University of Mosul

College of Science

Department of Physics

Second Stage

Heat and Thermodynamic

2024 – 2025

Lecture 12 : The Second Law & Carnot's reversible engine

Preparation

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Chapter sex

The Second Law

Physical description of the second law:

There are many physical phenomena that explain the basis of the second law in thermodynamics, and we mention them

1. Heat flow from one high temperature tank to another tank with a lower temperature than the first tank. Provided that no other changes occur in the surrounding environment, this means that the hot body cools with a lower temperature body and the opposite is not true.

2. Two gases mix uniformly automatically when placed in an isolated space, and they do not separate automatically after mixing.

3. The battery discharges through electrical resistance, and a certain amount of energy is released, and the opposite is not permissible.

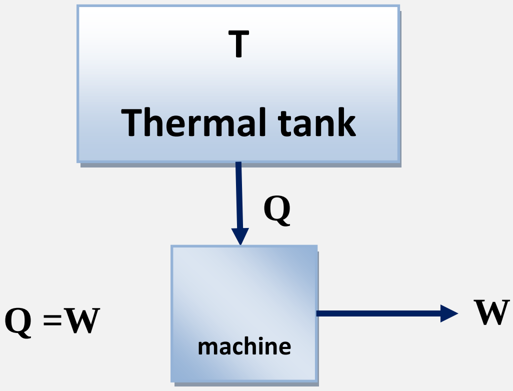
4. A heat machine cannot be designed to operate continuously and convert a quantity of heat from a heat tank to an equivalent amount of work.

5. The car discharges gasoline to ascend a certain height, and the petrol tank in it cannot recover the spent petrol when descending that high.

From the above points, we can conclude that natural phenomena are subject to a general law that determines the direction of their paths and does not allow their occurrence with opposite paths, and this is the second law in thermodynamics.

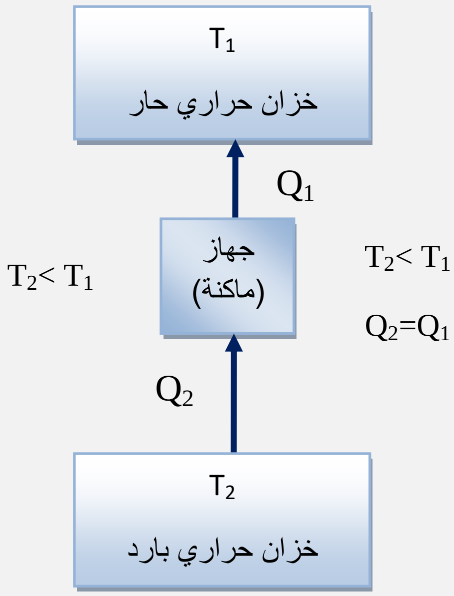
The second law has many formulas, the most important of which are the Kelvin-Planck formula and the Classius formula

1. **The Kelvin-Planck formula:** It is impossible to construct a practically complete cycle apparatus whose sole function is to produce work and exchange heat with one thermal tank (that is, to absorb a quantity of heat from one thermal tank and convert this heat into work.

