ENG 3165 LECTURE 4

THERMODYNAMICS COMPONENT

The Laws of Thermodynamics (Continued)

Introduction

- This Lecture is a conclusion on the “Laws of Thermodynamics” and the importance of the Second Law of Thermodynamics is elaborated as it provides context and direction to the First Law
- After completion of this Lecture students should be able to explain the related concepts of **Energy, Heat, Work, Entropy** and **Enthalpy** as defined in **Thermodynamics.**

SECOND LAW OF THERMODYNAMICS

- This A hot cup of coffee gets cooled off when exposed to the surrounding

Energy lost by coffee = Energy gained by surroundings

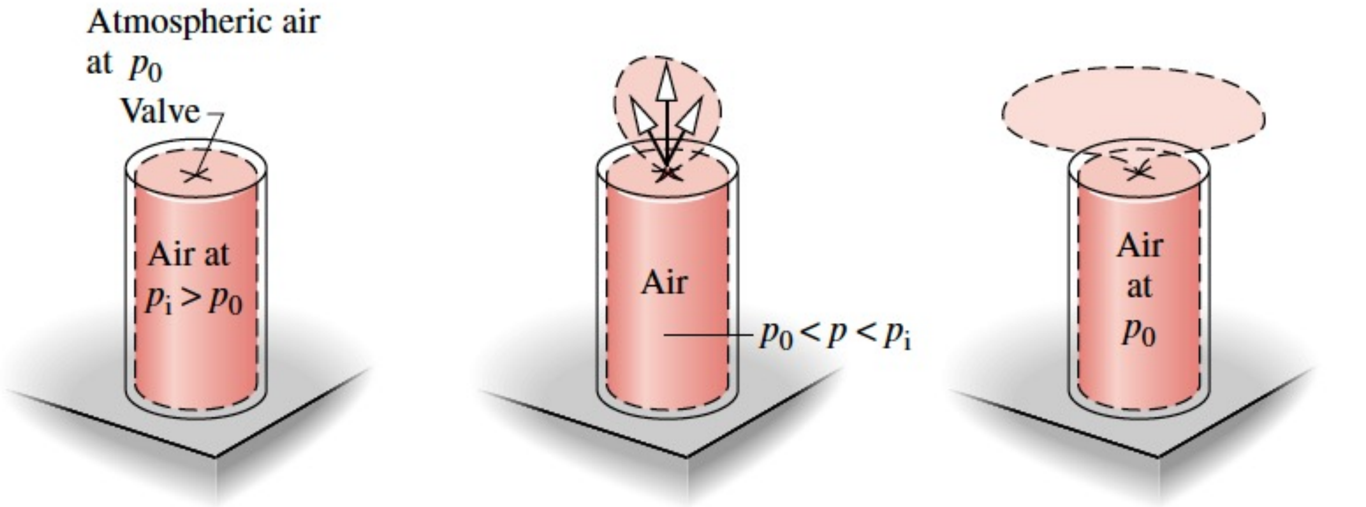
- In this case, the First Law of Thermodynamics has been fully satisfied!
- However, the converse is NOT true, i.e.

Taking out heat energy from surroundings ≠ Coffee getting hot

- But the First Law of Thermodynamics is satisfied!!

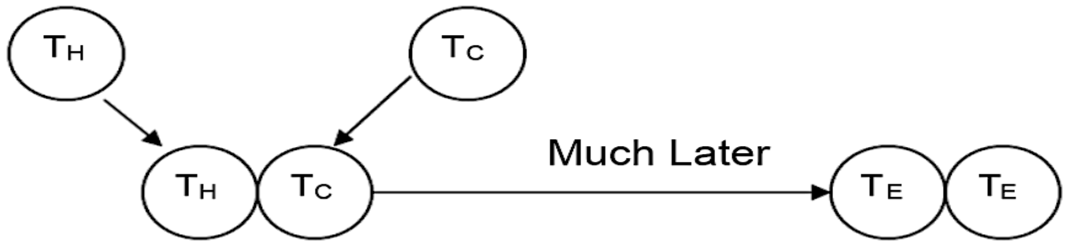
SECOND LAW OF THERMODYNAMICS

- It is a matter of everyday experience that there is a definite direction for spontaneous processes.
- Again consider the figure shown. Air held at a high pressure in a closed tank would flow spontaneously to the lower atmospheric pressure surroundings if the interconnecting valve were opened. Eventually fluid motions would cease and all of the air would be at the same pressure as the surroundings.
- It should be clear that the inverse process would not take place spontaneously, even though energy could be conserved: Air would not flow spontaneously from the surroundings at p_0 into the tank, returning the pressure to its initial value.
- **The initial condition can be restored, but not in a spontaneous process. An auxiliary device such as an air compressor would be required to return the air to the tank and restore the initial air pressure**

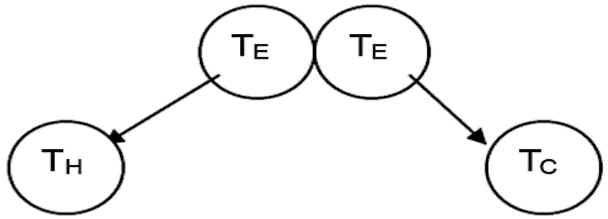


SECOND LAW OF THERMODYNAMICS

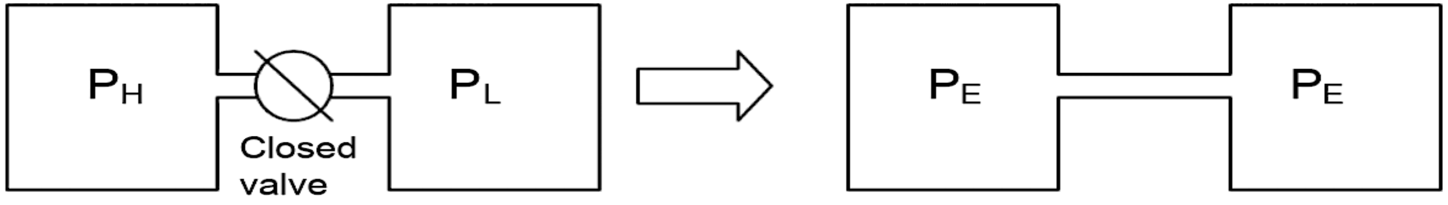
It is an observed fact that certain processes can only proceed spontaneously in one direction (hot coffee gets colder)



The following does not occur



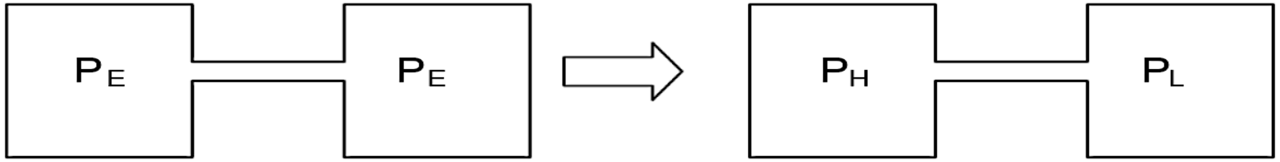
Another example, connecting high pressure tank with a low pressure tank:



where P_E is the final pressure

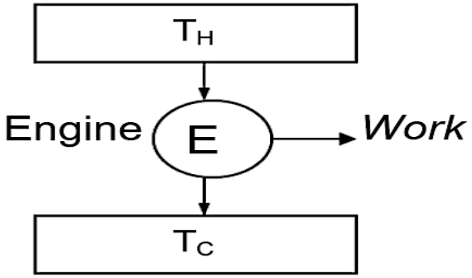
SECOND LAW OF THERMODYNAMICS

The following does not occur:



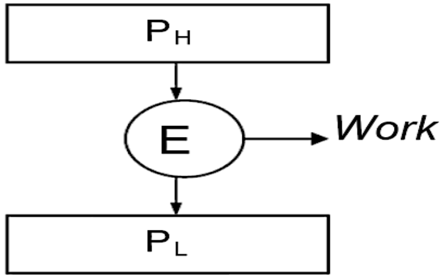
In both cases there is a possibility for doing work using an **engine**.

