THE SECOND LAW OF THERMODYNAMICS

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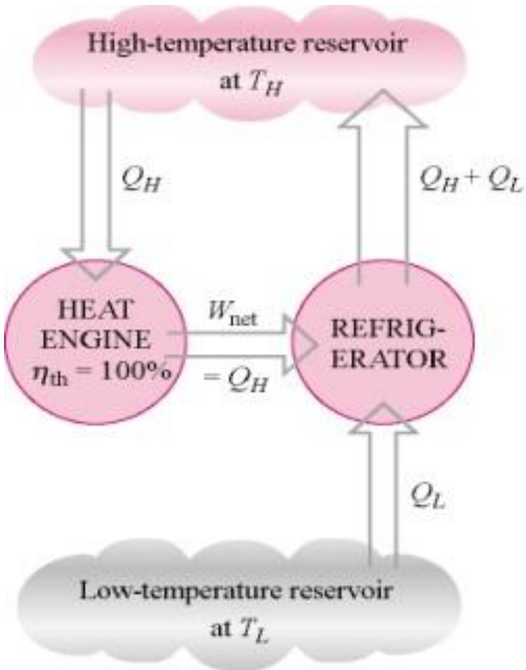
Reviewed

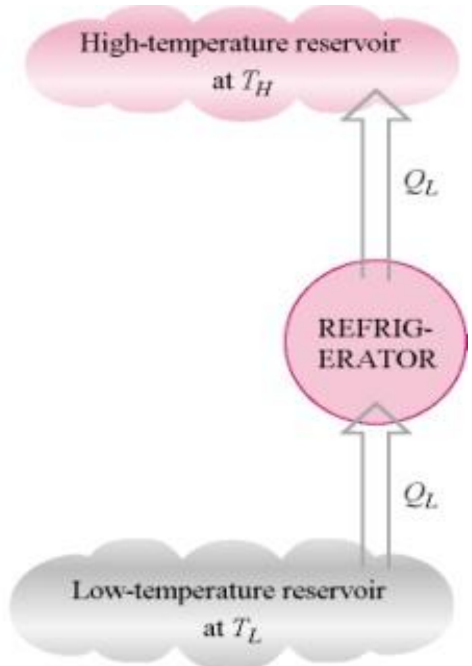
- *Heat Reservoirs*
- *Heat Engine*
- *Efficiency*
- *Refrigerator and Heat pump*
- *Coefficient of Performance*
- *Second law of thermodynamics*
    - *Kelvin-Plank Statement*
    - *Clausius Statement*
- *Equivalence of Statements*
- *Factors that Render Processes irreversible*

THE SECOND LAW OF THERMODYNAMICS

The combination of the heat engine and refrigerator in the left figure acts like a heat pump that transfers heat *QL* from the low-temperature reservoir without any external energy input. This is a violation of the Clausius statement of the second law.