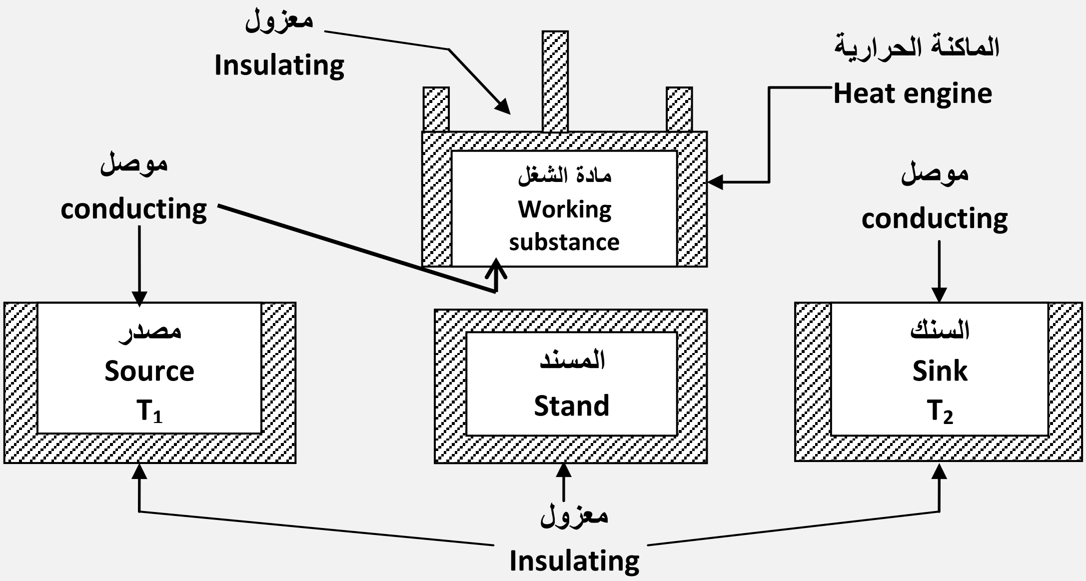


1. Reservoir: The term thermal reservoir is used to clarify the second law of thermodynamics, and it is defined as a device that has a large limited heat capacity and has the ability to absorb heat from the surrounding or subtract heat to the ocean in order to keep its temperature constant.

2. Classius formula: It is impossible to build a device that operates in a complete cycle. Its only function is to transfer heat from a cold object to a hot body.



Carnot's reversible engine



As it is known that thermal machines are used to convert thermal energy into mechanical work. In 1824, the French engineer Carnot was able to make improvements in the efficiency of the thermal machine.

Before starting to talk about improvements, We must get to know with the basics of the thermal machine, which are:

1. Source:

It is a device from which thermal energy can be obtained, whose wall is not good conductor of heat and its surface is a good conductor of heat, and one of its most important properties is that it has a high heat capacity and a constant temperature T_1.

2. Sink:

It is a device that can receive the amount of increase heat, whose wall is not good conductor of heat and its surface is a good conductor of heat, and one of its most important properties is that it has a high heat capacity and a constant temperature T_2.

3. Working substance: It is the substance in which heat is transferred to and from it, such as a gas or liquid.

4. The simple heat engine:

Which consists of a cylinder whose wall is not good conductor of heat and its bottom is a good conductor of heat and contains a piston that moves up and down without any friction and contains the work material.

5. Stand:

The stand is used in the adiabatic process and is thermally insulated, meaning it does not exchange heat.

Carnot's Cycle:

A popular thermodynamic cycle is a cycle Carnot, and depends in its work on the basis of a series of inverted operations that take place between two degrees of temperature.

In order to obtain a maximum working capacity T_1 and T_2, the cycle is assumed to take place with a cylinder containing ideal fluid, and control the cylinder with a movable piston without weight and friction.