Example 1:



Such an engine can take heat from the hot body to form steam and then direct the steam through a turbine

Example 2:



Such an engine can direct the gas stream directly through a turbine

The question that arises is how much work can be done, i.e., what is the maximum work produced by the engine?

SECOND LAW OF THERMODYNAMICS - SIGNIFICANCE

- When left to themselves, systems tend to undergo spontaneous changes until a condition of equilibrium is achieved, both internally and with their surroundings. In some cases equilibrium is reached quickly, in others it is achieved slowly.
- For example, some chemical reactions reach equilibrium in fractions of seconds; an ice cube requires a few minutes to melt; and it may take years for an iron bar to rust away.
- Whether the process is rapid or slow, it must of course satisfy conservation of energy. However, this alone would be insufficient for determining the final equilibrium state. Another general principle is required.

This is provided by the second law.

SECOND LAW OF THERMODYNAMICS - SIGNIFICANCE

- By exploiting the spontaneous processes it is possible for work to be developed as equilibrium is attained: **Instead of permitting the air to expand aimlessly into the lower-pressure surroundings, the stream could be passed through a turbine and work could be developed.**

- Accordingly, in this case there is a possibility for developing work that would not be exploited in an uncontrolled expansion.

- Recognizing this possibility for work, we can pose two questions:

1. What is the theoretical maximum value for the work that could be obtained?

2. What are the factors that would ensure the realization of the maximum value?

SECOND LAW OF THERMODYNAMICS - SIGNIFICANCE

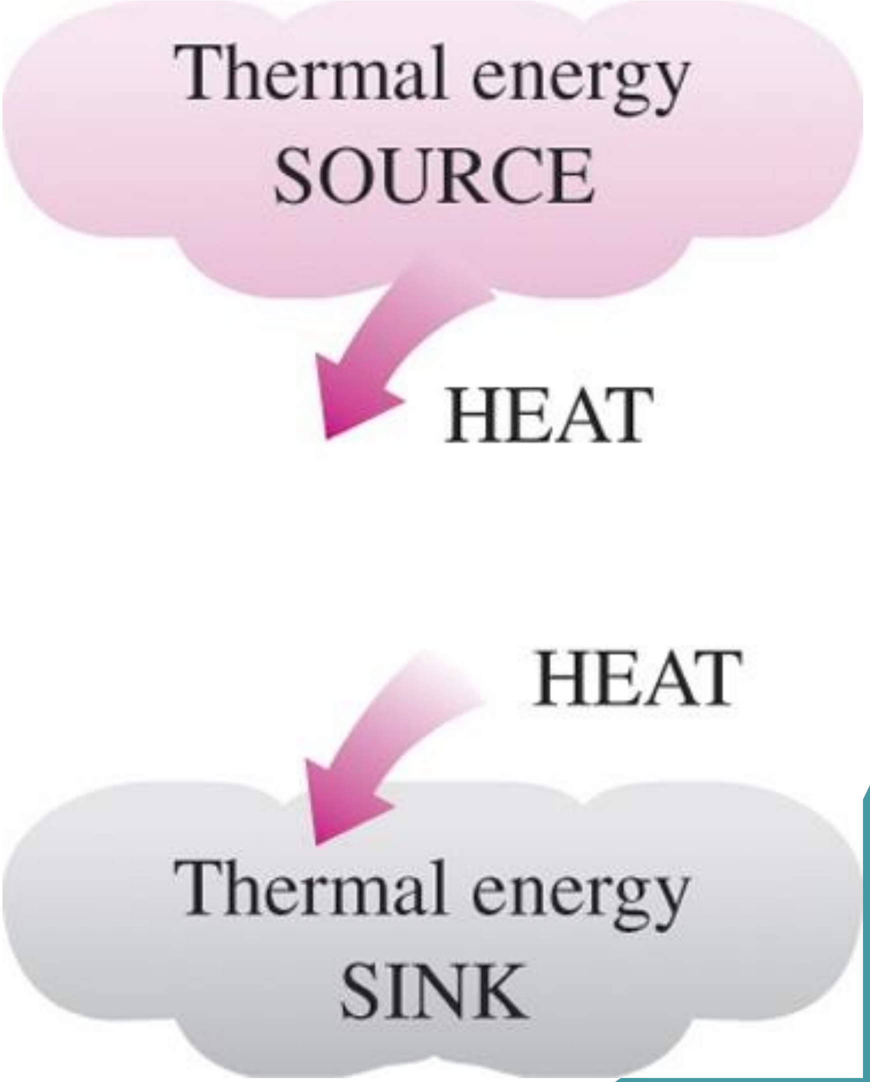
- The Second Law of Thermodynamics is not just limited to identify the direction of the process
- It also asserts that Energy has quantity as well **Quality.**
- It helps to determine the **Degree of Degradation** of energy during the process.
- It is also used to determine the **Theoretical Limits** for the performance of commonly used engineering systems such as Heat Engines and Refrigerators

SECOND LAW OF THERMODYNAMICS – THERMAL ENERGY RESERVOIR

- A **Thermal Energy Reservoir** is a hypothetical body with a relatively large **Thermal Energy Capacity** $(Mass \times Specific\ Heat)$ that can supply or absorb a finite amount of heat **without undergoing a change in temperature** e.g. ocean, lake, atmosphere, two-phase system, industrial furnace etc.

- A reservoir that supplies energy in the form of heat is known as a **SOURCE.**

- A reservoir that absorbs energy in the form of heat is known as a **SINK**.

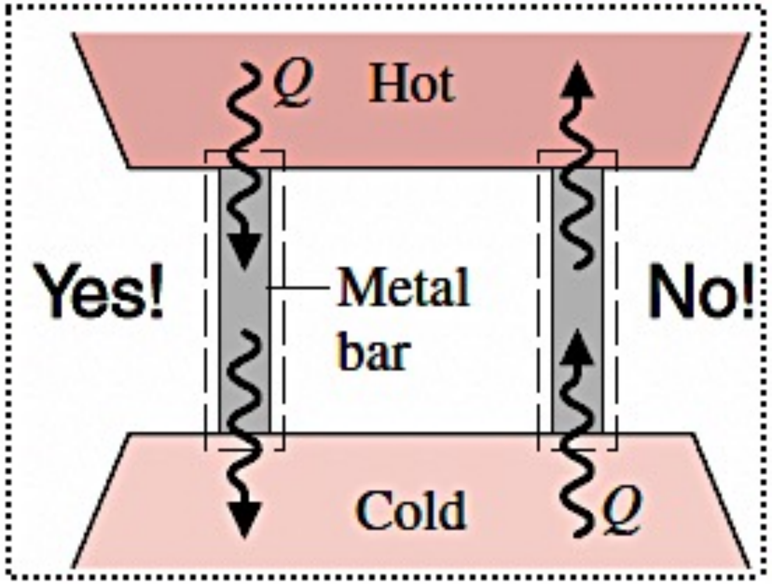


STATEMENTS OF THE SECOND LAW OF THERMODYNAMICS

- Among many alternative statements of the second law, two are frequently used in engineering thermodynamics.
- They are the **Clausius and Kelvin–Planck statements**. The objective of
- These two statements are **equivalent second law statements.**
- The equivalence of the Clausius and Kelvin–Planck statements can be demonstrated by showing that the violation of each statement implies the violation of the other.

