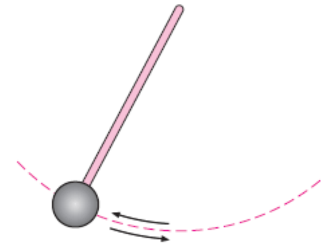
Reversible and Irreversible Processes

A **reversible process** is defined as a process that can be reversed without leaving any trace on the surroundings. That is, both the system and the surroundings are returned to their initial states at the end of the reverse process. Processes that are not reversible are called **irreversible proces**



(*a*) Frictionless pendulum

The system can be restored to its initial state following a process, regardless of whether the process is reversible or irreversible.

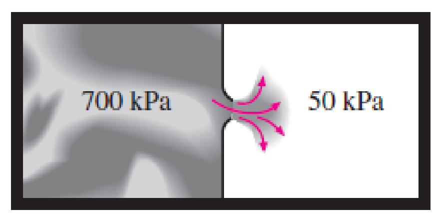
(*b*) Quasi-equilibrium expansion and compression of a gas

Reversible processes actually do not occur in nature. They are merely *idealizations* of actual processes. Reversible processes can be approximated by actual devices, but they can never be achieved. That is, all the processes occurring in nature are irreversible.

There are two reasons of why we interesting with fictitious reversible processes which are:

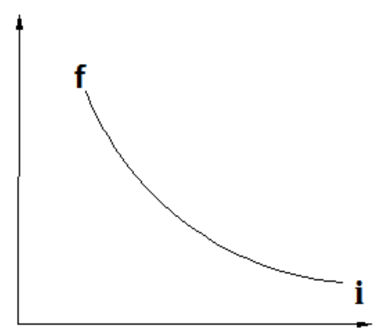
1. They are easy to analyze, since a system passes through a series of equilibrium states during a reversible process.
2. They serve as idealized models to which actual processes can be compared.

The factors that cause a process to be irreversible are called ***irreversibilities***. They include friction, **unrestrained expansion**, **mixing of two fluids**, **heat transfer across a finite temperature difference**, **electric resistance**, **inelastic deformation of solids**, and **chemical reactions**.



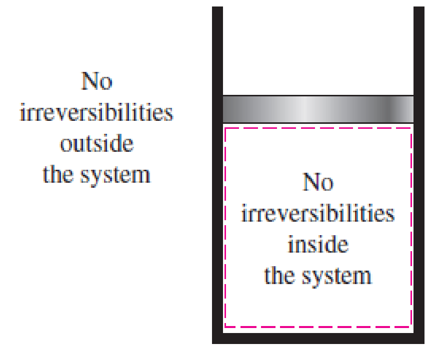
Unrestrained expansion

A process is called **internally reversible** if no irreversibilities occur within the boundaries of the system during the process. During an internally reversible process, a system proceeds through a series of equilibrium stat and when the process is reversed, the system passes through exactly the same equilibrium states while returning to its initial state. That is, the paths of the forward (i-f) and reverse processes (f-i) coincide for an internally reversible process. The quasi-equilibrium process is an example of an internally reversible process.



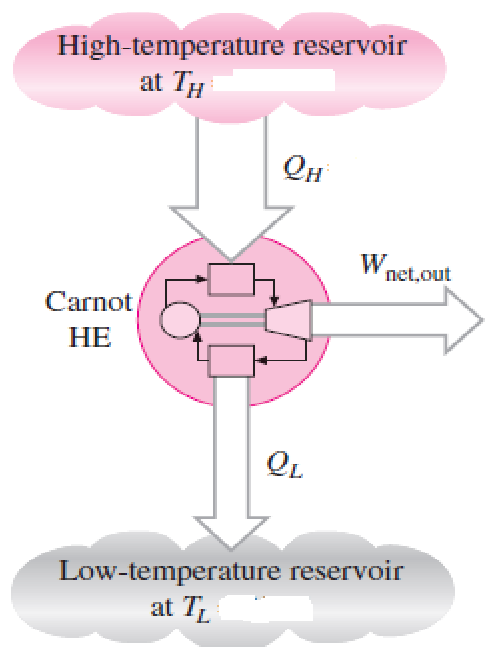
A process is called **externally reversible** if no irreversibilities occur outside the system boundaries during the process.

A process is called **totally reversible,** or simply **reversible,** if it involves no irreversibilities within the system or its surroundings.