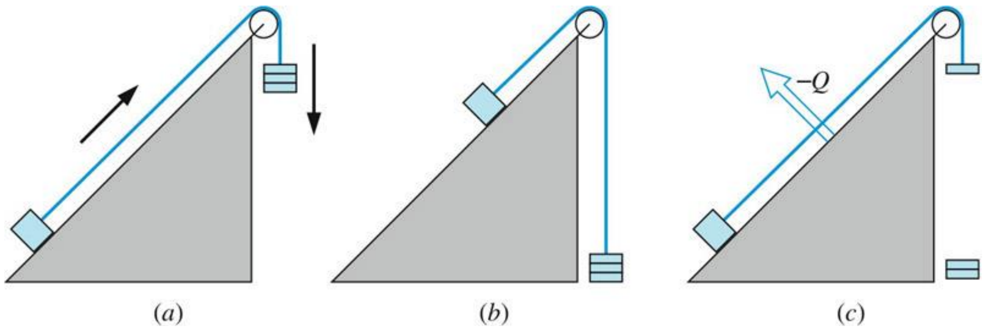


(*a*) A refrigerator which is powered by a 100% efficient heat engine

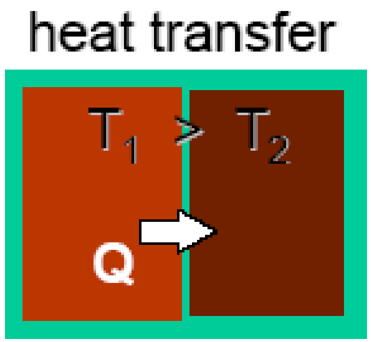


(*b*) The equivalent refrigerator

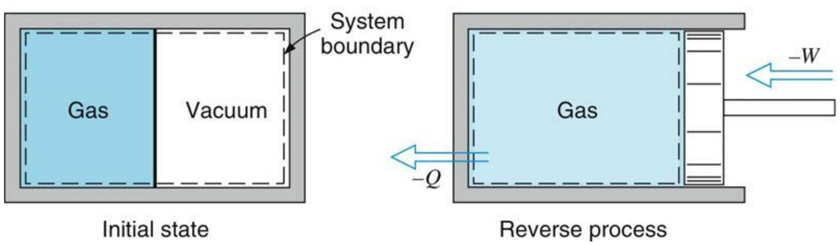
Factors that Render Processes irreversible



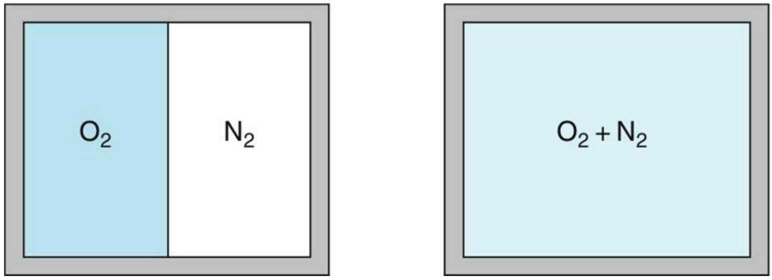
Friction



Heat Transfer through finite temperature difference



Unrestrained expansion



Mixing of two different substances

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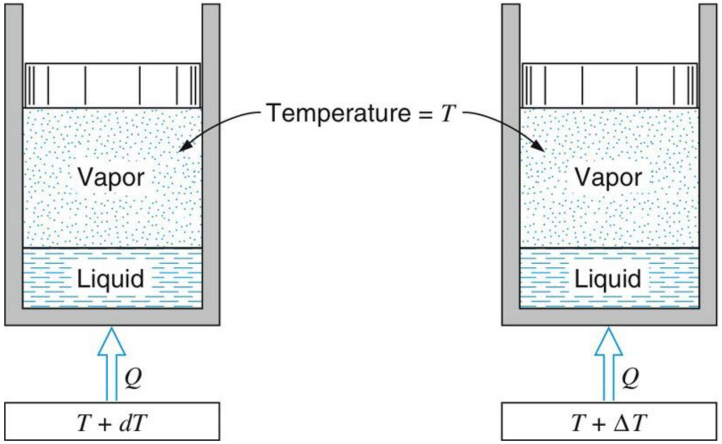
Reversible Processes

A reversible process is a quasi-equilibrium, or quasi-static, process with a more restrictive requirement.

Internally reversible process

The internally reversible process is a quasi-equilibrium process, which, once having taken place, can be reversed and in so doing leave no change in the system.

This says nothing about what happens to the surroundings about the system.



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Totally or externally reversible process

The externally reversible process is a quasi-equilibrium process, which, once having taken place, can be reversed and in so doing leave no change in the system or surroundings.