CLAUSIUS STATEMENT OF THE SECOND LAW

- The Clausius statement of the second law asserts that: ***"It is impossible for any system to operate in such a way that the sole result would be an energy transfer by heat from a cooler to a hotter body."***
- The Clausius statement **does not** rule out the possibility of transferring energy by heat from a cooler body to a hotter body, for this is exactly what refrigerators and heat pumps accomplish.
- However, cooling of food is accomplished by refrigerators driven by electric motors requiring work from their surroundings to operate.
- The Clausius statement implies that it is impossible to construct a refrigeration cycle that operates **without an input of work.**

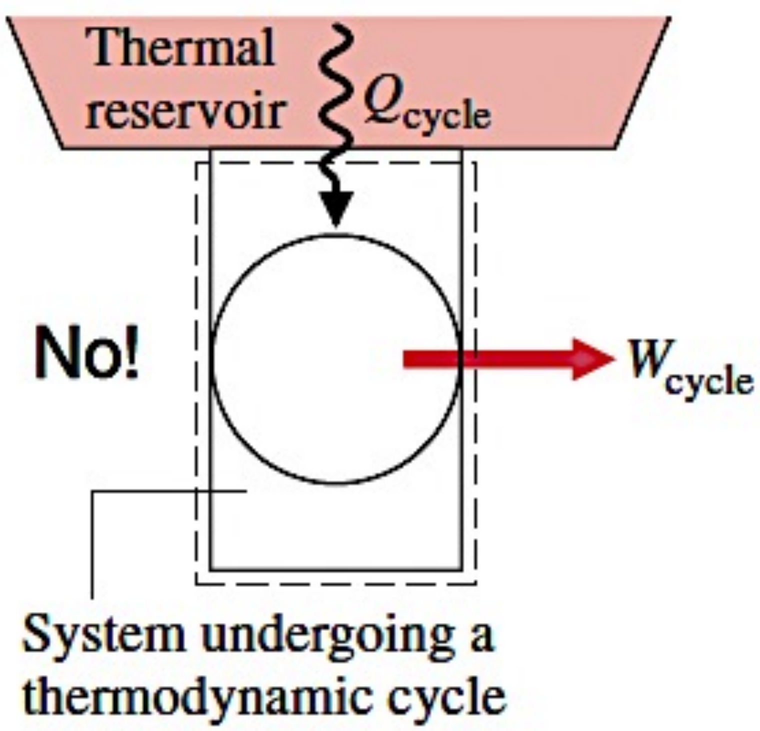


KELVIN-PLANCK STATEMENT OF THE SECOND LAW

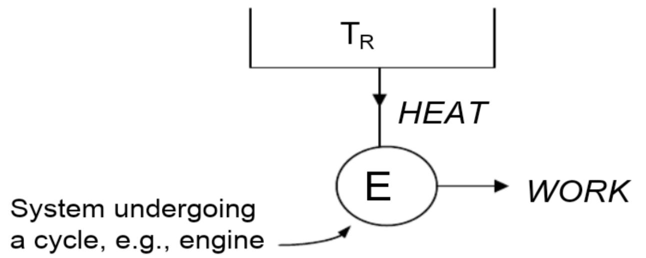
- The Kelvin–Planck statement of the second law: ***"It is impossible for any system to operate in a thermodynamic cycle and deliver a net amount of energy by work to its surroundings while receiving energy by heat transfer from a single thermal reservoir."***

- Second Law and Heat Engine: **It is impossible to extract an amount of heat from a hot reservoir and use it all to do work. Some amount of heat must be exhausted to a cold reservoir.**

- It means that the efficiency of a heat engine cycle is never 100%.



THE EVOLUTION OF THE SECOND LAW



NOT POSSIBLE according to K-P

The First Law of Thermodynamics is used to calculate end states of a system as it evolves, it does not answer the following questions:

1) In what direction does a spontaneous process go
2) What is the maximum possible work

The Second Law of Thermodynamics starts with a simple principal concerning the direction of heat flow and evolves into developing a new property called **entropy** (S)

<u>Clausius Statement</u>

It is *impossible* for a system to operate in such a way that the sole result is the transfer of heat from a cold to a hot body

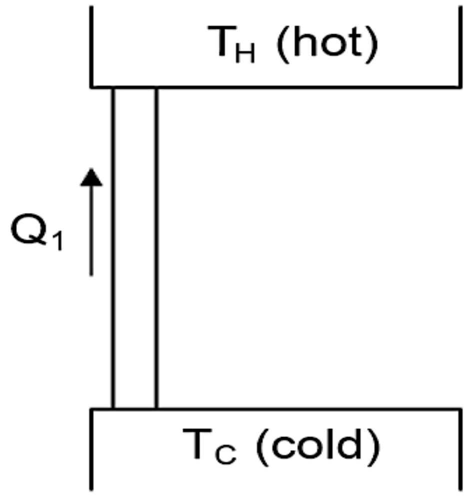
<u>Kelvin Planck Statement</u>

It is *impossible* for a system that operates in a cycle to generate work while transferring heat with a single **reservoir**

THE EVOLUTION OF THE SECOND LAW

Recall, a reservoir is a body that has so much thermal capacity that its temperature doesn't change when heat transfer occurs

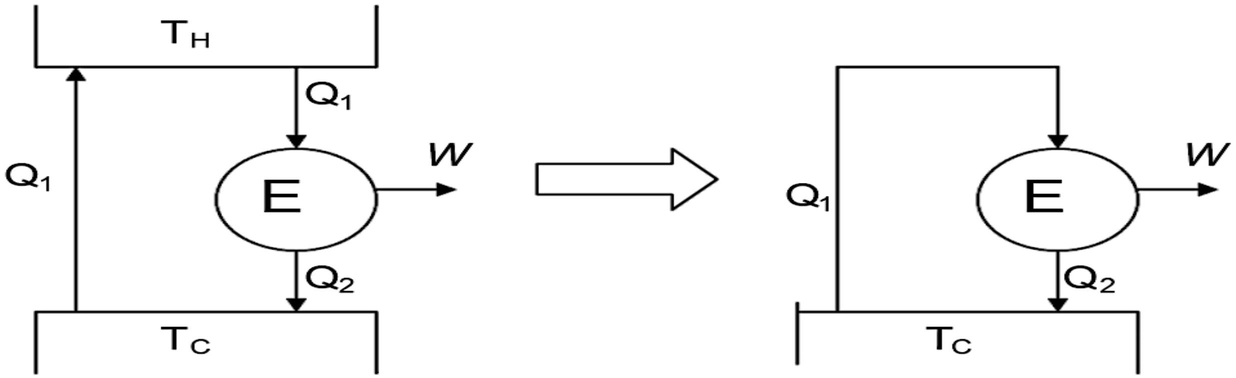
To illustrate the equivalence of the two statements consider the following:



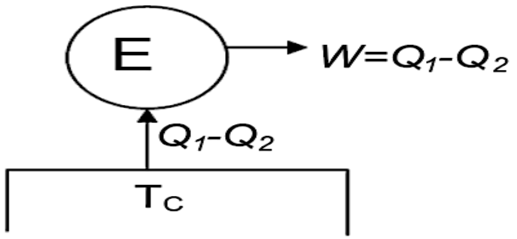
Connect two thermal reservoirs with high thermal conductivity metal and assume Q_1 heat flows from T_C to T_H which according to Clausius is *not* possible

THE EVOLUTION OF THE SECOND LAW

Then place a heat engine between T_H and T_C that draws Q_1 heat from the T_H reservoir and dumps Q_2 heat to the T_C reservoir



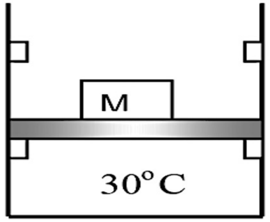
This is quivalent to



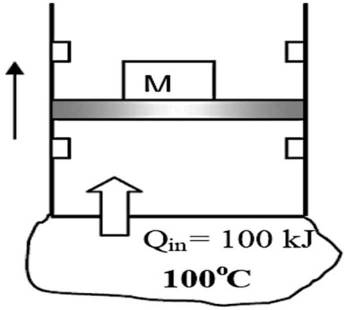
This engine takes heat from one reservoir (T_c) to produce work → this is *not* possible according to K-P statement and thus demonstrating the equivalency of the two statements

THERMAL INEFFICIENCIES

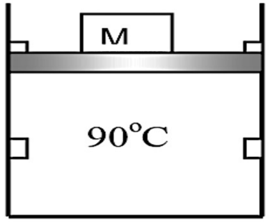
Can we have a 100% thermally efficient engine?
Consider the following simple heat engine designed to lift a weight of mass M