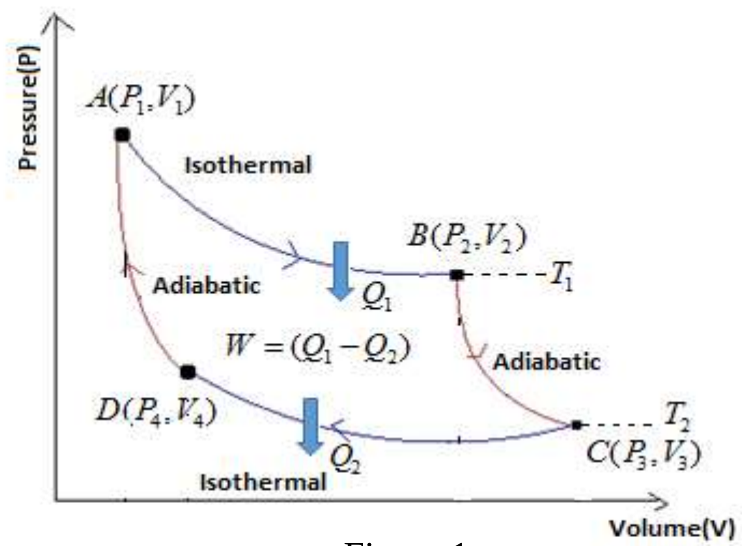


Figure 1

$A(P_1,V_1,T_1)$, $B(P_2,V_2,T_1)$,$C(P_3,V_3,T_2)$, $D(P_4,V_4,T_2)$

1. Place the machine containing the work material on the source with temperature T_1, meaning that the temperature of the work material is also T_1. Initially, the pressure and volume are P_1 and V_1 respectively. If we reduce the pressure, the volume will increase and as a result, the temperature will decrease and the pressure and volume will become P_2 and V_2 respectively, but since the machine has the ability to exchange heat from the source, it will acquire the amount of heat that it lost during expansion to remain at the same temperature as the source T_1, and accordingly it will Work is done in this process known as the isothermal process. So the curve AB in Fig. 1 shows the isothermal process (A → B the gas is expanding isothermally)

If we assume that the amount of heat that the machine absorbed from the source was Q_1 when it accomplished a work amounting to W_1, then the work should be:

$$\boldsymbol{W_1 = \int_{V_1}^{V_2} P.dV \quad , \qquad PV = RT \quad , \qquad P = \frac{RT}{V}}$$

$$\boldsymbol{W_1 = \int_{V_1}^{V_2} \frac{RT_1}{V}.dV = RT_1 \int_{V_1}^{V_2} \frac{dV}{V} \ldots..(1)}$$

$$\boldsymbol{\therefore W_1 = RT_1 \ln \frac{V_2}{V_1} \ldots.(2)}$$

2. Place the machine containing the work material on the stand. If we reduce the pressure again, the volume will increase and as a result the temperature will decrease to T_2 when the pressure and volume become P_3 and V_3 respectively, but since the pad is thermally insulated, it will not exchange heat with the machine and the degree will remain Heat at T_2,

Accordingly, work will be performed in this adiabatic process shown in the curve BC in Fig. 1 at the expense of the internal energy (B → C the gas is expanding adiabatically)

That is, the gas expands drastically or adiabatically , where its internal energy decreases, its temperature decreases from ($T = T_1$) to T_2, and the gas performs work on the surrounding atmosphere

So the work done from B to C is.

$$\mathbf{W_2 = \int_{V_2}^{V_3} P.dV\,,}$$

$$\mathbf{PV^{\gamma}\,(Adaibatic\ process) = constant = c\ \ ,P = \frac{c}{V^{\gamma}}}$$

$$\mathbf{W_2 = \int_{V_2}^{V_3} \frac{C}{V^{\gamma}}.dV = \ C\int_{V_2}^{V_3} \frac{dV}{V^{\gamma}} = C\int_{V_2}^{V_3} V^{-\gamma}dV \ldots\ldots(3)}$$

$$\mathbf{W_2 = \frac{\mathit{C}}{1-\gamma}[\mathit{V}^{-\gamma+1}]_{V_2}^{V_3} \ = \frac{1}{1-\gamma}\mathit{C}\,[\mathit{V}^{1-\gamma}]_{V_2}^{V_3} \ldots\ldots\ldots(4)}$$

For the upper limit we substitute for C

$$\mathbf{C = P_3V_3^{\gamma}}$$

For the lower limit we substitute for C

$$\mathbf{C = P_2V_2^{\gamma}}$$

$$\mathbf{\therefore W_2 = \frac{1}{1-\gamma}\ [P_3V_3^{\gamma}.\mathit{V}_3^{1-\gamma} - P_2V_2^{\gamma}.\mathit{V}_2^{1-\gamma}] \ldots\ldots\ldots(5)}$$

OR

$$\mathbf{W_2 \ = \frac{1}{1-\gamma}\ [P_3\mathit{V}_3 - P_2V_2] \ldots\ldots\ldots(6)}$$