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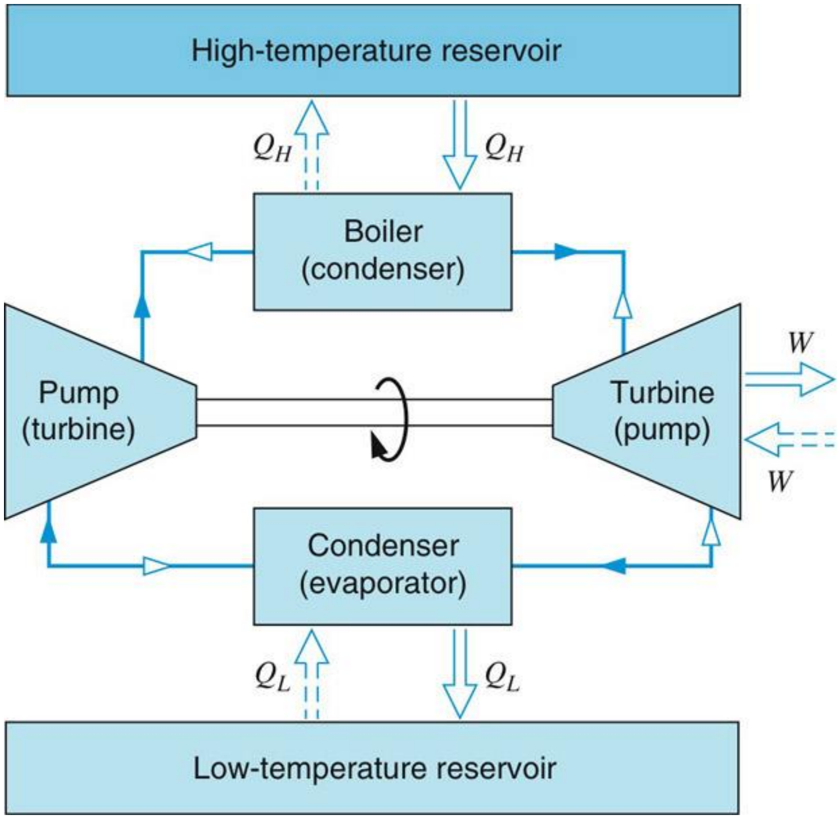
The Carnot Cycle

Carnot was the first to introduce the concept of cyclic operation and devised a reversible cycle that is composed of four reversible processes, two isothermal and two adiabatic processes.



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Process 1-2: Reversible isothermal heat addition at high temperature, $T_H > T_L$, to the working fluid in a piston/cylinder device that does boundary work.

Process 2-3: Reversible adiabatic expansion during which the system does work as the working fluid temperature decreases from T_H to T_L.

Process 3-4: The system is brought in contact with a heat reservoir at $T_L < T_H$ and a reversible isothermal heat exchange takes place while work of compression is done on the system.

Process 4-1: A reversible adiabatic compression process increases the working fluid temperature from T_L to T_H

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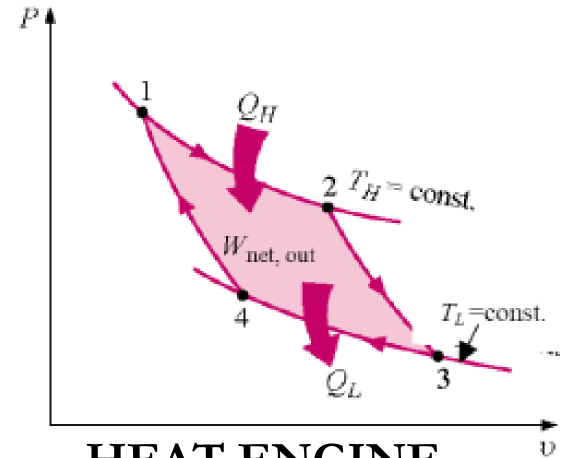
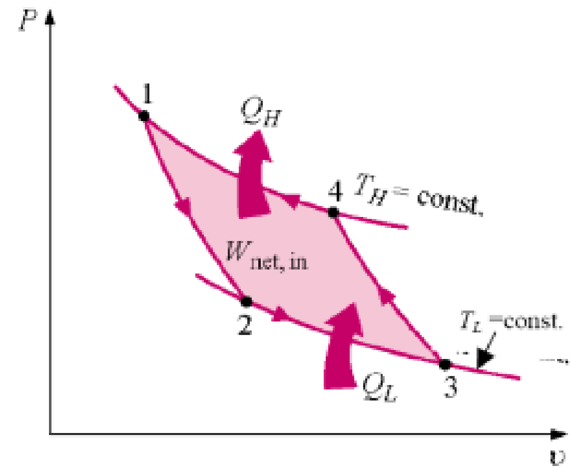
You may have observed that power cycles operate in the clockwise direction when plotted on a process diagram. The Carnot cycle may be reversed, in which it operates as a refrigerator. The refrigeration cycle operates in the counterclockwise direction.



