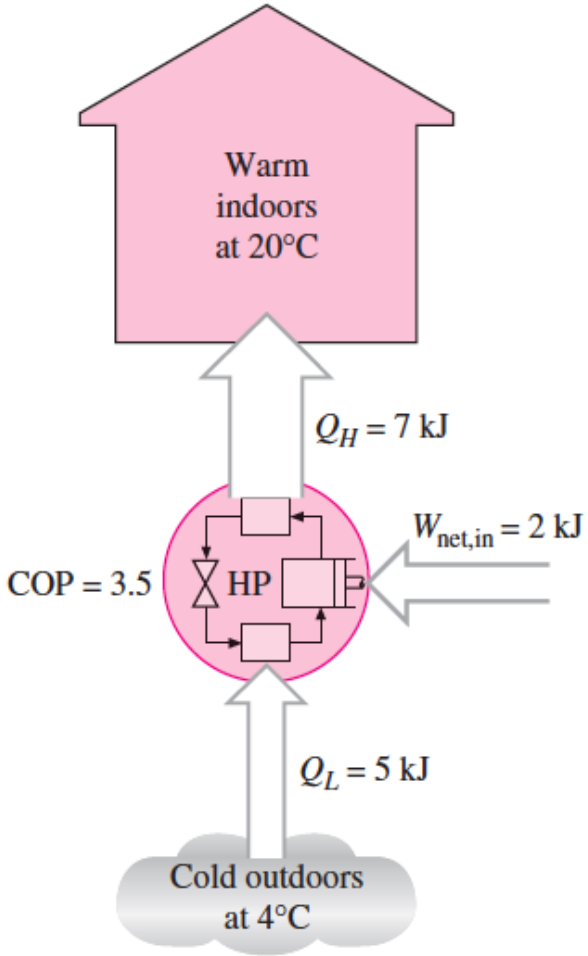


Heat pumps

- In the case of a heat pumps, the desired effect is the heat transfer at high temperature
- The coefficient of performance of a heat pump is defined by:

$$COP_H = \frac{Q_H}{W_{net,in}} = \frac{Q_H}{Q_H - Q_L} \Leftrightarrow COP_H = COP_L + 1$$

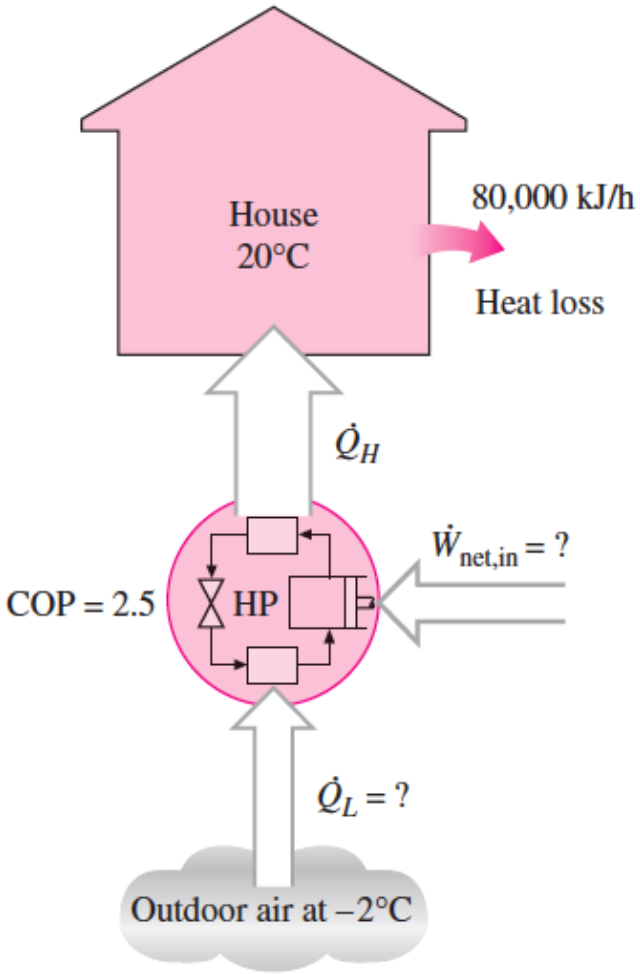




Heat pumps

- Example 6-4: Heating a House by a Heat Pump

A heat pump is used to meet the heating requirements of a house and maintain it at 20°C. On a day when the outdoor air temperature drops to - 2°C, the house is estimated to lose heat at a rate of 80,000 kJ/h. If the heat pump under these conditions has a COP of 2.5, determine (a) the power consumed by the heat pump and (b) the rate at which heat is absorbed from the cold outdoor air.



