

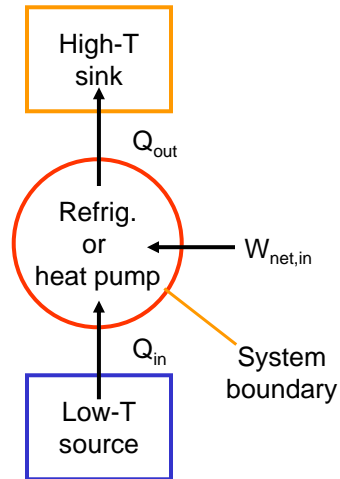
V. The Second Law of Thermodynamics

C. Refrigerators and Heat Pumps

1. Introduction

a. Cyclic devices that maintain a room or container at a roughly constant temperature. An air conditioner is a refrigerator.

b. Simple schematic of refrigerator or heat pump.



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2. The coefficient of performance

a. Refrigerator

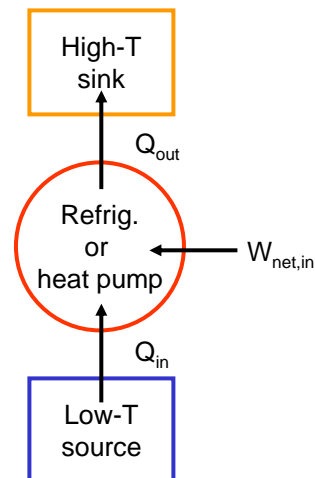
$$(6-7, 6-9) \quad COP_R = \frac{Q_{in}}{W_{net,in}} = \frac{Q_{in}}{Q_{out} - Q_{in}}$$

$$\text{or } COP_R = \frac{\dot{Q}_{in}}{\dot{Q}_{out} - \dot{Q}_{in}}$$

b. Heat pump

$$(6-10, 6-11) \quad COP_{HP} = \frac{Q_{out}}{W_{net,in}} = \frac{Q_{out}}{Q_{out} - Q_{in}}$$

$$\text{or } COP_{HP} = \frac{\dot{Q}_{out}}{\dot{Q}_{out} - \dot{Q}_{in}}$$

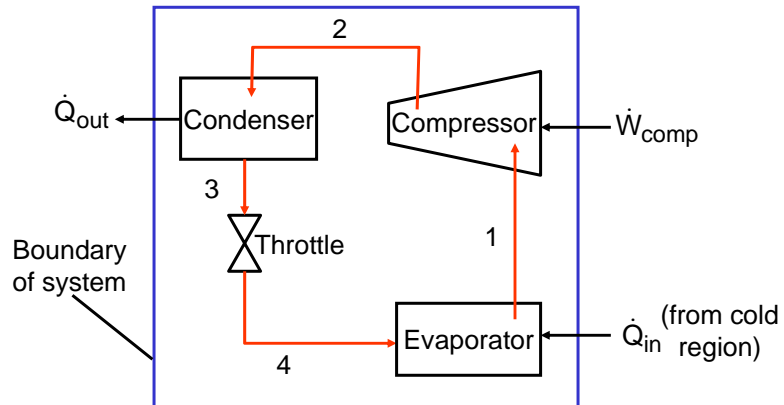


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3. A closer look at refrigeration equipment

a. Schematic of equipment

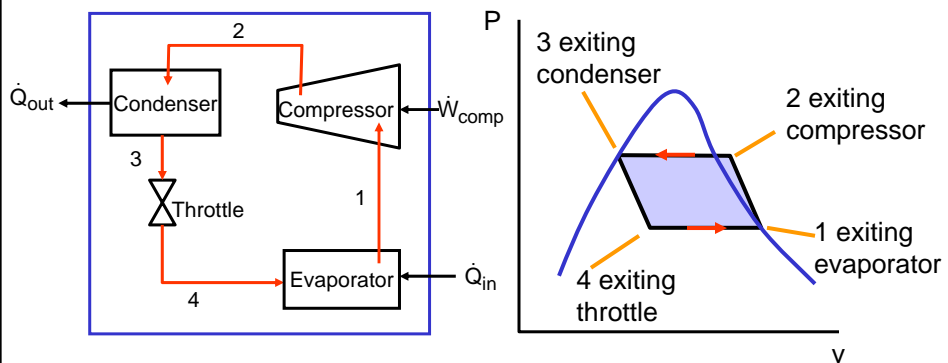


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3. A closer look at refrigeration equipment

b. Schematic and sketch on Pv diagram

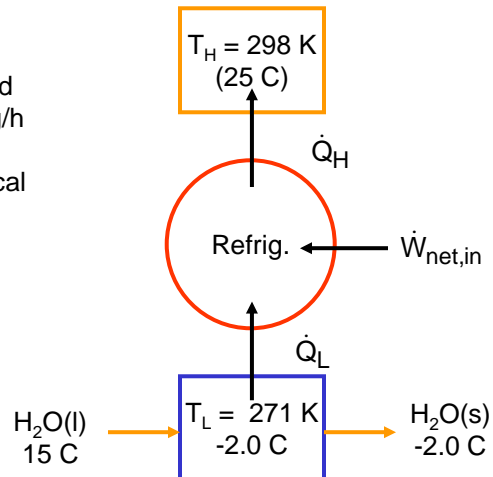


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4. Example. The ice-making plant sketched at right makes 500 kg/h of ice. Determine the annual cost of electrical power if $COP_R = 2.0$ and the cost of electricity is \$0.059/kWh.