HEAT ENGINE



REFRIGERATION (REVERSE CARNOT CYCLE)

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Two propositions regarding the efficiency of a Carnot Cycle:

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 heat reservoir, and a refrigerator cannot operate without net work input from an external source.

Consider heat engines operating between two fixed temperature reservoirs at $T_H > T_L$. We draw two conclusions about the thermal efficiency of reversible and irreversible heat engines, known as the Propositions

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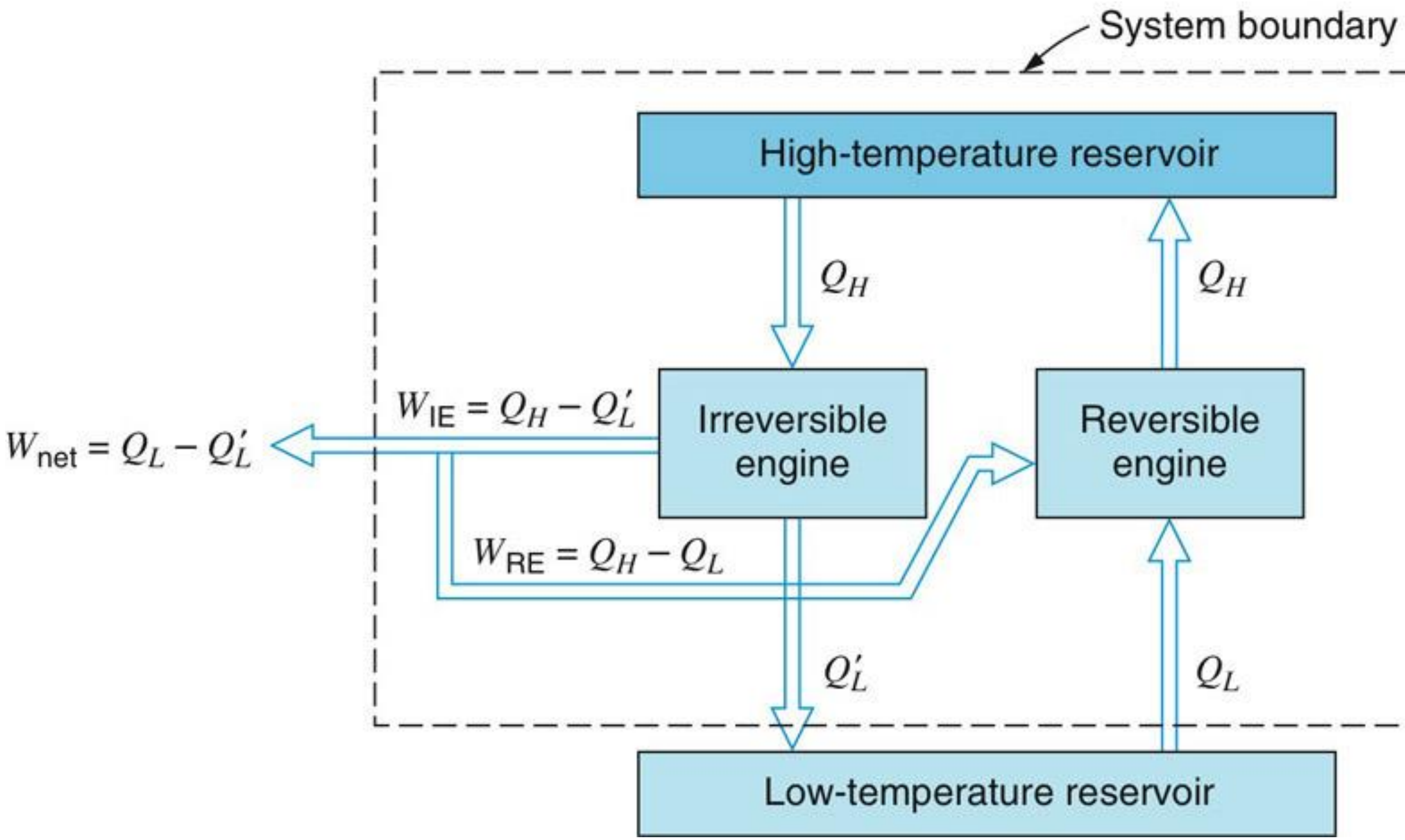
First proposition