Heat Pump

Clausius Statement

- Clausius Statement of the second law of thermodynamics:

It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

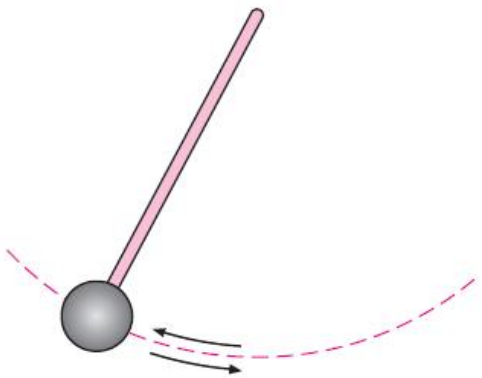
Said in a different manner: if you want to transfer heat from a low temperature reservoir to a high temperature reservoir, you need to provide work.

Both the Kelvin–Planck and the Clausius statements of the second law cannot be proved. To date, no experiment has been conducted that contradicts the second law.

The Kelvin–Planck and the Clausius statements are equivalent in their consequences, and either statement can be used as the expression of the second law of thermodynamics.

Reversible and irreversible processes

- The second law of thermodynamics states that it is not possible to build a heat engine whose efficiency is 100% (or a heat pump whose COP would be ∞).
- Then, what would be the maximum efficiency of a heat engine?
- To answer this, we need to introduce the concepts of reversible and irreversible processes.
- *A **reversible process** is defined as a process that can be reversed without leaving any trace on the surroundings*
- *In practice, a process is never fully reversible*. We consider them for two reasons
  - They can be described, as they correspond to a succession of (quasi-) equilibrium states.
  - They are ideal models to which the actual process can be compared. They correspond to a maximum of power generation for heat engines and to a minimum of power consumption for heat pumps.



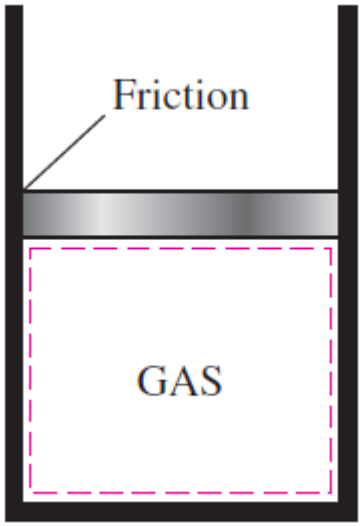
(*a*) Frictionless pendulum

(*b*) Quasi-equilibrium expansion and compression of a gas

Irreversibilities

- A few examples of irreversibilities:
  - **Friction**

When two bodies in contact are forced to move relative to each other (a piston in a cylinder, for example), a friction force that opposes the motion develops at the interface of these two bodies,and some work is needed to overcome this friction force. The energy supplied as work is eventually converted to heat during the process and is transferred to the bodies in contact, as evidenced by a temperature rise at the interface. When the direction of the motion is reversed, the bodies are restored to their original position, but the interface does not cool, and heat is not converted back to work. Instead, more of the work is converted to heat while overcoming the friction forces that also oppose the reverse motion.



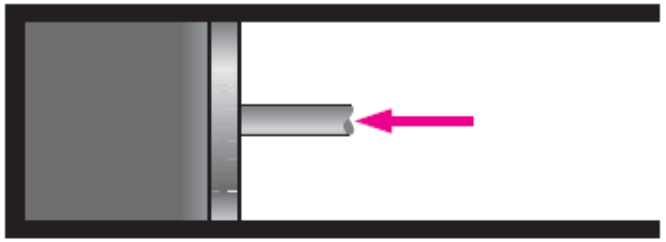
Since the system (the moving bodies) and the surroundings cannot be returned to their original states, the process is irreversible.

Irreversibilities

❖ **Fast compression or expansion**

The work consumed during a fast compression of gas in a cylinder is higher than the work produced during the fast expansion. As consequence, the system does not come back to its original state and thereby affects the surrounding.

In the case of reversible compression/expansion, the work consumed to compress the gaz is exactly equal to the work produced during the expansion.