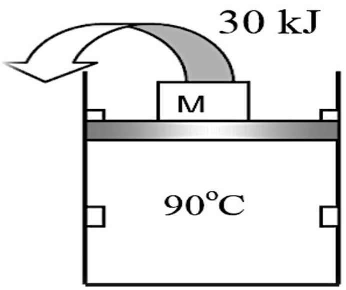
Engine consists of a frictionless, adiabatic piston-cylinder device with two sets of stops and weight placed on the piston. Initial temperature of the gas is 30°C



Add 100 kJ of heat *Q* to the gas from a source at 100°C
- gas heats up
- gas expands raising the piston

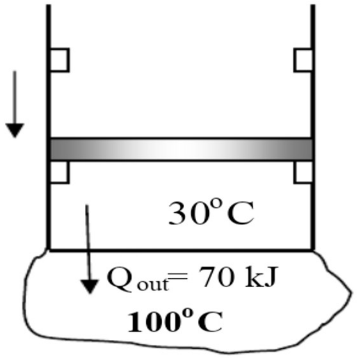


$Q = W + \Delta U$
- heat goes into work done, *W*, to raise the piston → this results in a PE increase of the mass (say 30 kJ)
- the remaining 70 kJ goes into increasing the temperature of the gas

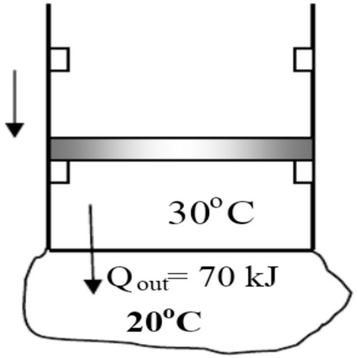


Load is removed and gas temperature is 90°C
* Even under ideal conditions (frictionles and adiabatic) more heat added than work done

To complete the cycle, cool the gas back to 30°C



For 100% efficiency the 70 kJ excess energy added to the gas must be returned to the 100°C source for later use
→ results in heat flow from cold to hot, *Clausius statement says not possible*



Must transfer heat to colder reservoir, say 20°C, to drop temperature back to 30°C
70 kJ excess energy rejected

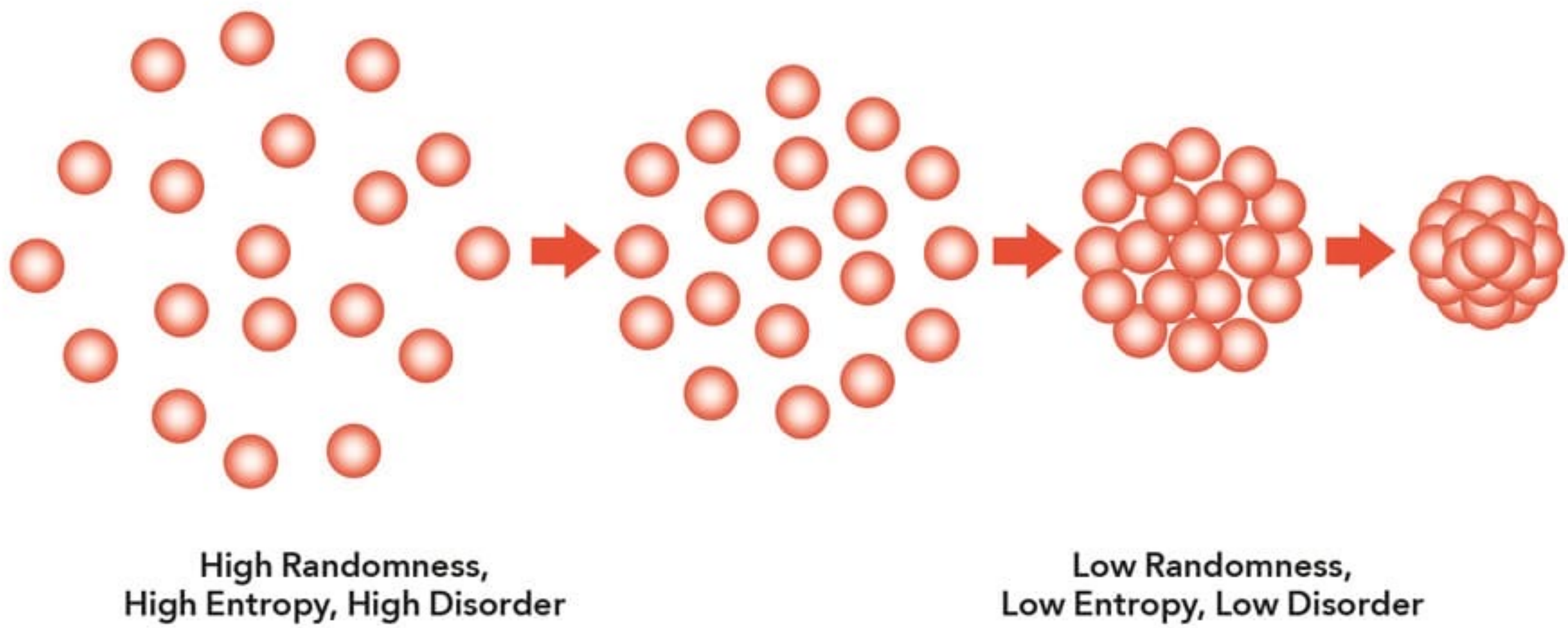
This energy cannot be re-used in the cycle because the lowest working fluid temperature is 30°C → **waste energy**

We can conclude that every heat engine must waste some energy by transferring it to a low-temperature reservoir in order to complete the cycle, even under idealized conditions

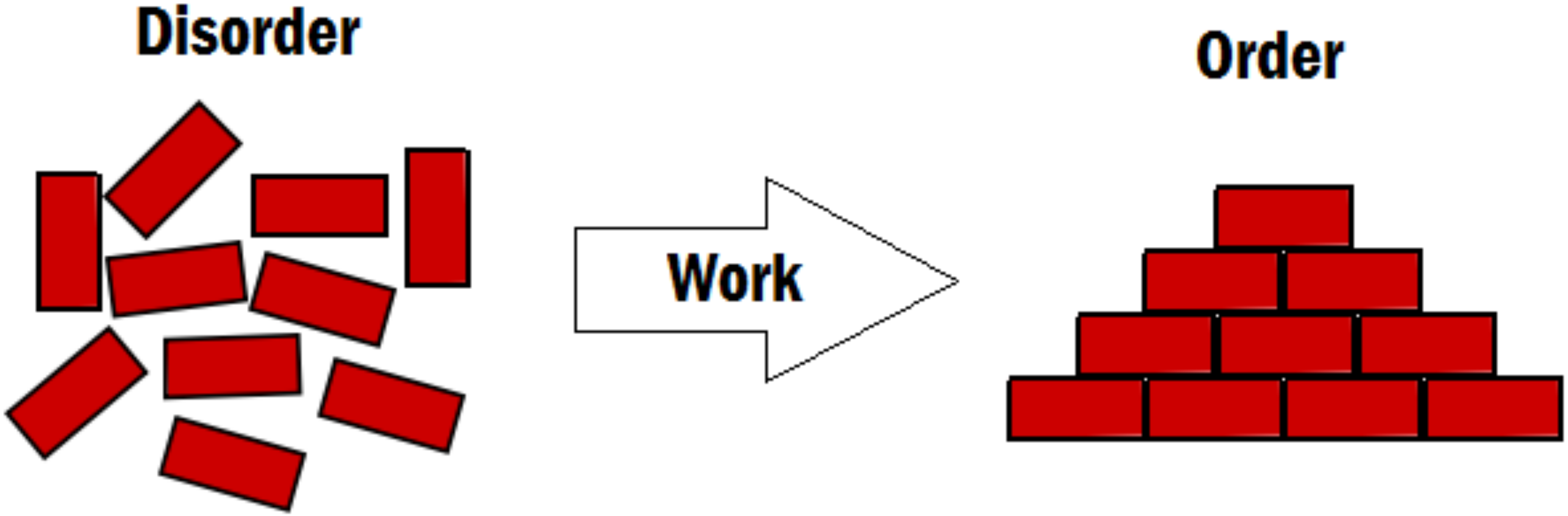
This is consistent with the Kelvin Planck statement

THERMAL INEFFICIENCIES

ENTROPY


High Randomness,
High Entropy, High Disorder
Low Randomness,
Low Entropy, Low Disorder

ENTROPY



ENTROPY

- It is the measure of the disorder in the system.