The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.

$$\eta_{th} < \eta_{th,Carnot}$$



System boundary
High-temperature reservoir
Q_H
Q_H
$W_{IE} = Q_H - Q_L'$
$W_{net} = Q_L - Q_L'$
Irreversible engine
Reversible engine
$W_{RE} = Q_H - Q_L$
Q_L'
Q_L
Low-temperature reservoir

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Second Proposition:

The efficiencies of all reversible heat engines operating between the same two constant-temperature heat reservoirs have the same efficiency.

As the result of the above, Lord Kelvin in 1848 used energy as a thermodynamic property to define temperature and devised a temperature scale that is independent of the thermodynamic substance.

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The Thermodynamic Temperature Scale

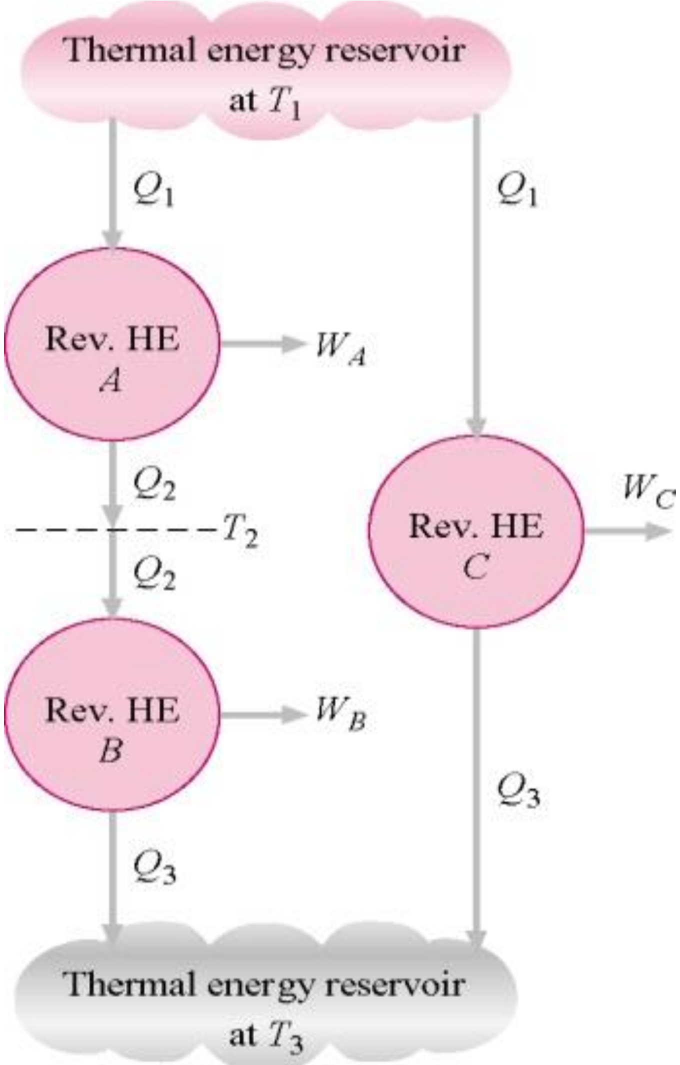
The following is Lord Kelvin's

Carnot heat engine arrangement.