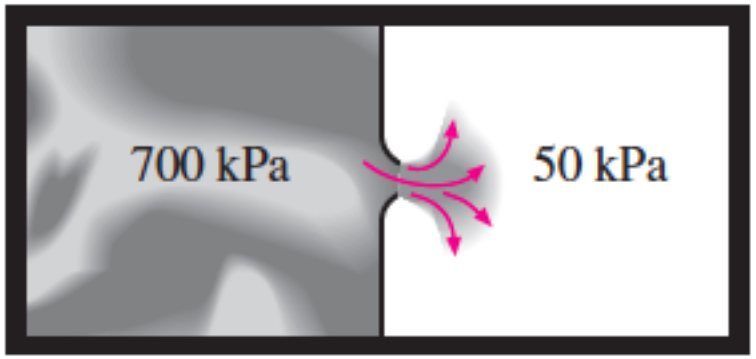
(*a*) Fast compression

(*b*) Fast expansion

Irreversibilities

❖ **Free expansion**

Let's consider a gas separated from a vacuum by a membrane. When the membrane is ruptured, the gas fills the entire tank. The only way to restore the system to its original state is to compress it to its initial volume, while transferring heat from the gas until it reaches its initial temperature.



From the conservation of energy considerations, it can easily be shown that the amount of heat transferred from the gas equals the amount of work done on the gas by the surroundings. The restoration of the surroundings involves conversion of this heat completely to work, which would violate the second law. Therefore, unrestrained expansion of a gas is an irreversible process.

Irreversibilities

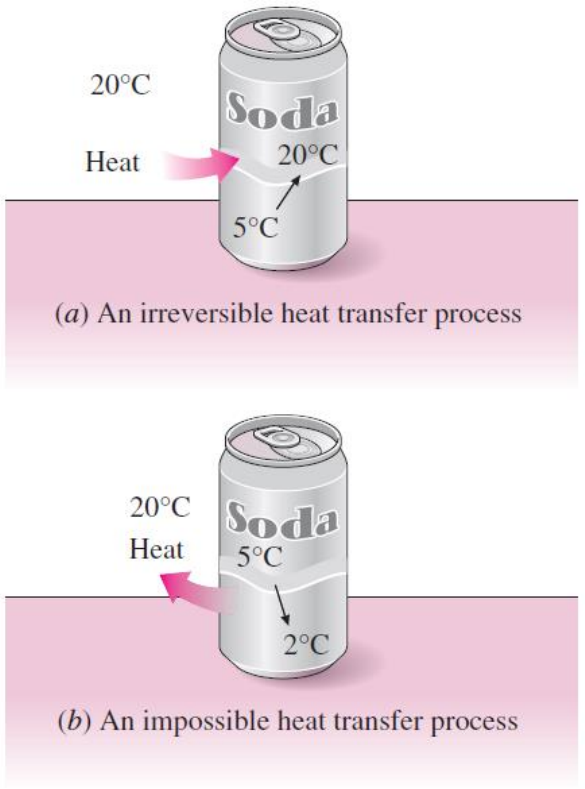
❖ **Finite temperature differences**

Consider a can of cold soda left in a warm room. Heat is transferred from the warmer room air to the cooler soda. The only way this process can be reversed and the soda restored to its original temperature is to provide refrigeration, which requires some work input.

At the end of the reverse process, the soda will be restored to its initial state, but the surroundings will not be. The internal energy of the surroundings will increase by an amount equal in magnitude to the work supplied to the refrigerator.

The restoration of the surroundings to the initial state can be done only by converting this excess internal energy completely to work, which is impossible to do without violating the second law.

<u>Heat transfer can occur only when there is a temperature difference. Therefore, it is impossible to have a reversible heat transfer process</u>



