Chemical Engineering (Thermodynamics I) (UCH305)

Dr. Neetu Singh
Associate Professor
Department of Chemical Engineering

Thapar Institute of Engineering & Technology
(Deemed to be University)
Bhadson Road, Patiala, Punjab, Pin-147004
Contact No. : +91-175-2393201
Email : info@thapar.edu

THAPAR INSTITUTE
OF ENGINEERING & TECHNOLOGY
(Deemed to be University)

Lecture 20

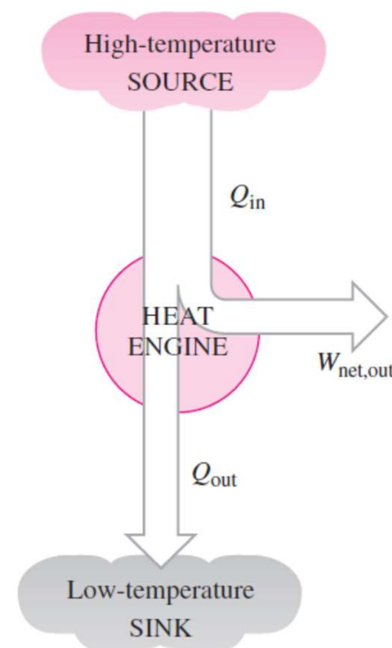
Reversible and Irreversible Processes

Reversible and Irreversible Processes

- The second law of thermodynamics states that no heat engine can have an efficiency of 100 percent.

- Then, what is the highest efficiency that a heat engine can possibly have?

- Before we can answer this question,
  - we need to define an ***idealized process first***,
    - * which is called the ***reversible process***.



- The cyclic process occurred in a certain direction.

- Once having taken place, these processes cannot reverse themselves spontaneously and restore the system to its **initial state**.

- For this reason, they are classified as ***irreversible processes***.

- Once a cup of hot coffee cools, it will not heat up by retrieving the heat it lost from the surroundings.

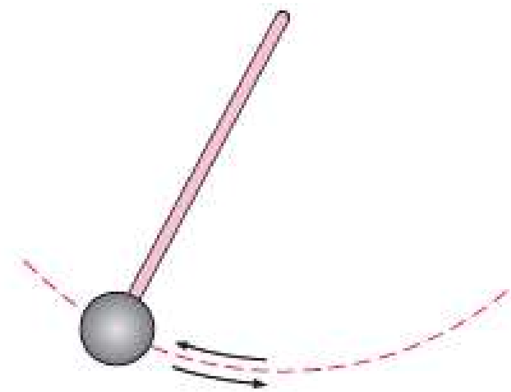
- If it could, the surroundings, as well as the system (coffee), would be restored to their original condition, and this would be a reversible process.

- A **reversible process is defined as a** process that can be reversed without leaving any trace on the surroundings.

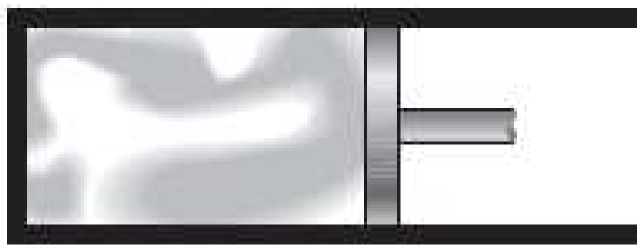
- That is, both the system and the surroundings are returned to their initial states at the end of the reverse process.

- This is possible only if the net heat and net work exchange between the system and the surroundings is ***zero*** for the combined (original and reverse) process.

- Processes that are not reversible are called **irreversible processes.**



Frictionless pendulum



Quasi-equilibrium expansion and compression of a gas

Irreversibilities

- The factors that cause a process to be irreversible are called *irreversibilities*.