Since the thermal efficiency in general is

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

$$\eta_{th} = 1 - \psi(T_L, T_H)$$



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Considering engines A, B, and C

$$\frac{Q_1}{Q_2} = \psi(T_1, T_2)$$

$$\frac{Q_2}{Q_3} = \psi(T_2, T_3)$$

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

Since

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

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This looks like

$$\psi\left(T_1,T_3\right)=\psi\left(T_1,T_2\right)\cdot\psi\left(T_2,T_3\right)$$

The left side is the function of T_1 and T_3 and therefore the right side of this equation must be a function of T_1 and T_3. From this fact we can conclude that the form of the function ψ must be such that

$$\psi(T_1,T_2)=\frac{f(T_1)}{f(T_2)} \qquad \psi(T_2,T_3)=\frac{f(T_2)}{f(T_3)}$$

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in this way $f(T_2)$ will cancel from the product of $\psi(T_1,T_2)$ X $\psi(T_2, T_3)$. Therefore we conclude that

$$\frac{Q_1}{Q_3} = \psi(T_1, T_3) = \frac{f(T_1)}{f(T_3)}$$

In general terms

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

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

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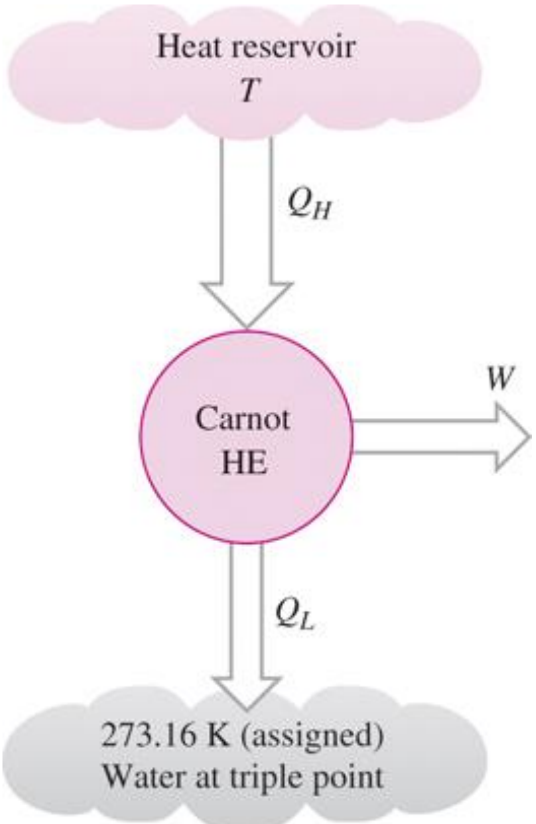
The Carnot thermal efficiency becomes

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

This means that if the thermal efficiency of a Carnot cycle operating between two given constant temperature reservoirs is known, the ratio of the two absolute temperatures is also known.