Equation of ideal gas for one mole (PV=RT)

$$\mathbf{W_2 = \frac{\mathit{R}}{1-\gamma}\ [\mathit{T}_3 - T_2]}$$

$$W_2 = \frac{R}{1-\gamma}\ [T_2 - T_1]\,, \qquad T_1 > T_2$$

$$W_2 = \frac{R}{\gamma - 1}\ [T_1 - T_2] \ldots\ldots\ldots\ldots (7)$$

3. Place the machine containing the work material over the spine with a temperature of T_2, increase the pressure, the volume will decrease from V_3 to V_4 and as a result, the temperature will increase, but what happens is that the temperature resulting from the process of increasing the pressure from P_3 to P_4 will be thrown into the sink. To keep the initial temperature, T_2. This process is isothermal and as shown by curve CD in Fig. 1, (C → D gas compresses isothermally).

If we assume that the amount of heat Q_2 that flows from the gas to the thermal tank at a temperature of T_2, a work of W_3 is performed on the gas

$$W_3 = \int_{V_3}^{V_4} P.\,dV \quad , \qquad PV = RT_2 \quad , \qquad P = \frac{RT_2}{V}$$

$$W_3 = RT_2 \int_{V_3}^{V_4} \frac{dV}{V} = RT_2\,[\ln V]_{V_3}^{V_4} \ldots\ldots\ldots\ldots\ldots (8)$$

$V_3 > V_4$

$$\therefore W_3 = -\,RT_2 \ln\frac{V_3}{V_4} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

A negative sign means that the work was performed on the work material (system).

4. Place the machine on the stand again. If we increase the pressure, the volume will decrease from V_4 to V_1. As a result, the temperature will increase to T_1, but there will be no heat exchange with the stand and thus the process will be

adiabatic. And here we get to point A and we've done a full turn, (D → A the gas compressed adiabatically)

That is, the gas is drastically compressed or adiabatically, as its internal energy increases, its temperature rises from T_2 to T_1, and it performs a work of W4 on the gas.

So the work done from D to A is

$$\mathbf{W_4 = \int_{V_4}^{V_1} P.dV = -\int_{V_4}^{V_1} \frac{C}{V^{\gamma}}.dV}$$

$$\mathbf{W_4 = \frac{1}{1-\gamma}\ [P_1 V_1 - P_4 V_4] \dots\dots\dots (10)}$$

$$\mathbf{W_4 = -\frac{R}{\gamma-1}\ [T_1 - T_2] \dots\dots\dots\dots (11), \qquad T_1 > T_2}$$

Notice the negative sign again.

The net work performed during the cyclical process is:

$W=W_1+W_2+W_3+W_4$……………..(12)

$$\mathbf{w = RT_1 \ln\frac{V_2}{V_1} + \frac{R}{\gamma-1}[T_1 - T_2] - RT_2 \ln\frac{V_3}{V_4} - \frac{R}{\gamma-1}[T_1 - T_2]}$$

$$\mathbf{W = RT_1 \ln\frac{V_2}{V_1} + \frac{R}{\gamma-1}[T_1 - T_2] - RT_2 \ln\frac{V_3}{V_4} - \frac{R}{\gamma-1}[T_1 - T_2] \dots (13)}$$

$$\mathbf{W = RT_1 \ln\frac{V_2}{V_1} - RT_2 \ln\frac{V_3}{V_4} \dots\dots\dots\dots\dots\dots (14)}$$

As for the net amount of heat during the cyclic process:

$Q=Q_1-Q_2$…………………….(15)

The Carnot cycle consists of four processes that are reversible:

1. Isothermal reversibility.

2. Adiabatic reversal (work done by the system).

3. Isothermal reversibility.

4. Adiabatic reversal (work done on the system).

The above can be generalized to say: Any cyclic process defined by two isothermal and two regulatory transitions completes the Carnot cycle.