- They include :

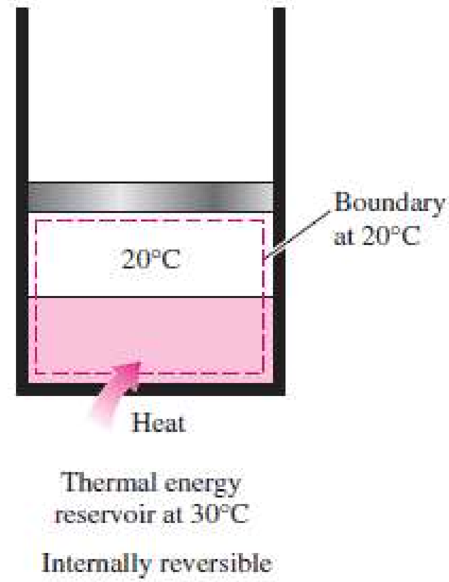
  ✓friction,
  ✓electric resistance,
  ✓heat transfer across a finite temperature difference,
  ✓inelastic deformation of solids, (i.e. plastic deformation), and
  ✓chemical reactions.
  ✓unrestrained expansion,
  ✓mixing of two fluids,

- The presence of any of these effects renders a process ***irreversible***.

- A reversible process involves ***none*** of these.

Internally and Externally Reversible Processes

- A ***process*** is called ***internally reversible*** if no irreversibilities occur within the boundaries of the system during the process.



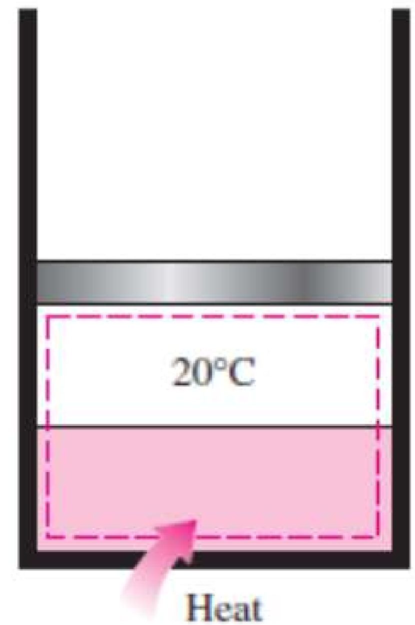
- During an internally reversible process,
  - a system proceeds through a series of equilibrium states, and
  - when the process is reversed, the
    * system passes through exactly the same equilibrium states while returning to its initial state.

- That is, the paths of the forward and reverse processes 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 out-side the system boundaries during the process.

- Heat transfer between a reservoir and a system is an externally reversible process
  - if the outer surface of the system is at the temperature of the reservoir.
    * But, it never possible.



Thermal energy reservoir at 20.000...1°C

The Carnot Cycle

- The heat engines are cyclic devices and that the working fluid of a heat engine returns to its initial state at the end of each cycle.

- Work is done by the working fluid during one part of the cycle and on the working fluid during another part of cycle.

- The difference between these two is the net work delivered by the heat engine.

- The efficiency of a heat-engine cycle greatly depends on how the individual processes that make up the cycle are executed.

- The net work, thus the cycle efficiency, can be maximized by using processes that require the least amount of work and deliver the most, that is, by using *reversible processes*.

- Therefore, it is no surprise that the most efficient cycles are reversible cycles, that is, cycles that consist entirely of reversible processes.

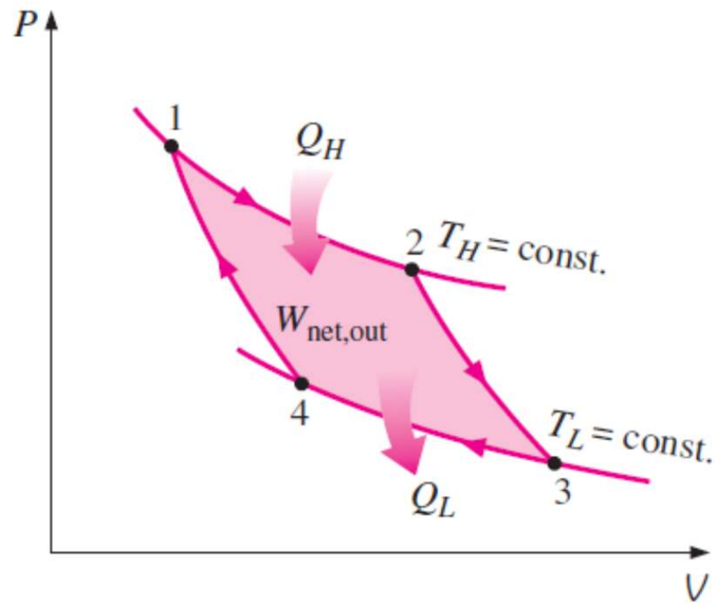
- Reversible cycles cannot be achieved in practice because the irreversibilities associated with each process cannot be eliminated.