- The temperature scale is called the Kelvin scale.
- The temperature on this scale is called absolute temperature.
- A temperature scale that is independent of the properties of the substances that are used to measure temperature is called a thermodynamic temperature scale.



$$T = 273.16\,\frac{Q_H}{Q_L}$$

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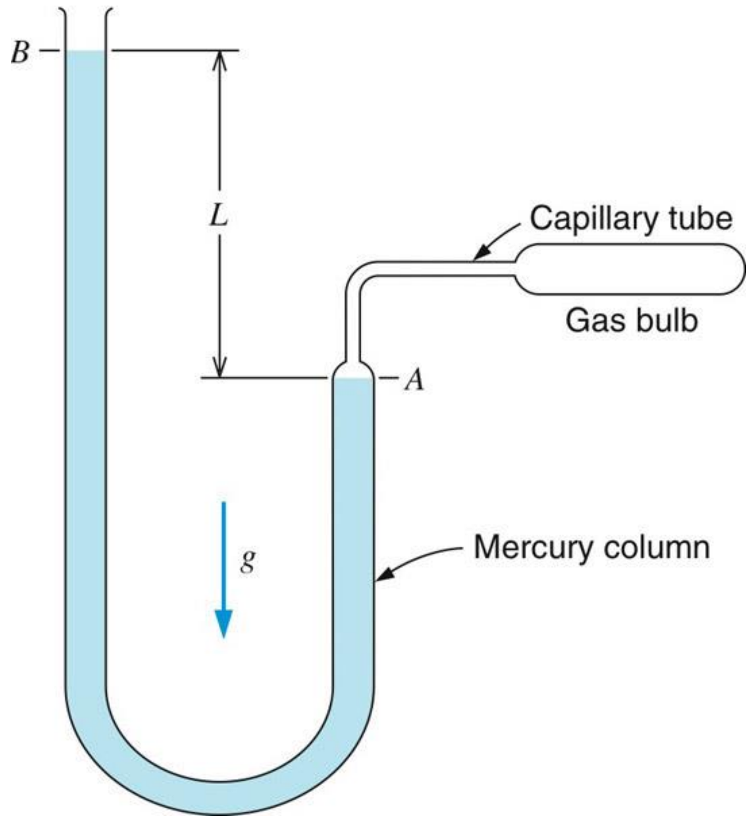
Constant volume gas thermometer



$$T = 273.16\left(\frac{P}{P_{t.p.}}\right)$$

Ideal vs Real machines

$$Heat\ Engine\ \eta_{real\ thermal} = 1 - \frac{Q_L}{Q_H} \leq 1 - \frac{T_L}{T_H}$$

$$\text{Re}\ frigerator\ \beta_{real} = \frac{Q_L}{Q_H - Q_L} \leq \frac{T_L}{T_H - T_L}$$

$$Heat\ Pump\ \beta'_{real} = \frac{Q_H}{Q_H - Q_L} \leq \frac{T_H}{T_H - T_L}$$

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Example

A Carnot heat engine receives 500 kJ of heat per cycle from a high-temperature heat reservoir at 652^{o}C and rejects heat to a low-temperature heat reservoir at 30^{o}C. Determine

(a) The thermal efficiency of this Carnot engine.

(b) The amount of heat rejected to the low-temperature heat reservoir.

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Example

An inventor claims to have invented a heat engine that develops a thermal efficiency of 80 percent when operating between two heat reservoirs at 1000 K and 300 K. Evaluate his claim.

Example:

A dwelling requires 633 MJ per day to maintain its temperature at 21°C when the outside temperature is 0°C. A) if an electric heat pump is used to supply this energy, determined the minimum theoretical work input for one day operation in kJ/day. B) Evaluating electricity at Rs. 8/kW.h, determine the minimum theoretical cost to operate the heat pump, in Rs/day

Example:

A coal fired power plant has an efficiency of 35% and produces net 500 MW of electricity. Coal releases 25 000 kJ/kg as it burns so how much coal is used per hour?

Example:

A water cooler for drinking water should cool 25 L/h water from 18°C to 10°C using a small refrigeration unit with a COP of 2.5. Find the rate of cooling required and the power input to the unit.

Example:

A farmer runs a heat pump with a 2 kW motor. It should keep a chicken hatchery at 30°C, which loses energy at a rate of 10 kW to the colder ambient T_{amb}. What is the minimum coefficient of performance that will be acceptable for the heat pump?

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