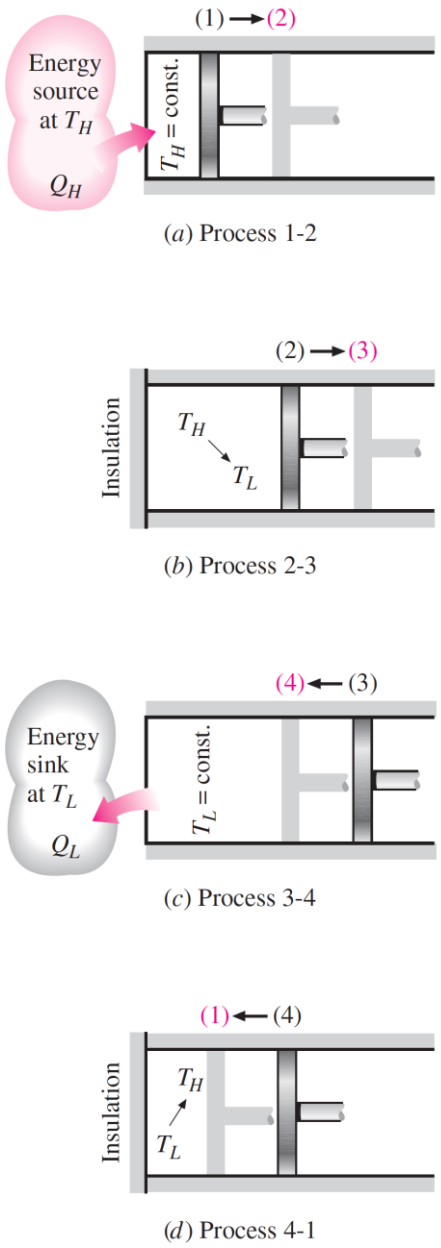
The Carnot Cycle

- A heat engine is a cyclic device. During a part of the cycle, work is produced by the fluid. In other parts of the cycle work is provided to the fluid. The different between these two values is the net work delivered by the heat engine.
- To maximise the net work, it is necessary to maximise the work produced and minimise the work provided to the fluid. Therefore, these evolutions must be **reversible**.
- As a consequence, **reversible cycles** are cycles whose efficiency is maximum
- Reversible cycles correspond to the theoretical upper limit for the efficiency of heat engines (but also for the COP of heat pumps).
- The **Carnot Cycle** is a reversible cycle. It is the most efficiency cycle operating between a heat source and a heat sink. The machine describing this cycle is called the **Carnot heat engine**.

The Carnot Cycle

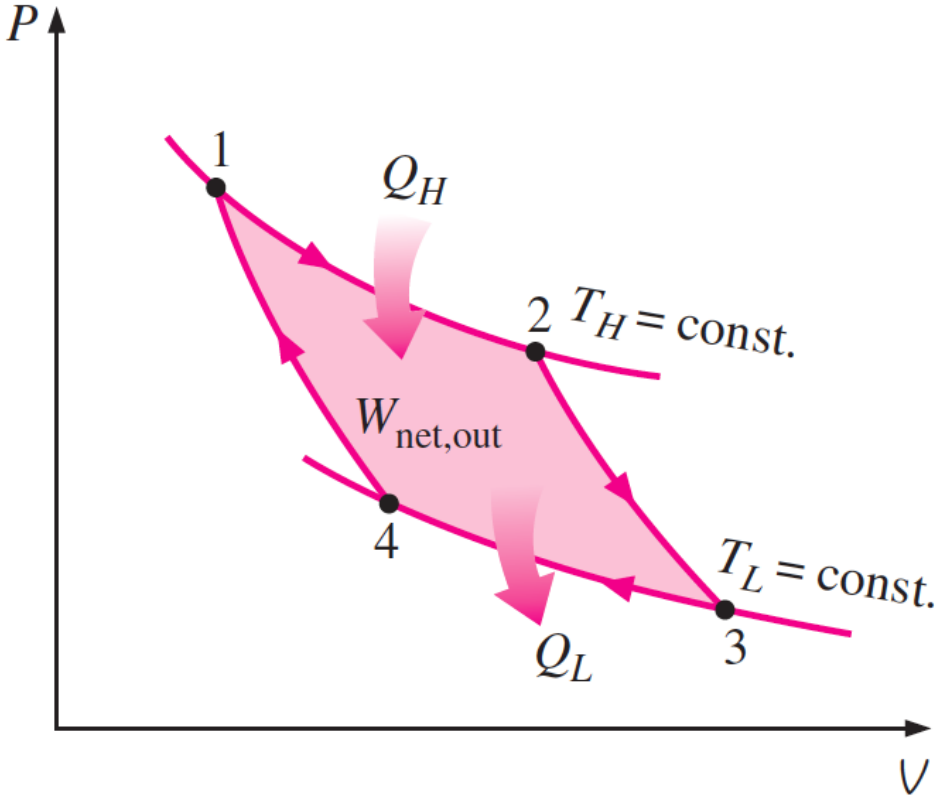
- The Carnot cycle describes 4 reversible processes: two **isothermal** processes and two **adiabatic** processes:

1. <u>Isothermal expansion from state 1 to state 2</u>. The gas in the cylinder are the heat source are both at temperature T_H. A quantity Q_H of heat is transferred from the source to the gas. Meanwhile the gas temperature is maintained at T_H.
2. <u>Adiabatic expansion from state 2 to state 3</u>. The gas does not receive any more heat from the source. It temperature decreases during the expansion.
3. <u>Isothermal compression from state 3 to state 4</u>. A quantity Q_C of heat is evacuated to the surrounding (heat sink) both the gas and the heat sink are maintainted a temperature T_C.
4. <u>Adiabatic compression from state 4 to state 1.</u>