Efficiency of the machine

To finding the efficiency of the machine, **,** we have

- Points A and D lie on the same adiabatic curve (AD), and accordingly

$$\mathbf{T_1 V_1^{\gamma-1} = T_2 V_4^{\gamma-1}}$$

$$\mathbf{\frac{T_2}{T_1} = \left(\frac{V_1}{V_4}\right)^{\gamma-1} \quad \dots \dots \dots \dots \dots (16)}$$

- Likewise, the two points C and B lie on the same adiabatic curve (BC) ,

$$\mathbf{\frac{T_2}{T_1} = \left(\frac{V_2}{V_3}\right)^{\gamma-1} \quad \dots \dots \dots \dots \dots (17)}$$

From Equations 16 and 17 we get

$$\mathbf{\left(\frac{V_1}{V_4}\right)^{\gamma-1} = \left(\frac{V_2}{V_3}\right)^{\gamma-1}}$$

$$\mathbf{\frac{V_1}{V_4} = \frac{V_2}{V_3}}$$

OR

$$\frac{V_2}{V_1} = \frac{V_3}{V_4} \ldots\ldots\ldots\ldots\ldots\ldots (18)$$

Substituting 18 into equation 14, we get

$$W = RT_1 \ln\frac{V_2}{V_1} - RT_2 \ln\frac{V_2}{V_1}$$

$$W = R\ln\frac{V_2}{V_1}[T_1 - T_2] \ldots\ldots\ldots\ldots\ldots. (19)$$

As efficiency is equal

$$\eta = \frac{W(\text{الطاقة المطلوبة})}{Q_H(\text{الطاقة المكلفة})} = \frac{\text{out put energy}}{\text{input energy}}$$

The power supplied from the source is only from A to B which is also equal to the work

$$Q_1 = RT_1 \ln\frac{V_2}{V_1} \ldots\ldots\ldots\ldots (20)$$

Then the efficiency will be

$$\eta = \frac{R\ln\frac{V_2}{V_1}[T_1 - T_2]}{RT_1 \ln\frac{V_2}{V_1}} = \frac{T_1 - T_2}{T_1}$$

$$\eta = 1 - \frac{T_2}{T_1} \ldots\ldots\ldots\ldots\ldots\ldots. (21)$$

$$\eta = 1 - \frac{Q_2}{Q_1} \ldots\ldots\ldots\ldots\ldots\ldots. (22)$$

From equations 21 and 22 we find

$$\frac{T_2}{T_1} = \frac{Q_2}{Q_1}$$

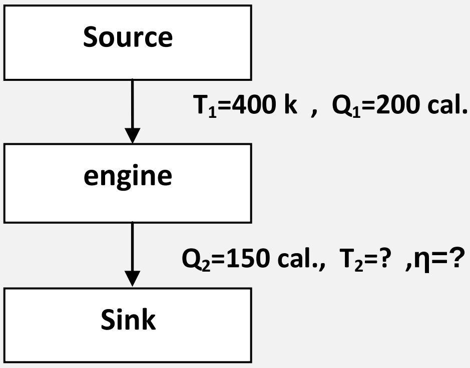
$$OR \quad \frac{T_1}{T_2} = \frac{Q_1}{Q_2}$$

This does not mean that T_1 and Q_1 are equal or T_2 and Q_2 are equal, but only the proportions are equal

Which

$\mathbf{T_1 \neq Q_1}$ **,** $\mathbf{T_2 \neq Q_2}$

Example : *A Carnot machine temperature 400K source takes 200 cal. Of thermal energy at this temperature and subtracted 150cal. To the sink. 1. What is the temperature value of the sink? 2. Calculate the efficiency of the machine*