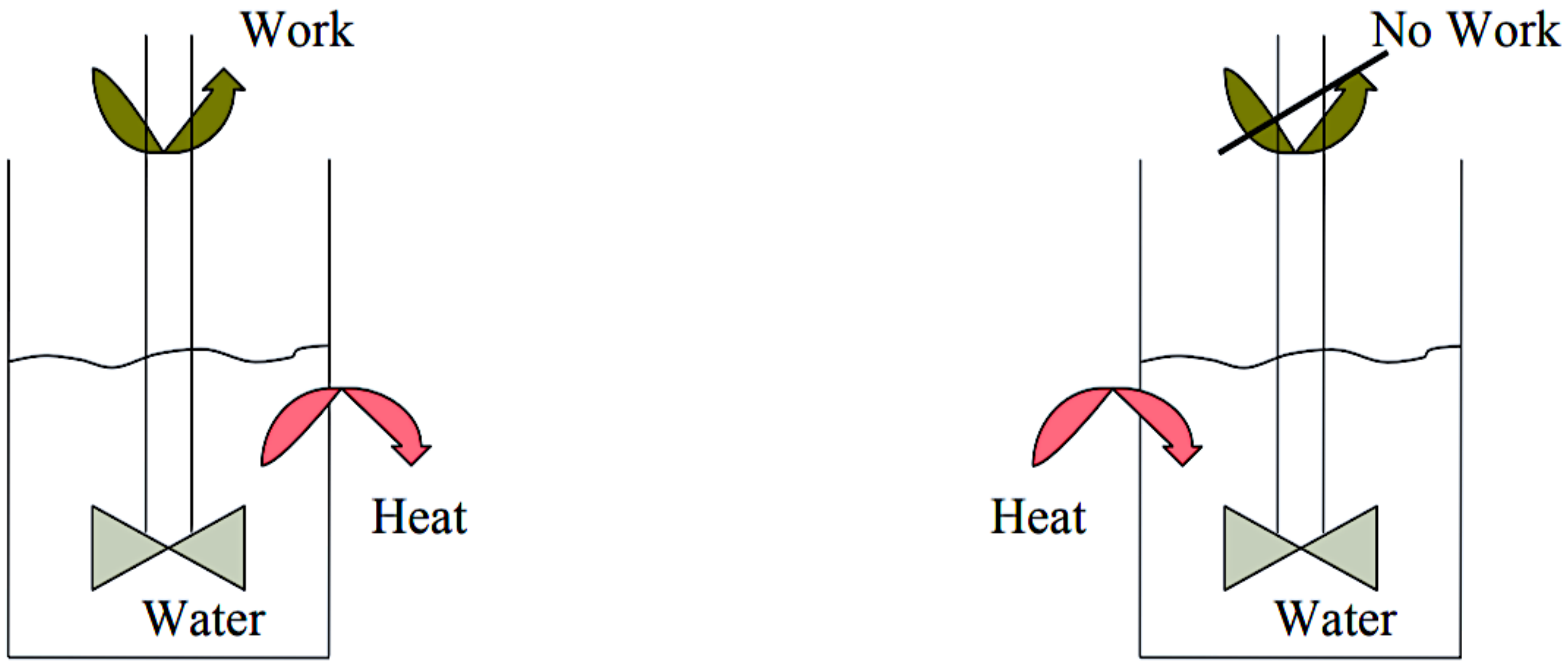
- As the change in entropy can be described as the heat added (or lost) per unit temperature

$$\Delta S = Q/T$$

where $\boldsymbol{\Delta S}$ is the change in entropy,

- $\boldsymbol{Q}$ is the heat flow into or out of a system, and T is the absolute temperature in degrees Kelvin (K).

HEAT ENGINES



From such examples, it can be concluded that,

- Work can be converted to Heat.
- BUT, Converting Heat to Work requires *special devices*.

These devices are known as Heat Engines.

CHARACTERISTICS HEAT ENGINES

- They receive the Heat from High-Temp Reservoir (i.e. Source)

  (e.g. Solar Energy, Oil Furnace, Nuclear Reactor, etc.).

  They convert part of this Heat to Work

  (Usually in form of rotating shaft).
- They reject the remaining Heat to Low-Temp Reservoir (i.e. Sink)

  (e.g. Atmosphere, River, etc.)
- They operate on a CYCLE.

Heat Engines are generally Work – Producing devices,

e.g. Gas Turbines, I.C. Engines, Steam Power Plants, etc.

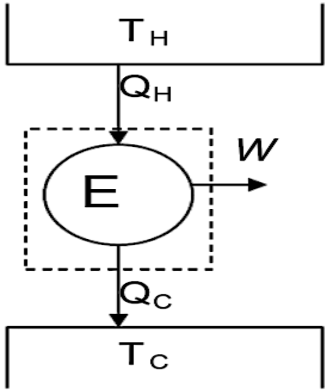
Basic characteristics of heat engine are:

1) Receive heat, Q_H, from a high temperature source

2) Convert part of this heat to work, W

3) Reject the remaining waste heat, Q_C, to a low temperature sink

4) Operate on a cycle



These devices involve a working fluid to and from which heat is transferred

First Law applied to the heat engine cycle yields

$$\cancel{\Delta E} = Q_{net} - W$$
$$0 = (Q_{in} - Q_{out}) - W$$
$$0 = (Q_H - Q_C) - W \qquad \therefore W_{\substack{heat\\engine}} = Q_H - Q_C$$

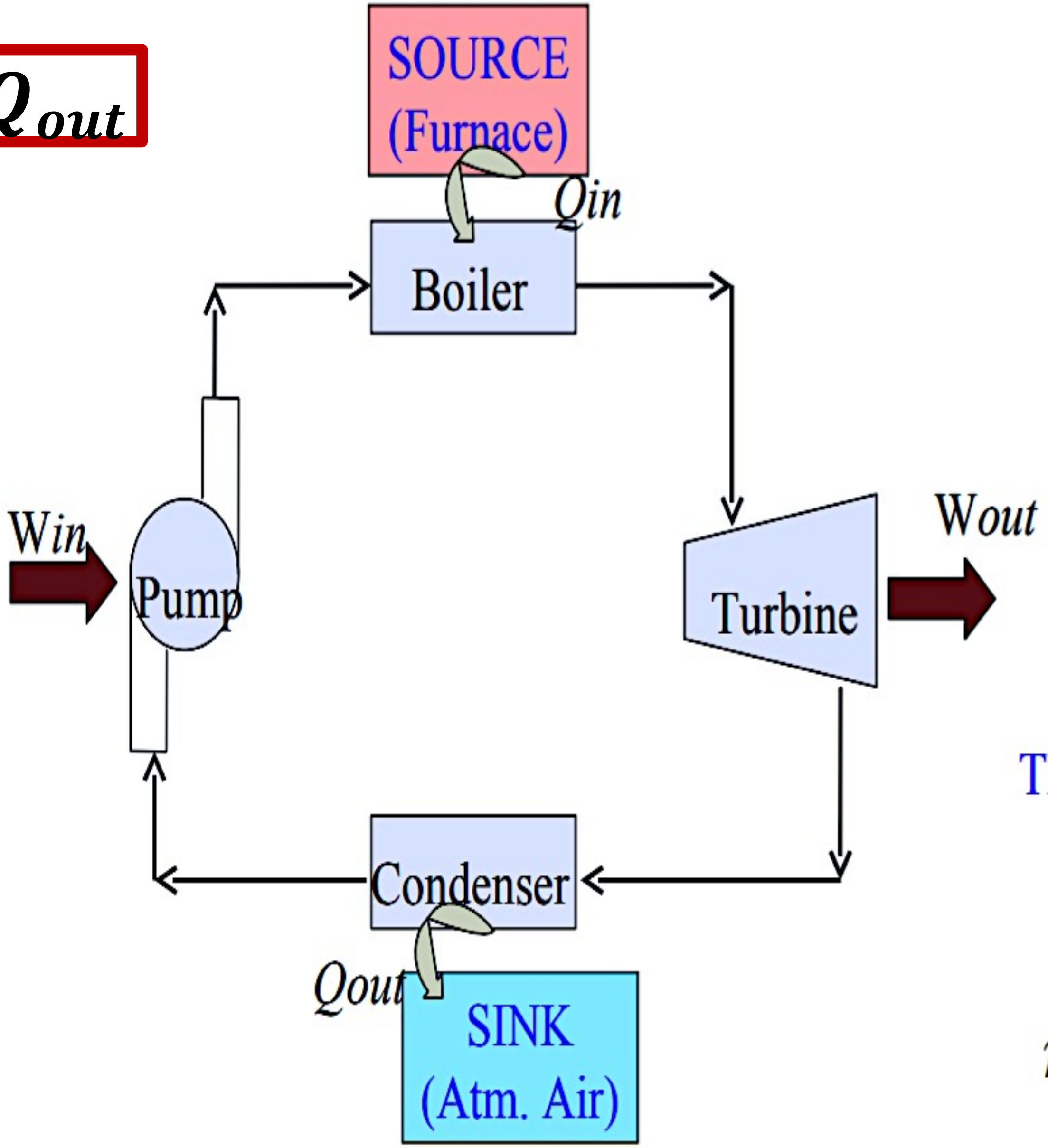
The efficiency of the cycle is defined as