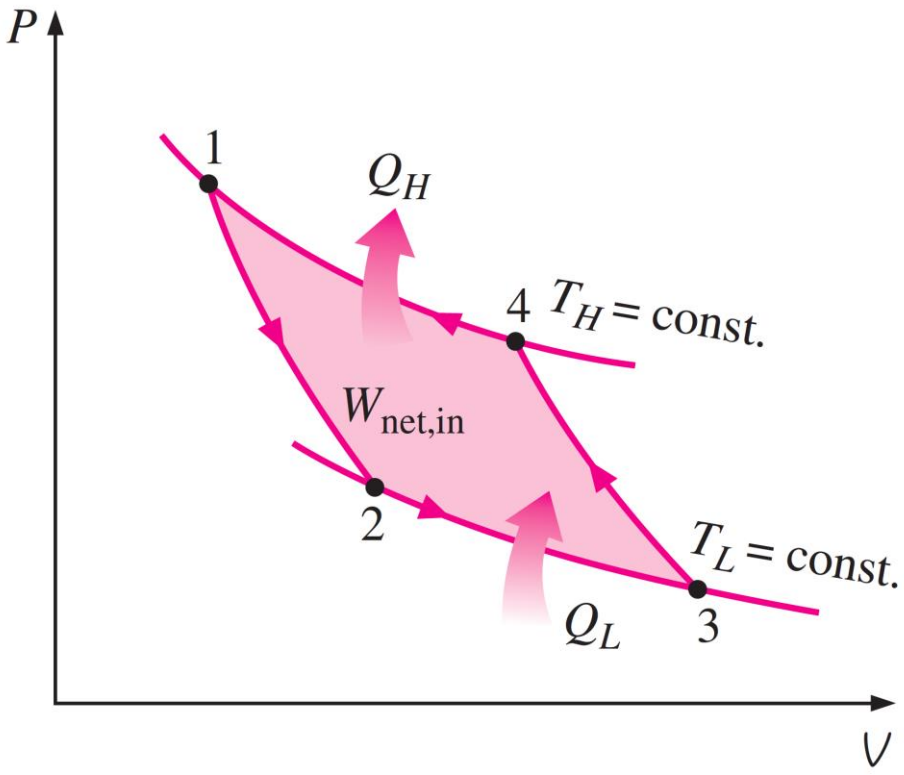
The Carnot Cycle

- The Carnot cycle can be represented in the P-V diagram. The area under the process curve is the work done/provided by the gas. The red area is the net work.



The reversed Carnot cycle

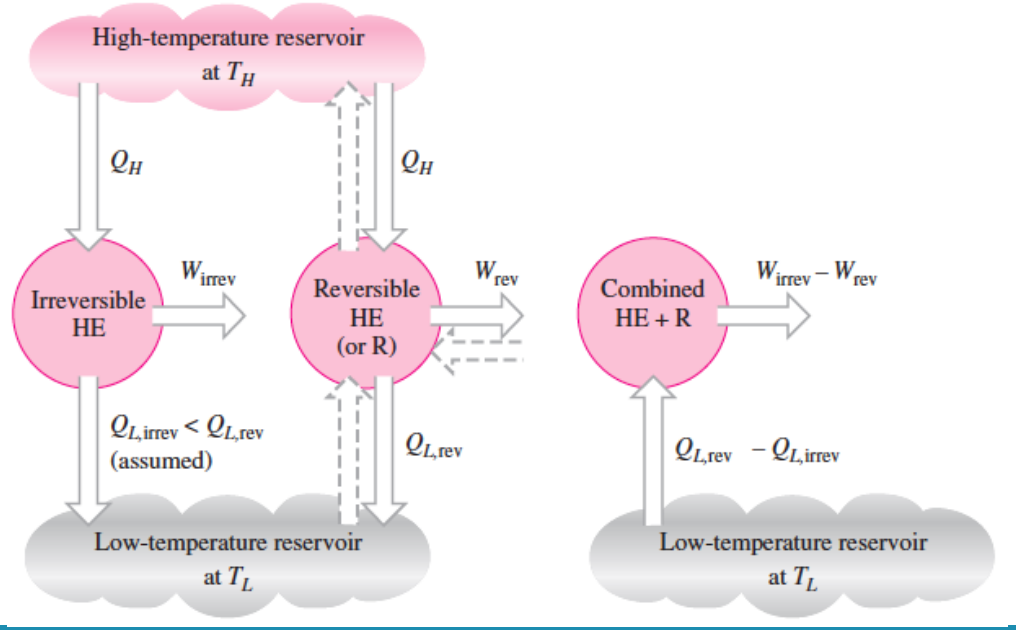
- By reversing the Carnot cycle (remember that all processes are reversible!), we obtaine the Carnot refrigeration cycle.