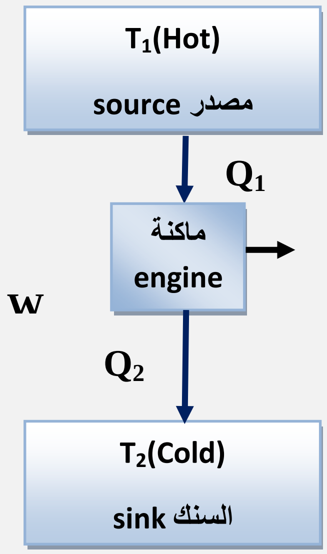
$$\frac{Q_1}{T_1} = \frac{Q_2}{T_2}$$

$$T_2 = T_1 \frac{Q_2}{Q_1} = 400 \times \frac{500}{200}$$

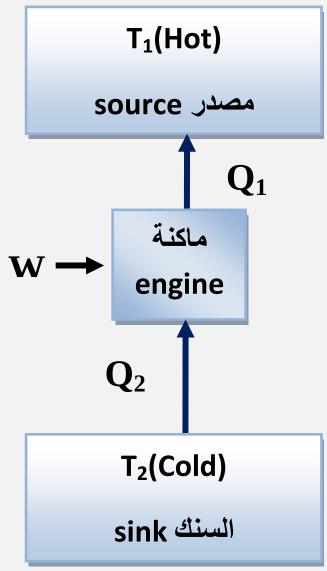
T_2= 300K

$$\eta = 1 - \frac{T_2}{T_1} = 1 - \frac{300}{400} = 0.25 \times 100 = 25\%$$

Refrigerator



ماكنة حرارية
Heat engine



Refrigerator الثلاجة

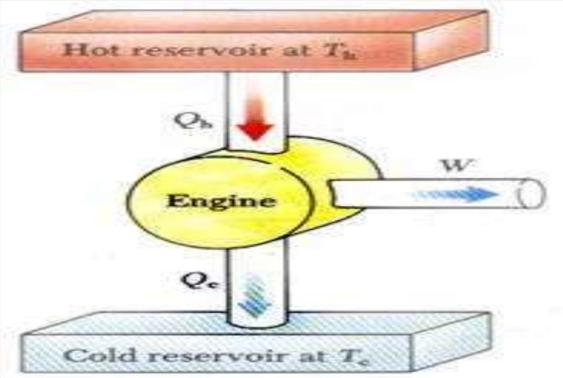
The Carnot machine is a reverse machine, that is, it has the ability to work in opposite directions, thus it can be used as a thermal machine, when it absorbs a quantity of heat Q_1 from the source whose temperature is T_1 and uses an amount of energy Q_1 to accomplish a certain amount of work W and then subtracts the amount of remaining energy Q_2 to the pin The installed Sink has a temperature of T_2.

But if the Carnot machine works as a refrigerator, it absorbs a quantity of heat Q_2 from the sink with a temperature of T_2, and thus it uses a portion of this energy to accomplish the work W and subtracts the amount of energy Q_1 to the source whose temperature is T_1, as shown in the figure above.

In the second case (like a refrigerator), we see that the heat flows from the body that is at a low temperature to the body that has a high temperature, with the help of external work done (external work done) on the work material, and this cannot be done unless the cycle is reversible.

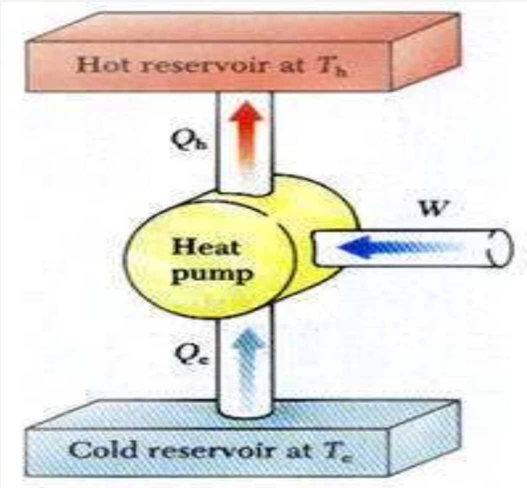
Refrigerators

Through previous lectures in which we explained the idea of the Heat Engine, we find that the engine is a machine that converts thermal energy into mechanical energy through a system that is taken in a cycle of thermodynamic processes so that it absorbs heat from the hot warehouse and expels heat to the cold warehouse and the system makes work On the surrounding . The figure below shows the idea of the thermal engine working and the arrows show the heat transfer and work done by the system.