- Probably the best known reversible cycle is the ***Carnot cycle***, first proposed in 1824 by French engineer Sadi Carnot.

- The theoretical heat engine that operates on the *Carnot cycle* is called the **Carnot heat engine.**

- The Carnot cycle is composed of four reversible processes:
  - two isothermal processes, and
  - two adiabatic processes.

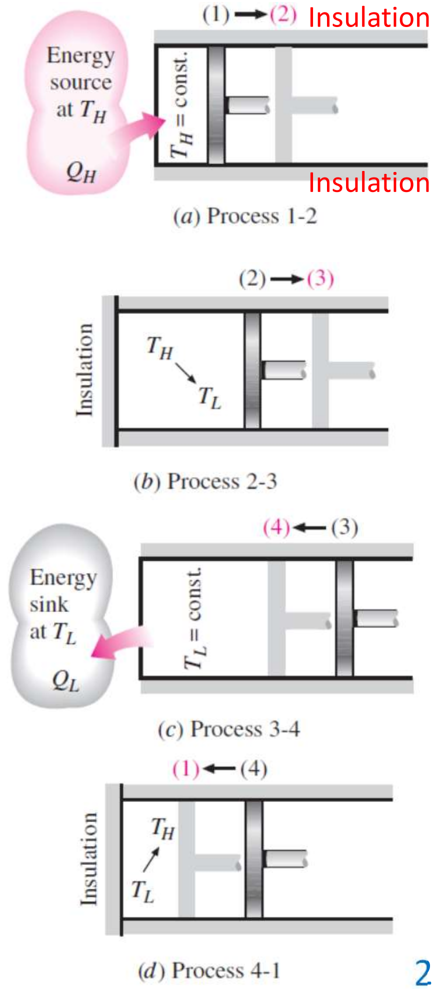
    * and it can be executed either in a closed or a steady-flow system.



- Consider a closed system that consists of a gas contained in an adiabatic piston–cylinder device, as shown in Fig.

- The insulation of the cylinder head is such that it may be removed to bring the cylinder into contact with reservoirs to provide heat transfer.

- The four reversible processes that make up the Carnot cycle are as follows:
  - Reversible Isothermal Expansion (1 – 2)
  - Reversible Adiabatic Expansion (2 – 3)
  - Reversible Isothermal Compression (3 – 4)
  - Reversible Adiabatic Compression (4 – 1)



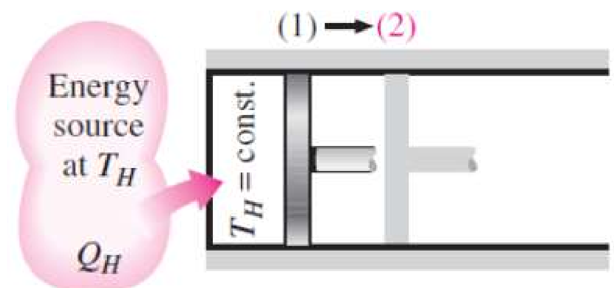
Reversible Isothermal Expansion

- **Reversible Isothermal Expansion** (process 1-2, T_H constant).

- Initially (state 1), the temperature of the gas is T_H and the cylinder head is in close contact with a source at temperature T_H.

- The gas is allowed to expand slowly, doing work on the surroundings.

- As the gas expands, the temperature of the gas tends to decrease.



(*a*) Process 1-2

- But as soon as the temperature drops by an infinitesimal amount dT, some heat is transferred from the reservoir into the gas, raising the gas temperature to T_H.

- Thus, the gas temperature is kept constant at T_H.

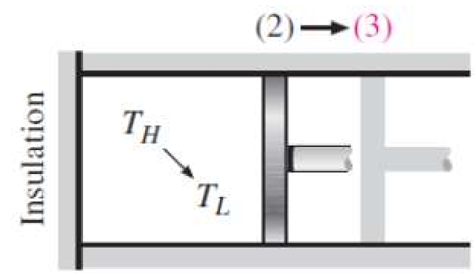
- Since the temperature difference between the gas and the reservoir never exceeds a differential amount dT, this is a reversible heat transfer process.

- It continues until the piston reaches position 2.

- The amount of total heat transferred to the gas during this process is Q_H.