The Carnot principles

- Principle 1: The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.
- Principle 2: The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.

The violation of either statement results in the violation of the second law of thermodynamics, as shown below:



The Carnot principles

Demonstration of the first Carnot principle:

- Let's consider an irreversible engine and a reversible engine operating between the same reservoirs.
- Let's assume (agains Carnot's principles) that the irreversible engine produces more work than the reversible one.
- The reversible cycle can be turned into a heat pump. This heat pump provides the hot reservoir a heat quantity equal to that consumed by the irreversible engine.
- If we use this heat for the irreversible engine, the overal system is a device that provides work by exchanging heat with a single reservoir, which goes agains the second law of thermodynamics.

The thermodynamic temperature scale

- Principle 2: The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.

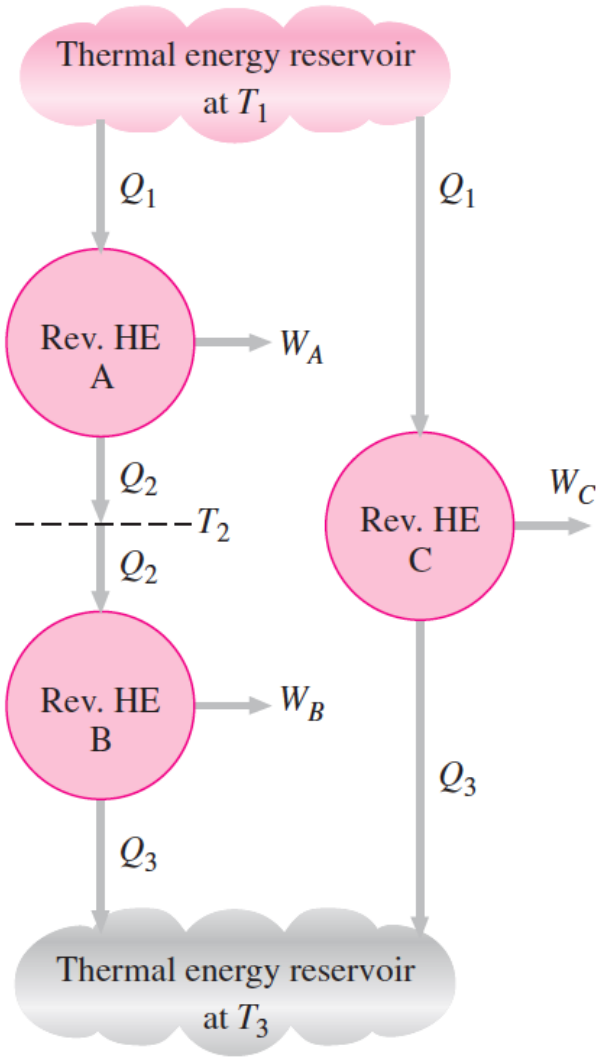
- This is demonstrated in a similar manner to the first principle
- If we rephrase this, we can say that the efficiency of a reversible engine is independent of the working fluid employed and its properties, the way the cycle is executed, or the type of reversible engine used
- The efficiency is a function of the reservoir temperatures only:

$$\eta_{th,rev} = g(T_H, T_L) \Leftrightarrow \frac{Q_H}{Q_L} = f(T_H, T_L)$$

because :

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

The thermodynamic temperature scale



- To determine the function *f*, let's image the three heat engines shown on the figure.

For heat device, we have:

$$\frac{Q_1}{Q_2} = f(T_1, T_2)\,; \frac{Q_2}{Q_3} = f(T_2, T_3); \frac{Q_1}{Q_3} = f(T_1, T_3)$$

but we also know that :

$$\frac{Q_1}{Q_3} = \frac{Q_1}{Q_2} . \frac{Q_2}{Q_3}$$

Therefore :

$$f(T_1, T_3) = f(T_1, T_2) . f(T_2, T_3)$$

The thermodynamic temperature scale

$$f(T_1, T_3) = f(T_1, T_2).f(T_2, T_3)$$

In order for the right side of the question to depend only on T_1 and T_3, the following conditions must be satisfied :

$$f(T_1, T_2) = \frac{\Phi(T_1)}{\Phi(T_2)} \; and \; f(T_2, T_3) = \frac{\Phi(T_2)}{\Phi(T_3)}$$