The Carnot Heat Engine

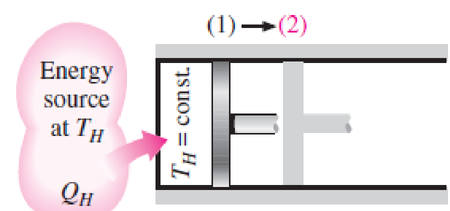
The hypothetical heat engine that operates on the reversible Carnot cycle is called the **Carnot heat engine.**



Carnot cycle is the **most efficient** cycle that can operate between two constant-temperature reservoirs. Even though the Carnot cycle cannot be achieved in reality. It can be executed either in a closed or a steady-flow systems.

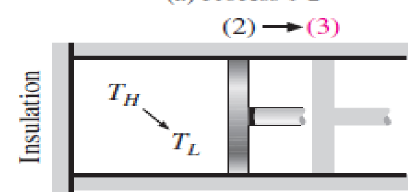
The important point to be made here is that the Carnot HE cycle, regardless of what the working substance may be, always has the same four basic reversible processes. These processes are:

1. A reversible isothermal expansion process (1-2) in which heat (Q_H) is transferred from the high-temperature (T_H) reservoir to the working fluid.



(*a*) Process 1-2

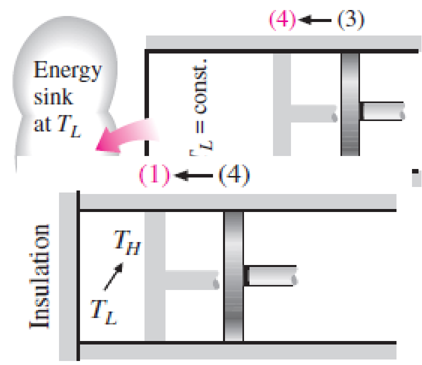
2. A reversible adiabatic expansion process (2 -3) (turbine or expander) where the work in done by the system and the temperature of the working fluid decreases from the high temperature (T_H) to the low temperature (T_L) .



(*b*) Process 2-3

3. A reversible isothermal compression (3-4) process in Which heat (Q_L)is transferred to the low-temperature (T_L) reservoir.

4. A reversible adiabatic compression process (pump or compressor) in which the temperature of the working fluid increases from the low temperature (T_L) to the high temperature (T_H) and the work is input to the system.



(*d*) Process 4-1

$$W_{exp} = W_{12} + W_{23} = Area(123)$$
$$W_{comp} = W_{34} + W_{41} = Area(341)$$
$$W_{net} = W_{exp} - W_{comp} = Area(12341)$$

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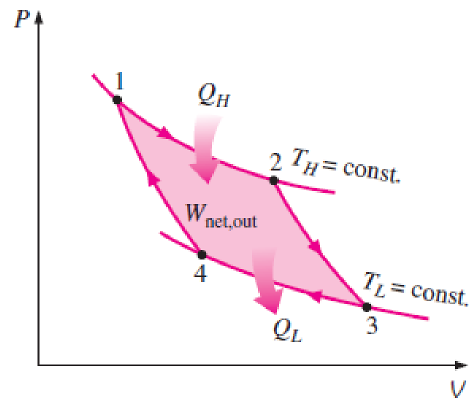
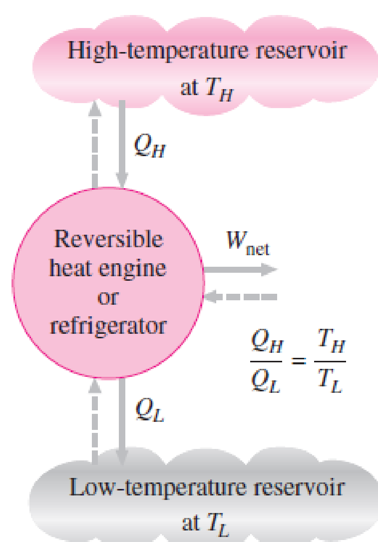


Thermodynamic temperature scale specifies that the Temperature is independent of the properties of the substances that are used to measure temperature.