Reversible Adiabatic Expansion

- **Reversible Adiabatic Expansion** (process 2-3, temperature drops from T_H to T_L).
- At state 2, the reservoir that was in contact with the cylinder head is removed and replaced by insulation so that the system becomes adiabatic.
- The gas continues to expand slowly, doing work on the surroundings until its temperature drops from T_H to T_L (state 3).

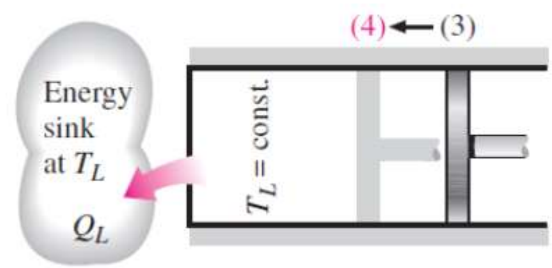


(b) Process 2-3

- The piston is assumed to be frictionless and the process to be quasi-quilibrium, so the process is reversible as well as adiabatic.

Reversible Isothermal Compression

- **Reversible Isothermal Compression** (process 3-4, T_L constant).
- At state 3, the insulation at the cylinder head is removed, and the cylinder is brought into contact with a sink at temperature T_L.
- Now the piston is pushed inward by an external force, doing work on the gas.
- As the gas is compressed, its temperature tends to rise.
- But as soon as it rises by an infinitesimal amount dT, heat is transferred from the gas to the sink, causing the gas temperature to drop to T_L.



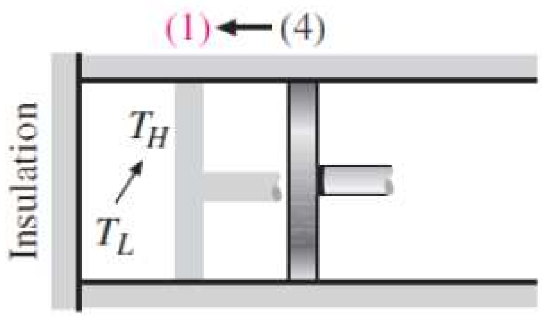
(c) Process 3-4

- Thus, the gas temperature remains constant at T_L.
- Since the temperature difference between the gas and the sink never exceeds a differential amount dT, this is a reversible heat transfer process.
- It continues until the piston reaches state 4.
- The amount of heat rejected from the gas during this process is Q_L.

Reversible Adiabatic Compression

- **Reversible Adiabatic Compression** (process 4-1, temperature rises from T_L to T_H).

- State 4 is such that when the low-temperature reservoir is removed, the insulation is put back on the cylinder head, and the gas is compressed in a reversible manner, the gas returns to its initial state (state 1).



(*d*) Process 4-1

- The temperature rises from T_L to T_H during this reversible adiabatic compression process, which completes the cycle.

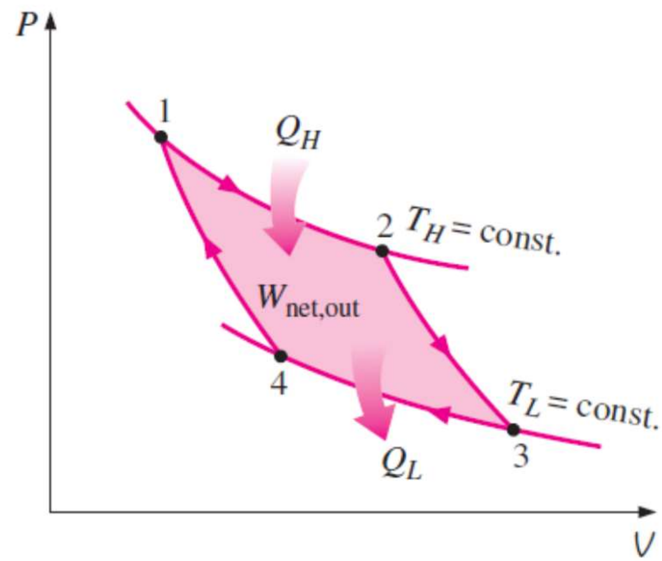
p-V diagram of the Carnot cycle

- The area under the process curve of *p-V diagram* represents the boundary work for quasi-equilibrium (internally reversible) processes.

- The area under curve 1-2-3 is the work done by the gas during the expansion part of the cycle.

- The area under curve 3-4-1 is the work done on the gas during the compression part of the cycle.

- The area enclosed by the path of the cycle (area 1-2-3-4-1) is the difference between these two and represents the net work done during the cycle.