And therefore,

$$\frac{Q_1}{Q_3} = \frac{\Phi(T_1)}{\Phi(T_3)}$$

The thermodynamic temperature scale

More generally, for any reversible heat engine operating between T_L and T_H, we have :

$$\frac{Q_H}{Q_L} = \frac{\Phi(T_H)}{\Phi(T_L)}$$

The choice of the functions $\Phi(T)$ is arbitrary. Kelvin proposed $\Phi(T) = T$
In that case,

$$\left(\frac{Q_H}{Q_L}\right)_{rév} = \frac{T_H}{T_L}$$

Where the temperature are in K.

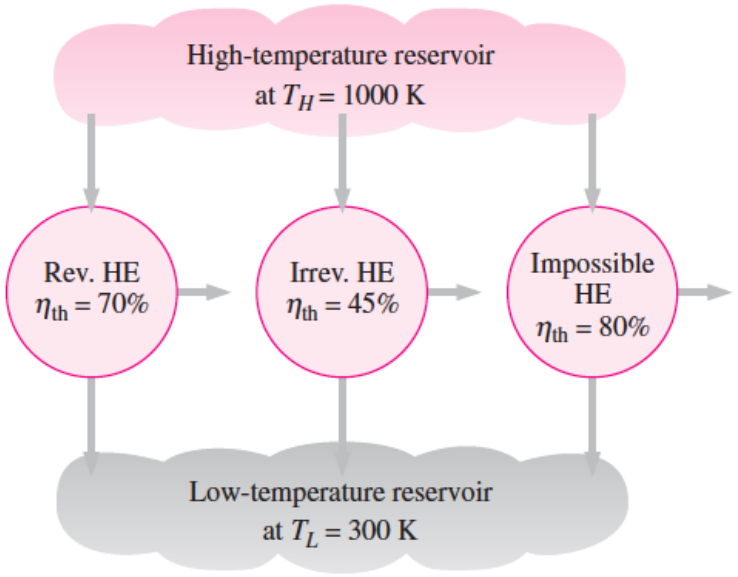
The Carnot heat engine

- The hypothetical heat engine that operates on the reversible Carnot cycle is called the Carnot heat engine. The thermal efficiency is given by:

$$\eta_{th,rév} = 1 - \frac{T_L}{T_H}$$

- It is the highest possible thermal efficiency between T_H et T_L. Any irreversible machine (i.e. real machine) has a lower efficiency.

- To increase the efficiency:
  - Increase T_H
  - Decrease T_L.



The Carnot refrigerator and heat pump

- For any (reversible or not) refrigeration machine or heat pump, the COP is given by:

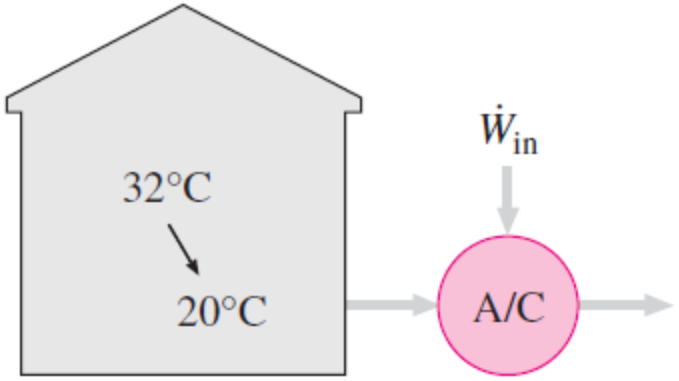
$$COP_C = \frac{1}{\frac{Q_H}{Q_L} - 1} \quad et \quad COP_H = \frac{1}{1 - \frac{Q_L}{Q_H}}$$

- If these machine operated according to the reversed Carnot cycle, the COPs become:

$$COP_C = \frac{1}{\frac{T_H}{T_L} - 1} \quad et \quad COP_H = \frac{1}{1 - \frac{T_L}{T_H}}$$