Heat engine

As for the idea of a refrigerator, it is the opposite of the idea of a thermal engine, where the refrigerator uses the external work that is exerted on the system so that the system, through a thermodynamic cycle, absorbs heat from the cold store and losses heat to the hot reservoir . Thus, the refrigerator cools the hot reservoir by absorbing heat from it, which is the part inside the home refrigerator.



Coefficient of performance

Since the refrigerator cycle is the opposite of the thermal machine cycle, the efficiency of the refrigerator cannot be calculated. Therefore, we will define a new physical quantity, which is the achievement factor.

The performance factor is defined as the ratio between the amount of heat Q_2 to the required energy W, i.e. that

$$E_C = \frac{\text{heat of absorbed from cold reservior}}{\text{work done on refrigerater}}$$

$$\text{Coefficient of performance} = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2} \ldots\ldots\ldots\ldots..(1)$$

Example: *If we assume that a machine absorbed energy up to 200 joules from a thermal tank at a low temperature and prepared the work material with additional external work within the limits of 100 joules, then the total energy presented to the thermal tank whose temperature is higher than the first thermal tank is around 300 joules*

200 + 100 = 300 joules.

So here is the performance parameter

$$\text{Coefficient of performance} = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2} = \frac{200}{300 - 200} = 2$$

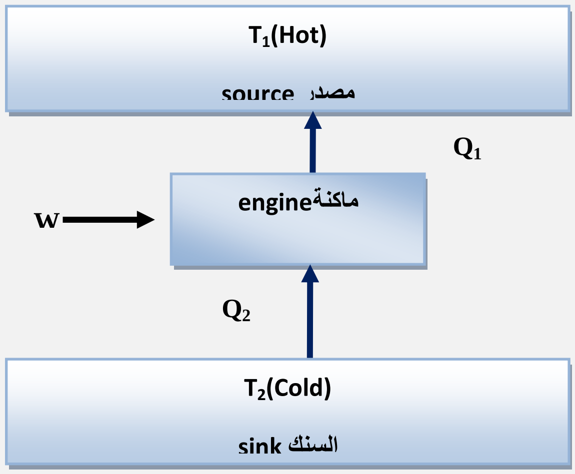
Example: *A freezer working between a temperature of 0C° and a temperature of 27 C°, so if a quantity of water with a mass of 3 Kgm and a temperature of 32 C° is placed in the freezer in order to turn into 0C° ice, then if you know that the working material of the freezer is rotated by an electric motor with a capacity of 750 Watt Its efficiency is 85%*

1. How many calories do the freezer throw to the perimeter of the room?

2. Calculate the work performed by the frozen?

3. Calculate the value of the frozen performance factor?

4. Calculate the time required to freeze the water .



Refrigerator الثلاجة

Answer 1. The latent heat of melting ice L = 80Cal/ gm

$$Q_2 = Q'_2(32 \rightarrow 0) + Q''_2(0 \rightarrow 0\text{ice})$$

Quantity of heat = mass x specific heat x temperature difference

Q_2= 3 x 10^3 x 1 x (32-0)+ 3 x 10^3 x 80= 336 x 10^3Cal.

$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2}$$

$$Q_1 = Q_2 \times \frac{T_1}{T_2} = 336 \times 10^3 \frac{27 + 273}{0 + 273} = 369 \times 10^3 \text{Cal.}$$

$$E_C = \frac{Q_2}{Q_1 - Q_2} = \frac{336 \times 10^3}{(369 - 336) \times 10^3} = 10.18$$

$$W = Q_1 - Q_2 = (369 - 336) \times 10^3 = 33 \times 10^3$$

$$\mathbf{P = \frac{W}{t} \rightarrow t = \frac{W}{P} = \frac{33 \times 10^3 \times 4.2}{750 \times 0.85} = 44 \times 4.2\ Sec}$$