Work done relations for isothermal and adiabatic processes

Isothermal processes:

$$W = p_1 V_1 \, ln\left(\frac{V_2}{V_1}\right)$$

Adiabatic process:

$$W = \frac{p_2 V_2 - p_1 V_1}{1-\gamma} = \frac{p_1 V_1 - p_2 V_2}{\gamma - 1}$$

$$W = \frac{mR(T_1 - T_2)}{\gamma - 1}$$

Heat Engines

$$\eta_{th} = \frac{W_{net,out}}{Q_H} = \frac{(Q_H - Q_L)}{Q_H} = \frac{(T_H - T_L)}{T_H}$$

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

- Being a reversible cycle, the Carnot cycle is the most efficient cycle operating between two specified temperature limits.

- Even though the Carnot cycle cannot be achieved in reality, the efficiency of actual cycles can be improved by attempting to approximate the Carnot cycle more closely.

- The thermal efficiencies of actual and reversible heat engines operating between the same temperature limits compare as follows:
  - $\eta_{th} < \eta_{th,rev}$ irreversible heat engine,
  - $\eta_{th} = \eta_{th,rev}$ reversible heat engine, and
  - $\eta_{th} > \eta_{th,rev}$ impossible heat engine.

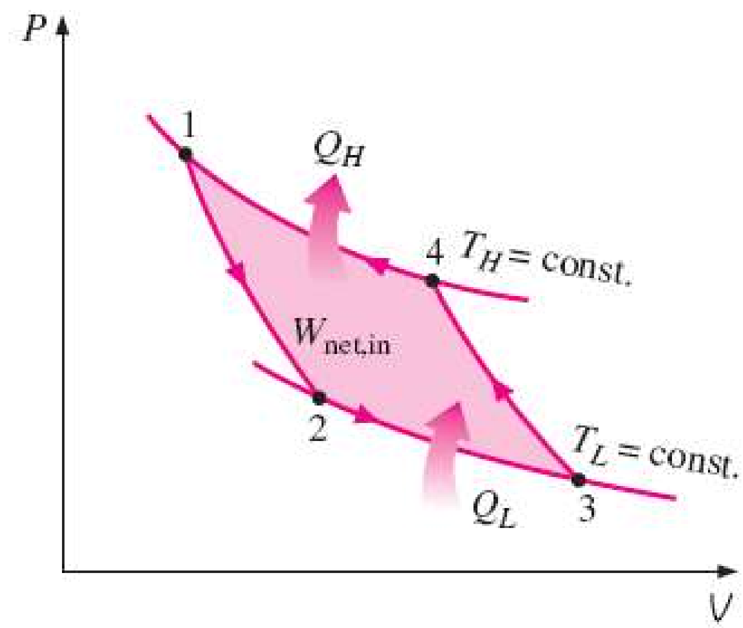
THE REVERSED CARNOT CYCLE

The Carnot heat-engine cycle is a totally reversible cycle. Therefore, all the processes that comprise it can be *reversed*, and becomes the Carnot refrigeration cycle.

• In this case, the cycle remains exactly the same, except that the directions of any heat and work interactions are reversed:

• Heat in the amount of Q_L is absorbed from the low-temperature reservoir, heat in the amount of Q_H is rejected to a high-temperature reservoir, and a work input of W_{net}, in is required to accomplish all this.

• The *P*-*V* diagram of the reversed Carnot cycle is the same as for the Carnot cycle, except that the directions of the processes are reversed.