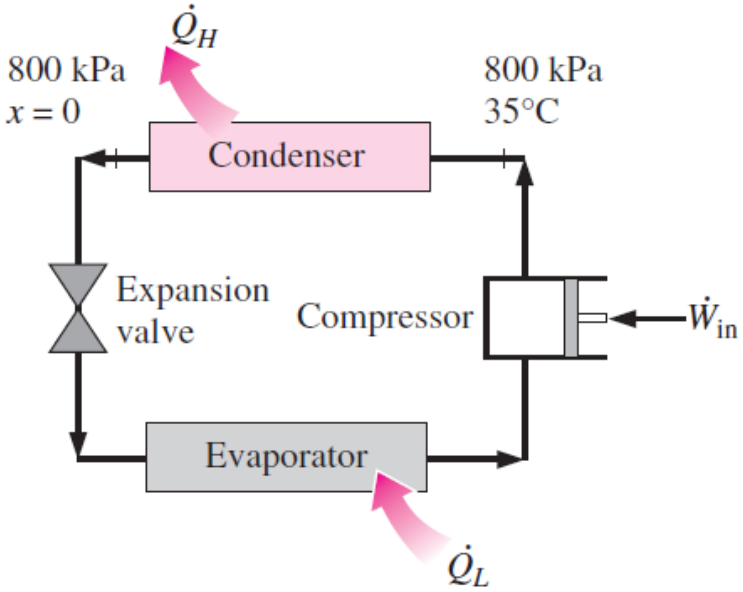
Exercises in EES

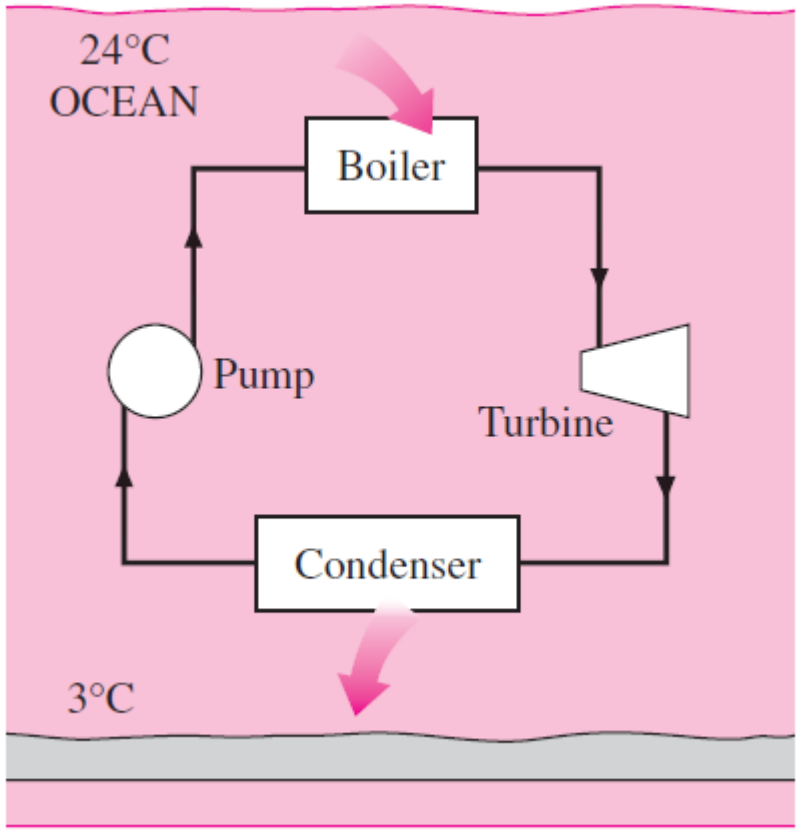
6–44 When a man returns to his well-sealed house on a summer day, he finds that the house is at 32°C. He turns on the air conditioner, which cools the entire house to 20°C in 15 min. If the COP of the air-conditioning system is 2.5, determine the power drawn by the air conditioner. Assume the entire mass within the house is equivalent to 800 kg of air for which $c_v = 0.72$ kJ/kg · °C and $c_p = 1.0$ kJ/kg · °C.



Exercises in EES

6–54 Refrigerant-134a enters the condenser of a residential heat pump at 800 kPa and 35°C at a rate of 0.018 kg/s and leaves at 800 kPa as a saturated liquid. If the compressor consumes 1.2 kW of power, determine (*a*) the COP of the heat pump and (*b*) the rate of heat absorption from the outside air.



Exercises in EES

6–76 In tropical climates, the water near the surface of the ocean remains warm throughout the year as a result of solar energy absorption. In the deeper parts of the ocean, however, the water remains at a relatively low temperature since the sun's rays cannot penetrate very far. It is proposed to take advantage of this temperature difference and construct a power plant that will absorb heat from the warm water near the surface and reject the waste heat to the cold water a few hundred meters below. Determine the maximum thermal efficiency of such a plant if the water temperatures at the two respective locations are 24 and 3°C.