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{net,in}}$$



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4. Example
 a. Energy balance over control volume defined by water in freezer to find \dot{Q}_L .

$$\dot{m}h_{in} - \dot{m}h_{out} - \dot{Q}_L = 0$$

$$\dot{Q}_L = \dot{m}(h_{in} - h_{out}) = \frac{500 \text{ kg}}{3600 \text{ s}} (62.99 - (-337.62)) \frac{\text{kJ}}{\text{kg}} = 55.64 \text{ kW}$$

- b. Cost calculation

$$\text{Cost} = \dot{W}_{net,in} \cdot \Delta t \cdot \text{rate} = \frac{\dot{Q}_L}{COP_R} \cdot \Delta t \cdot \text{rate}$$

$$\text{Cost} = \frac{55.64}{2.0} \text{ kW} \cdot 365 \cdot 24 \cdot \text{h} \cdot \frac{\$0.059}{\text{kWh}} = \$14,300/\text{yr}$$

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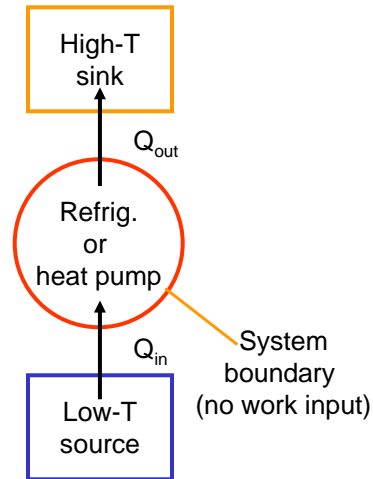
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5. Clausius Statement of Second Law

“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.”

(p. 292)

This means that $Q_{in} \leq 0$.



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D. Reversible and Irreversible Processes

1. We want to know the upper limit on the thermal efficiency and coefficient of performance. The Kelvin-Planck and Clausius statements do not provide upper limits. The upper limit will exist for an **idealized** process called a reversible process.
2. A process is **reversible** if the system and its surroundings can be returned to their initial states. To be reversible, (1) boundary work must be performed as a series of equilibrium steps, (2) heat transfer, must be across an infinitesimal temperature difference (dT), and (3) all processes must be frictionless.
3. An **irreversible processes** involves dissipative effects and nonquasiequilibrium steps. The system and its surroundings cannot be restored to their initial states if the process is irreversible. All real processes are irreversible. Our goal as engineers is to minimize the degree of irreversibility.

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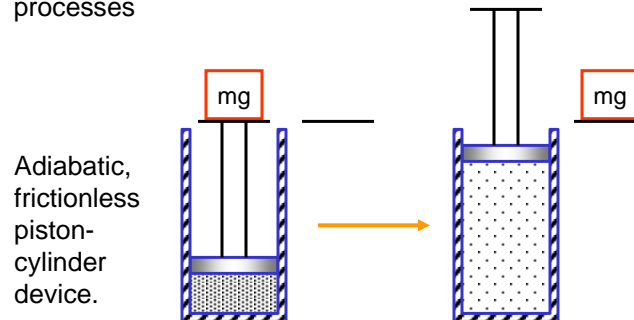
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4. **Internally reversible process** - nothing irreversible occurs within boundary of system.
5. **Externally reversible process** - nothing irreversible occurs outside the boundary of system.
6. **Totally reversible** or simply **reversible** - nothing irreversible within or outside the boundary of system.
7. All real processes are irreversible but many of our calculations ignore that fact because the assumption of reversibility makes the calculations easier. We go ahead assuming most processes are reversible and then correct our calculations to get approximate answers. The corrections are based on experience.

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8. A mechanical example of irreversible and reversible processes



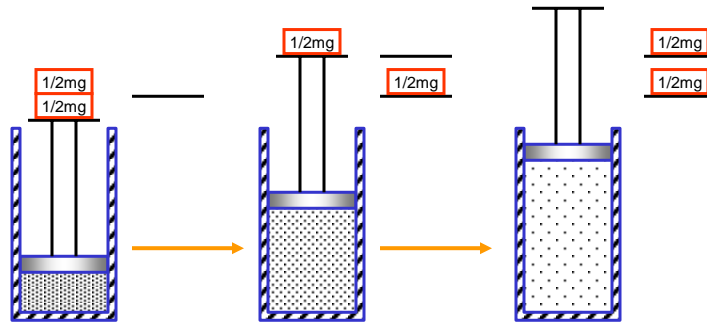
We would like to use the compressed gas in the cylinder to perform the maximum possible amount of useful work - defined as raising the weight, mg . If the weight is kicked to the shelf, no useful work is done.

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8. A mechanical example of irreversible and reversible processes

We try a different approach by dividing the weight into two parts.



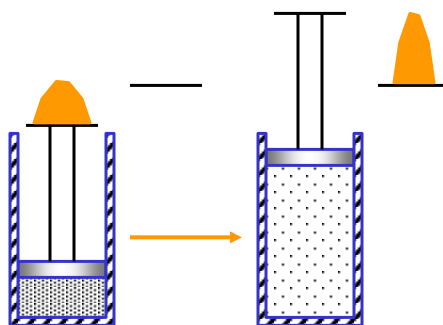
Dividing the weight into two parts allows us to accomplish more useful work than in the previous case because the weight has been raised and some work has been obtained. Can we do better?

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8. A mechanical example of irreversible and reversible processes

We suspect that we can do better by dividing the weight into many smaller pieces. If we replace the weight with a pile of sand and flick the particles of sand off one at a time, onto small shelves, we will be able to raise the weight an average of about half the stroke of the piston.



The only way we could conceivably obtain more work would be by making the particles of sand infinitely small. This imaginary process would be called a **reversible process**. For such process, the work performed by the gas is a maximum and is given by

$$W_{rev} = \int_{V_1}^{V_2} PdV$$

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