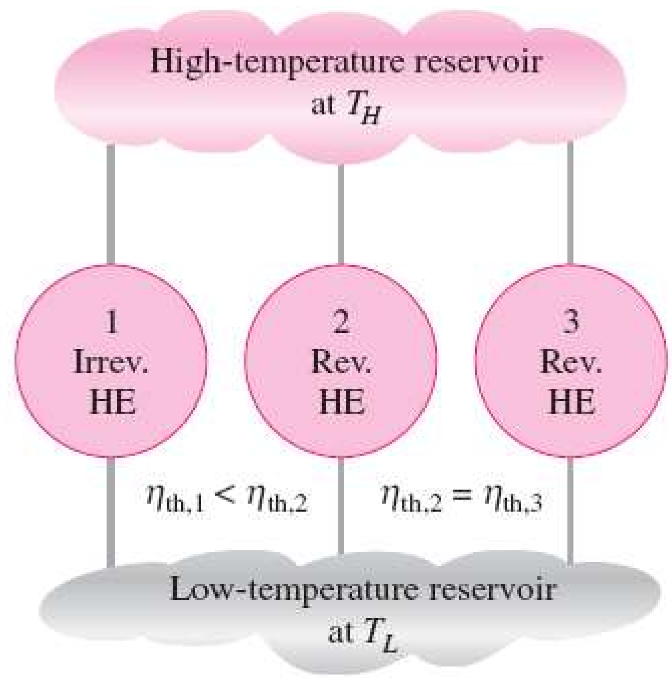


THE CARNOT PRINCIPLES

The second law of thermodynamics puts limits on the operation of cyclic devices as expressed by the Kelvin–Planck and Clausius statements. A heat engine cannot operate by exchanging heat with a single reservoir, and a refrigerator cannot operate without a net energy input from an external source.

We can draw valuable conclusions from these statements. Two conclusions pertain to the thermal efficiency of reversible and irreversible (i.e., actual) heat engines, and they are known as the Carnot principles, expressed as follows:

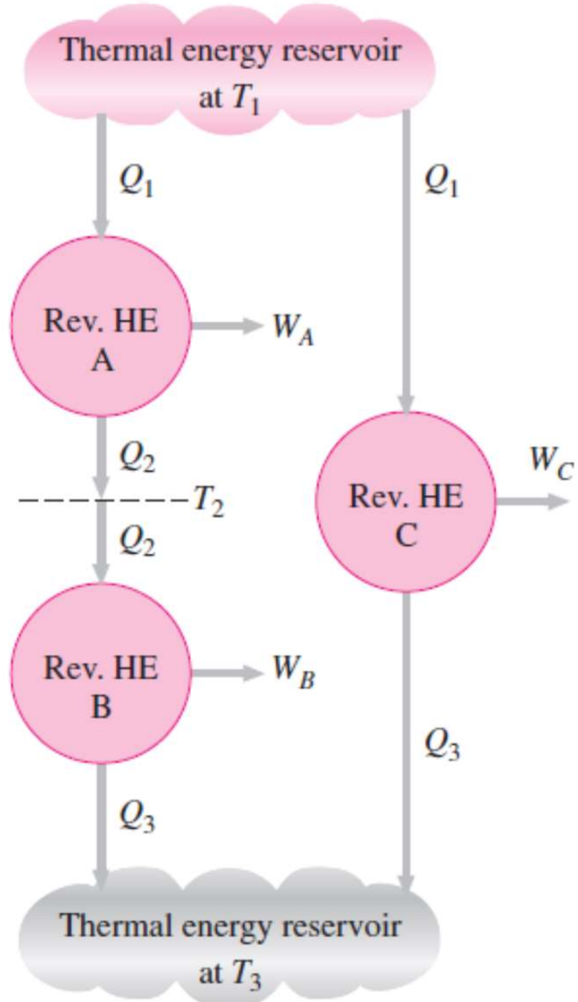
1. The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.
2. The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.



THE THERMODYNAMIC TEMPERATURE SCALE

A temperature scale that is independent of the properties of the substances that are used to measure temperature is called a **thermodynamic temperature scale.**

Such a temperature scale offers great conveniences in thermodynamic calculations.



The arrangement of heat engines used to develop the thermodynamic temperature scale.

THE CARNOT HEAT ENGINE

The hypothetical heat engine that operates on the reversible Carnot cycle is called the **Carnot heat engine. The thermal efficiency of any heat engine,** reversible or irreversible, is:

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

Q_H *is heat transferred to the heat engine from a high-temperature* reservoir at T_H, Q_L *is heat rejected to a low-temperature reservoir at* T_L.