$$\eta_{\substack{heat\\engine}} = \frac{\text{work done}}{\text{maximum work}} = \frac{W}{W_{MAX}}$$

THERMAL INEFFICIENCIES

HEAT ENGINES – POWER CYCLES

$$\boxed{W_{net} = Q_{in} - Q_{out}}$$



Part of Heat output that is converted to net Work output, is a measure of performance of the Heat Engine; and is known as the THERMAL EFFICIENCY of the Heat Engine.

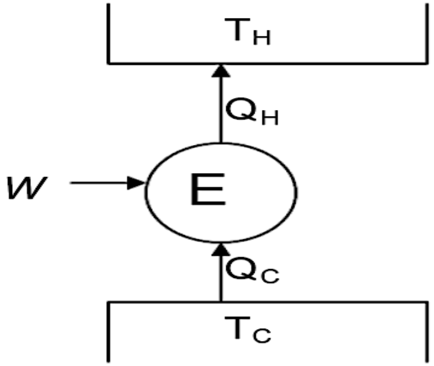
$$\text{Thermal Efficiency} = \frac{\text{Net Work Output}}{\text{Total Heat Input}}$$

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

REFRIGERATORS AND HEAT PUMPS

A refrigerator takes heat from a hot reservoir (hot room) and dumps it into a cooler reservoir (cooler outdoors).

The refrigeration cycle is the opposite of the heat engine requiring work input



Note: this is *not* inconsistent with Clausius' statement because the heat transfer from the cold to the hot reservoir is not spontaneous.

Applying First Law to the refrigeration cycle

$$\cancel{\Delta E} = Q_{net} - W$$
$$0 = (Q_{in} - Q_{out}) - (-W)$$
$$0 = (Q_C - Q_H) + \mathrm{W} \qquad \therefore W_{refr} = Q_H - Q_C$$

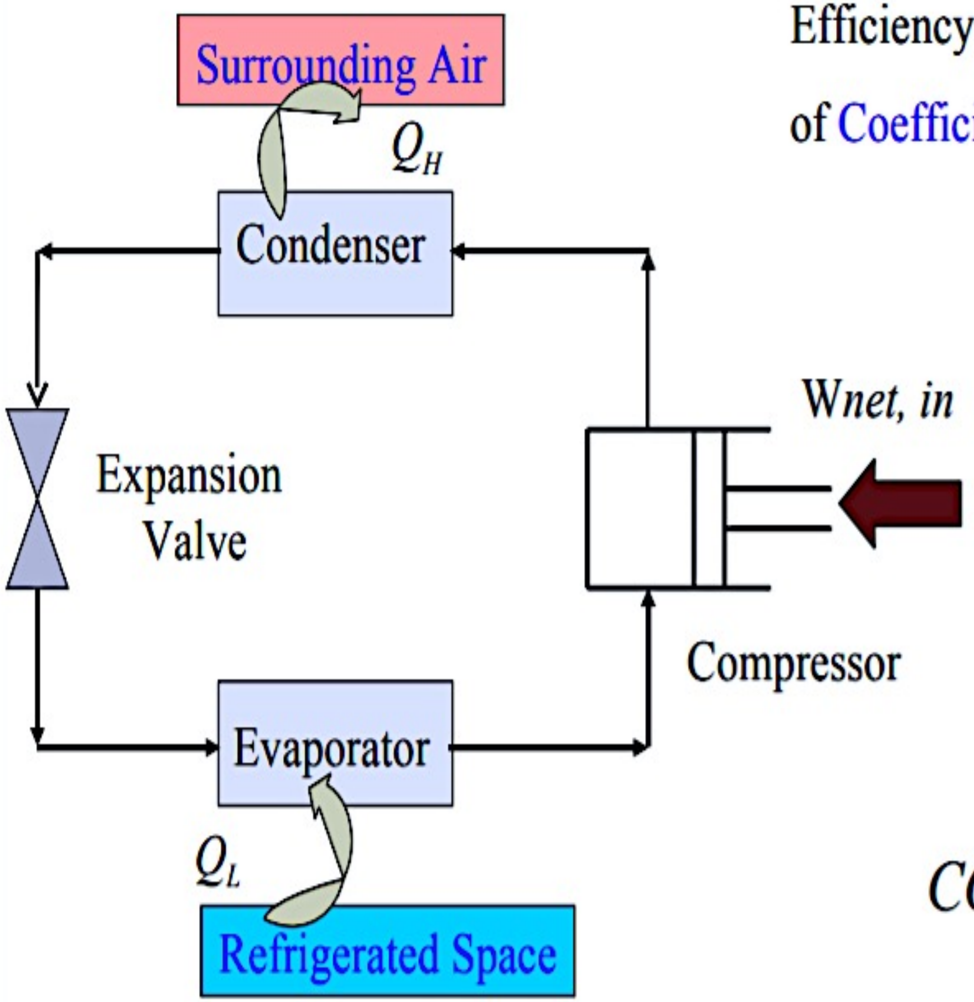
Coefficient of performance (COP) β defined as

$$\beta = \frac{\text{heat removed}}{\text{work done}} = \frac{Q_C}{W_{refr}} = \frac{Q_C}{Q_H - Q_C}$$

Typical values of β are 3-4

REFRIGERATORS AND HEAT PUMP CYCLES

$$\boxed{W_{net} = Q_{out} - Q_{in}}$$



Efficiency of a Refrigerator is expressed in terms of Coefficient of Performance $(COP)_R$.

$$COP_R = \frac{Desired\ Output}{Required\ Input} = \frac{Q_L}{W_{net,in}}$$

First Law of Thermodynamics gives;