Kelvin scale stated that the temperature ratios depend on the ratios of heat transfer between a reversible heat engine and the reservoirs and are independent of the physical properties of any substance.

$$\frac{Q_L}{Q_H} = \frac{T_L}{T_H}$$

Where T_L and T_H are absolute temperatures (K)



The thermal efficiency of any heat engine (reversible or irreversible) is:

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

For reversible heat engines, the heat transfer ratio in the above relation can be replaced by the ratio of the absolute temperatures of the two reservoirs,

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

This relation is often referred to as the Carnot efficiency, which is the highest efficiency of a heat engine operating between the two thermal energy reservoirs. The thermal efficiencies of actual and reversible heat engines operating between the same temperature limits compare as follows:

$$\eta_{th} \begin{cases} < \eta_{th,rev} & \text{irreversible heat engine} \\ = \eta_{th,rev} & \text{reversible heat engine} \\ > \eta_{th,rev} & \text{impossible heat engine} \end{cases}$$

When the performance of actual heat engines is assessed, the efficiencies should not be compared to 100 percent; instead, they should be compared to the efficiency of a reversible heat engine operating between the same temperature limits.

<u>Ex</u>: A Carnot heat engine operates between a source at 727 ^{o}C and a sink at 27 ^{o}C. If the heat engine is supplied with heat at a rate of 800 kJ/min, determine (a) the thermal efficiency and (b) the power output of this heat engine.

Sol:

T_H=727 ^{o}C=727+273=1000 K

T_L=27 ^{o}C=27+273=300 K

$\dot{Q}_H = 800\ kJ/\min$

$\eta_{th,rev} = ?,\ \dot{W}_{net,out} = ?$

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H} = 1 - \frac{300}{1000} = 0.7 = 70\%$$

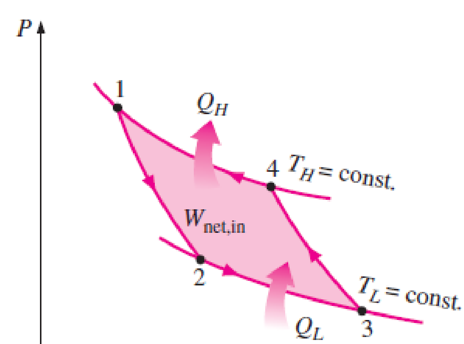
$$\eta_{th} = \frac{\dot{W}_{net,out}}{\dot{Q}_H}$$

$$0.7 = \frac{\dot{W}_{net,out}}{800}$$

$$\dot{W}_{net,out} = 560\ kJ/\min = 9.33\ kW$$

<u>The Carnot Refrigerator and Heat Pump</u>

The all the processes of Carnot heat-engine cycle can be *reversed*, in which case it becomes the



Carnot refrigeration cycle.

A refrigerator or a heat pump that operates on the reversed Carnot cycle is called a **Carnot refrigerator,** or a **Carnot heat pump.**

$$COP_{R,rev} = \frac{1}{\frac{Q_H}{Q_L} - 1} = \frac{1}{\frac{T_H}{T_L} - 1}$$

$$COP_{HP,rev} = \frac{1}{1 - \frac{Q_L}{Q_H}} = \frac{1}{1 - \frac{T_L}{T_H}}$$

These are the highest coefficients of performance that a refrigerator or a heat pump operating between the temperature limits of T_L and T_H can have.

The coefficients of performance of actual and reversible refrigerators operating between the same temperature limits can be compared as follows:

$$COP_R \begin{cases} < COP_{R,rev} & \text{irreversible refrigerator} \\ = COP_{R,rev} & \text{reversible refrigerator} \\ > COP_{R,rev} & \text{impossible refrigerator} \end{cases}$$

Ex: A Carnot refrigerator operates in a room in which the temperature is 25°C. The refrigerator consumes 500 W of power when operating and has a COP of 4.5. Determine (*a*) the rate of heat removal from the refrigerated space and (*b*) the temperature of the refrigerated space.

Sol:

T_H=25°C =25+273=298 K, $\dot{W}_{in,net} = 500\,W$, $COP_{R,rev} = 4.5$

$\dot{Q}_L = ?$, T_L=?

$$COP_{R,rev} = \frac{\dot{Q}_L}{\dot{W}_{net,in}}$$

$$4.5 = \frac{\dot{Q}_L}{500}$$

$$\dot{Q}_L = 2250\ W = 2.25\,kW = 2.25*60 = 135\ kJ/\min$$

Also,

$$COP_{R,rev} = \frac{1}{\frac{T_H}{T_L} - 1}$$

$$4.5 = \frac{1}{\frac{298}{T_L} - 1}$$

$$T_L = 243.82\ K = 243.82 - 273 = -29.18\ ^oC$$