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 as

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

Then the efficiency of a Carnot engine, or a[illegible] heat engine, becomes:

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

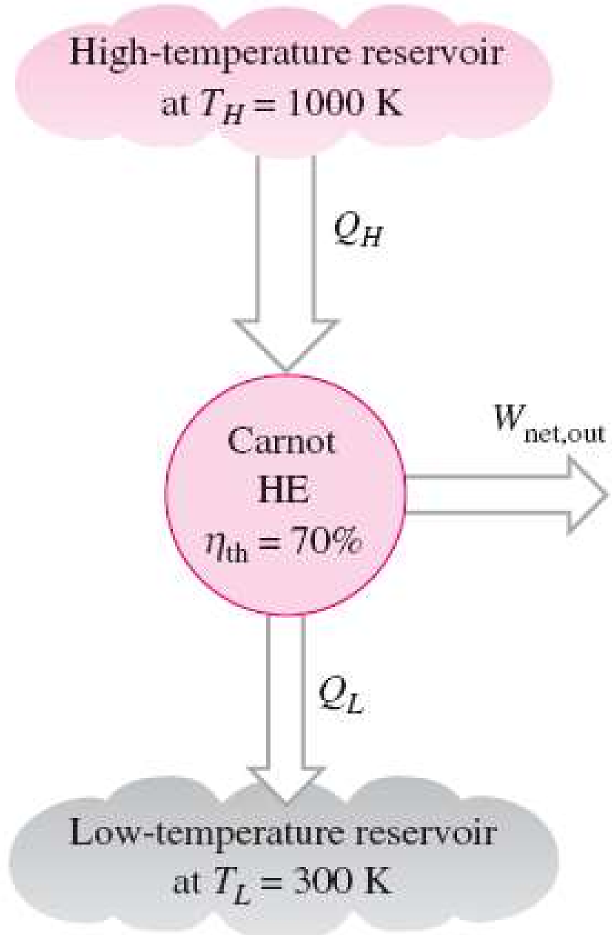
THE CARNOT HEAT ENGINE

The efficiency of a Carnot engine, or any reversible heat engine is:

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

This relation is often referred to as the **Carnot efficiency, since the** Carnot heat engine is the best known reversible engine.

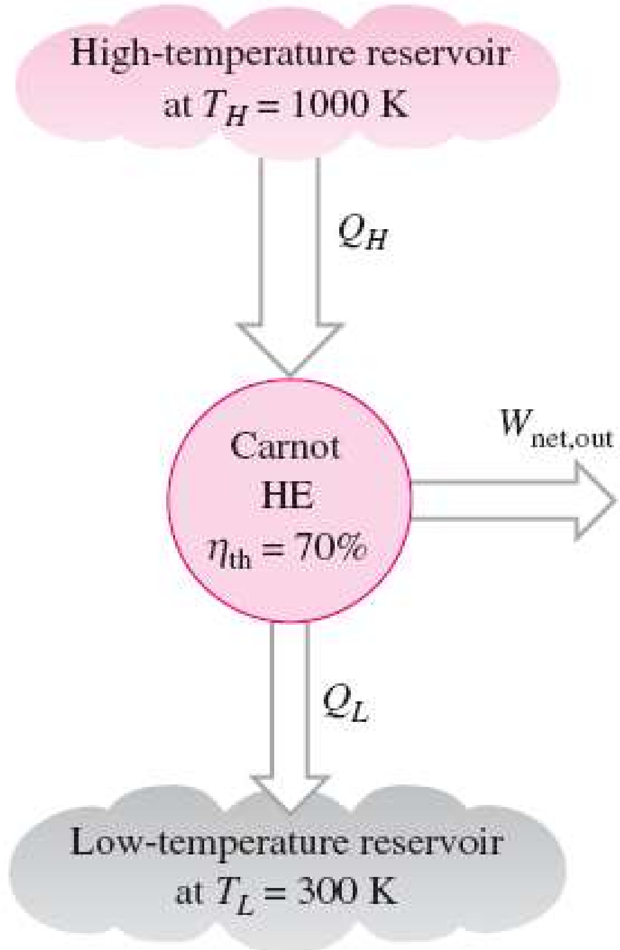
This is the highest efficiency a heat engine operating between the two thermal energy reservoirs at temperatures T_L *and* T_H *can have.*



THE CARNOT HEAT ENGINE

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

The Carnot heat engine is the most efficient of all heat engines operating between the same high- and low-temperature reservoirs.



References

1. *Rao, Y.V.C., Thermodynamics, Universities Press (2004).*
2. *Smith J. M. and Van Ness H. C., Chemical Engineering Thermodynamics, Tata McGraw-Hill (2007).*
3. *Nag, P.K., Engineering Thermodynamics, Tata McGraw Hill (2008) 3rd ed.*
4. *Cengel, Y. A. and Boles, M., Thermodynamics: An Engineeing Approach, Tata McGraw Hill (2008).*

Special Thanks to Professor D. Gangacharyulu.

Thank you for your Patience