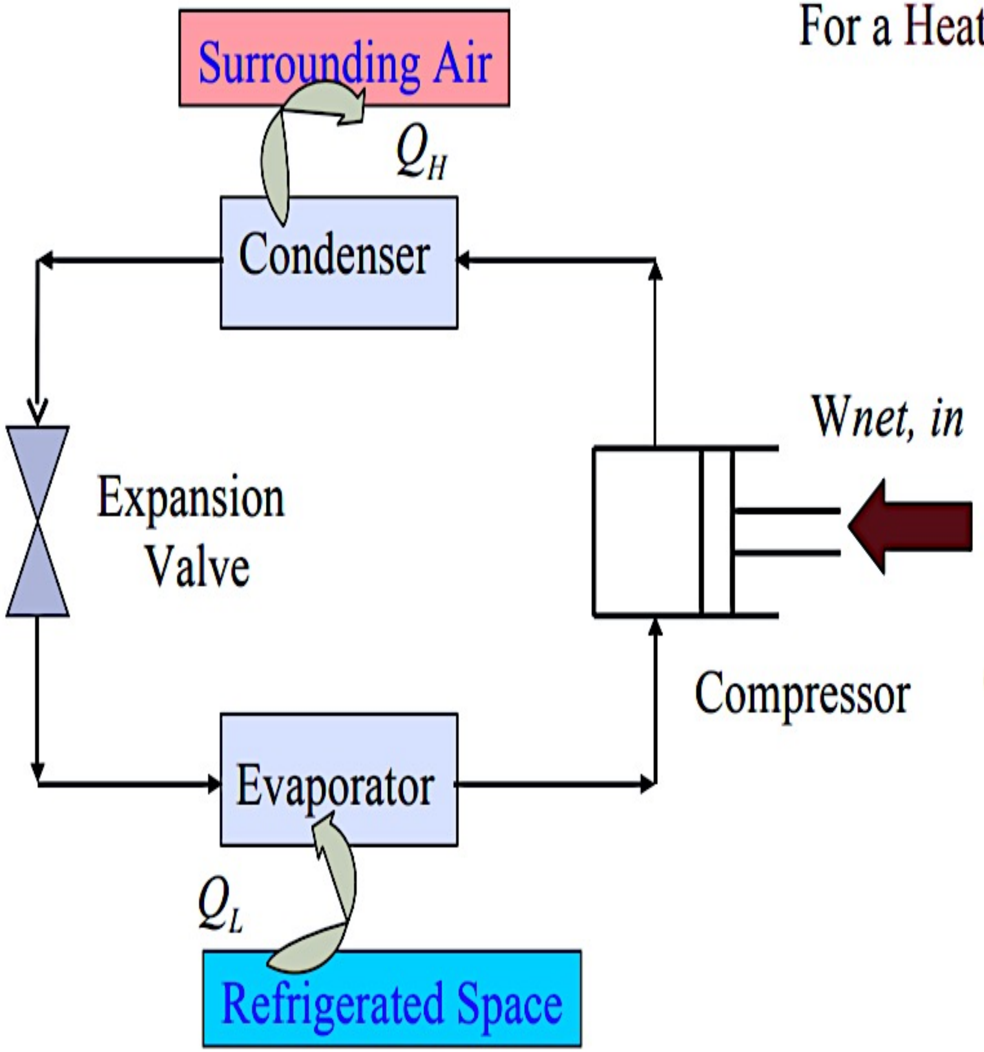
$$\boxed{Work_{net,in} = Q_H - Q_L}$$

$$COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{\left(Q_H/Q_L\right) - 1}$$

Thus, COP_R can be > 1

REFRIGERATORS AND HEAT PUMP CYCLES

$$\boxed{W_{net} = Q_{out} - Q_{in}}$$



For a Heat Pump, COP is expressed as $(COP)_{HP}$.

$$COP_{HP} = \frac{Desired\ Output}{Required\ Input} = \frac{Q_H}{W_{net,in}}$$

$$COP_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - \left(\frac{Q_L}{Q_H}\right)}$$

Thus;

$$\boxed{COP_{HP} = COP_R + 1}$$

THE THIRD LAW OF THERMODYNAMICS

- For a substance, if the random translational, rotational and vibrational types of motion of the atoms and molecules making up the substance are reduced to zero, then the substance is considered to become a perfect crystal form and the energies associated with these forms of motion will be reduced to zero.
- This is referred to as the GROUND STATE

- **THE THIRD LAW STATES THAT AT THE ABSOLUTE ZERO OF TEMPERATURE, THE ENTROPY OF A PERFECT CRYSTAL OF A SUBSTANCE IS ZERO**

SUMMARY

1. Zeroth Law (Universality of Temperature): Defines Temperature T

$$A \sim B \text{ AND } C \sim B \ \rightarrow A \sim C$$

2. First Law (Conservation of Energy): Defines Energy E

$$dU = dQ - dW$$

3. Second Law (Arrow of Time): Defines Entropy S

$$\frac{dS}{dt} \geq 0$$

4. Third Law (Quantum Mechanics): Gives Numerical Value to Entropy

$$\lim_{T \rightarrow 0} S(T) = 0$$

Summary: The Laws of Thermodynamics

- **Zeroth Law:** If object A is in thermal equilibrium with object B, and if object B is in thermal equilibrium with object C, then objects A and C are also in thermal equilibrium.
- **First Law:** Energy is always conserved. It can change forms: kinetic, potential, internal, etc.., but the total energy is constant. Another way to say it is that the change in thermal energy of a system of a system is equal to the sum of the work done on it and the amount of heat energy transferred to it.
- **Second Law:** During any natural process, the total amount of entropy in the universe always increases. Entropy can be defined informally as a measure of randomness or disorder in a system. Heat flows naturally from a hot to cooler surroundings as a consequence of the second law.

Summary: The Laws of Thermodynamics

1st Law – Conservation of Energy

2nd Law – As energy is converted into another form, some of it is lost to heat.

There are no 100% efficient machines; Entropy is always increasing; Perpetual motion machines are impossible.

Energy tends to go from more usable (higher quality) to less usable (lower quality). When you use energy, you lower its quality.

3rd Law – Entropy at absolute zero is exactly equal to zero.

Example 1.10 *A steam plant uses 3.045 tonne of coal per hour. The steam is fed to a turbine whose output is 4.1 MW. The calorific value of the coal is 28 MJ/kg. Determine the thermal efficiency of the plant.*

SOLUTION

$$= 3045 \text{ kg/h} = \frac{3045}{3600} = 0.846 \text{ kg/s}$$

$$\text{Energy liberated by coal} = (0.846 \times 28 \times 10^6) \text{ J/s}$$

$$\text{Power output from turbine} = (4.1 \times 10^6) \text{ W}$$

$$= (4.1 \times 10^6) \text{ J/s}$$

$$\text{Thermal } \eta = \frac{\text{Power output}}{\text{Energy liberated by coal}}$$

$$= \frac{4.1 \times 10^6}{0.846 \times 28 \times 10^6}$$

$$= \mathbf{0.173 \text{ or } 17.3\%}$$

A gas turbine plant delivers an output of 150 MW. The gas consumption is 55 000 m^3/h. The calorific value of the gas used is 38.3 MJ/m^3. Determine the thermal efficiency of the plant.

[25.6%]

Example 2.1 *In a process carried out on a closed system, the heat transferred into the system was 2500 kJ and the work transferred from the system was 1400 kJ. Determine the change in total energy, and state whether it is an increase or a decrease.*

SOLUTION

From equation [4]

$$E_2 - E_1 = Q - W$$
$$= 2500 - 1400$$
$$= \mathbf{1100\ J}$$

This is positive, so there is an increase in total energy.

Example 2.3 *During the working stroke of an engine the heat transferred out of the system was 150 kJ/kg of working substance. The internal energy also decreased by 400 kJ/kg of working substance. Determine the work done and state whether it is work done on or by the engine.*

SOLUTION

From equation [3], the non-flow energy equation

$$Q = \Delta u + W \quad (\Delta u \text{ because energies/kg are given})$$

From this

$$\begin{aligned} W &= Q - \Delta u \\ &= -150 - (-400) \quad (-400 \text{ because there is a decrease in internal energy}) \\ &= -150 + 400 \\ &= \mathbf{250\ kJ/kg} \end{aligned}$$

This is positive, so is work done by the engine per kilogram of working substance.

Questions

1. In a non-flow process there is a heat transfer loss of 1055 kJ and an internal energy increase of 210 kJ. Determine the work transfer and state whether the process is an expansion or a compression.

Solution

Solution

SOLUTION

$W = Q - \Delta U$

$= -1055 \text{ kJ} - 210 \text{ kJ}$

$\boxed{W = -1265 \text{ kJ}}$; a Compression

Example 2.4 In a steady-flow open system a fluid substance flows at the rate of 4 kg/s. It enters the system at a pressure of 600 kN/m^2, a velocity of 220 m/s, internal energy 2200 kJ/kg and specific volume 0.42 m^3/kg. It leaves the system at a pressure of 150 kN/m^2 a velocity of 145 m/s, internal energy 1650 kJ/kg and specific volume 1.5 m^3/kg. During its passage through the system, the substance has a loss by heat transfer of 40 kJ/kg to the surroundings.

Determine the power of the system, stating whether it is from or to the system. Neglect any change of gravitational potential energy.

SOLUTION

The steady-flow energy equation for the system is

$$u_1 + P_1 v_1 + \frac{C_1^{\,2}}{2} + Q = u_2 + P_2 v_2 + \frac{C_2^{\,2}}{2} + W$$

From this

$$W = (u_1 - u_2) + (P_1 v_1 - P_2 v_2) + \left(\frac{C_1^{\,2} - C_2^{\,2}}{2}\right) + Q$$

Working in kilojoules (kJ)

$$\text{Specific work} = W = (2200 - 1650) + (600 \times 0.42 - 150 \times 1.5) + \left(\frac{220^2 - 145^2}{2 \times 10^3}\right) - 40$$

(Q is -40 kJ/kg because the heat transfer is a loss from the system.)

$$\therefore \quad W = 550 + (252 - 225) + \frac{(48\,400 - 21\,025)}{2 \times 10^3} - 40$$

$$= 550 + 27 + \frac{27\,375}{2 \times 10^3} - 40$$

$$= 550 + 27 + 13.69 - 40$$

$$= \mathbf{550.69\ kJ/kg}$$

This is positive, so power is output from the system.

For a fluid substance flow rate of 4 kg/s

$$\text{Power output from the system} = 550.69 \times 4$$

$$= 2202.75\ \text{kJ/s}$$

$$= \mathbf{2202.75\ kW} \quad (1\ \text{kJ/s} = 1\ \text{kW})$$

Example 2.6 *Air passes through a gas turbine system at the rate of 4.5 kg/s. It enters the turbine system with a velocity of 90 m/s and a specific volume of 0.85 m^3/kg. It leaves the turbine system with a specific volume of 1.45 m^3/kg. The exit area of the turbine system is 0.038 m^2. In its passage through the turbine system, the specific enthalpy of the air is reduced by 200 kJ/kg and there is a heat transfer loss of 40 kJ/kg. Determine*

(a) the inlet area of the turbine in m^2

(b) the exit velocity of the air in m/s

(c) the power developed by the turbine system in kilowatts

(a)

At inlet

$$\dot{m} = \frac{A_1 C_1}{v_1} \quad \text{(see section 2.9 equation [4])}$$

$$\therefore \quad A_1 = \frac{\dot{m} v_1}{C_1}$$

$$= \frac{4.5 \times 0.85}{90}$$

$$= \mathbf{0.042\ m^2}$$

The inlet area is 0.042 m^2.

(b)
At exit

$$\dot{m} = \frac{A_2 C_2}{v_2}$$

$$\therefore \quad C_2 = \frac{\dot{m} v_2}{A_2}$$

$$= \frac{4.5 \times 1.45}{0.038}$$

$$= \mathbf{171.71\ m/s}$$

The exit velocity is 171.71 m/s.

(c)
The steady-flow energy equation for this system is

$$h_1 + \frac{C_1{}^2}{2} + Q = h_2 + \frac{C_2{}^2}{2} + W \quad \text{(see section 2.8, equation [8])}$$

from which

$$W = (h_1 - h_2) + \frac{(C_1{}^2 - C_2{}^2)}{2 \times 10^3} \quad \text{(energy in kJ/kg)}$$

$$= 200 + \frac{(90^2 - 171.71^2)}{2 \times 10^3} - 40 \quad \text{(loss by heat transfer)}$$

$$= 200 + \frac{(8100 - 29\,484.3)}{2 \times 10^3} - 40$$

$$= 200 - \frac{21\,384.3}{2 \times 10^3} - 40$$

$$= 200 - 10.7 - 40$$

$$= \mathbf{149.3\ kJ/kg}$$

$\therefore$ Power developed $= 149.3 \times 4.5$

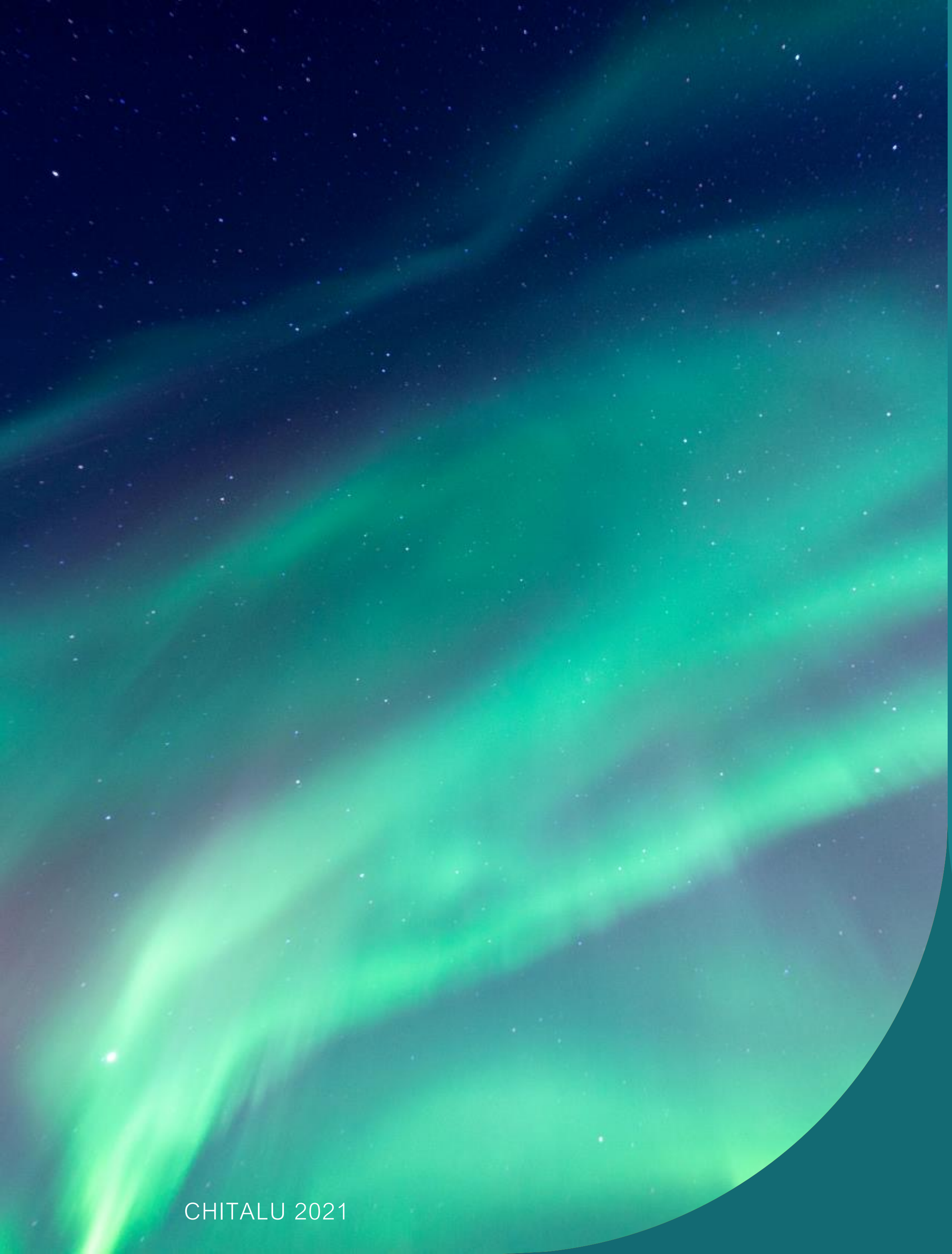
$= 671.85$ kJ/s

$=$ **671.85 kW** (1 kJ/s = 1 kW)

“Laws of Thermodynamics

1. You cannot win, you can only break even.
2. You can only break even at absolute zero
3. You cannot reach absolute zero”

Anonymous



Thank You

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