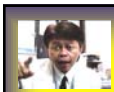

## Thermodynamics Lecture Series

**Assoc. Prof. Dr. J.J.**

## Second Law – Quality of Energy-Part1

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## Quotes

- It does not matter how slowly you go, so long as you do not stop.
  --Confucius
- To be wronged is nothing unless you continue to remember it.
  --Confucius



## Symbols

- ✓ Q
- ✓ q
- ✓ W
- ✓ ω
- ✓ V
- ✓ v
- ✓ E
- ✓ ϑ

$\dot{W}$

$\dot{Q}$

$\vec{\upsilon}$

$\dot{V}$

$\dot{m}$



## Introduction - Objectives

*Objectives:*

1. *Explain the need for the second law of thermodynamics on real processes.*
2. *State the general and the specific statements of the second law of thermodynamics.*
3. *State the meaning of reservoirs and working fluids.*
4. *List down the characteristics of heat engines.*

## Introduction - Objectives

*Objectives:*

5. *State the difference between thermodynamic heat engines and mechanical heat engines.*
6. *Sketch an energy-flow diagram indicating the flow of energy and label all the energies and all the reservoirs for a steam power plant.*
7. *Sketch a schematic diagram for a steam power plant and label all the energies, flow of energies and all the reservoirs.*

## Introduction - Objectives

*Objectives:*

8. *State the desired output and required input for a steam power plant.*
9. *State the meaning of engines' performance and obtain the performance of a steam power plant in terms of the heat exchange.*
10. *State the Kelvin-Planck statement on steam power plant.*

## Introduction - Objectives

*Objectives:*

11. *Sketch an energy-flow diagram indicating the flow of energy and label all the energies and all the reservoirs for a refrigerator.*
12. *Sketch a schematic diagram for a refrigerator and label all the energies, flow of energies and all the reservoirs.*
13. *State the desired output and required input for a refrigerator.*

## Introduction - Objectives

*Objectives:*

14. *Obtain the performance of a refrigerator in terms of the heat exchange.*
15. *Sketch an energy-flow diagram indicating the flow of energy and label all the energies and all the reservoirs for a heat pump.*
16. *Sketch a schematic diagram for a a heat pump and label all the energies, flow of energies and all the reservoirs.*

## Introduction - Objectives

*Objectives:*

17. *State the desired output and required input for a a heat pump.*
18. *Obtain the performance of a a heat pump in terms of the heat exchange.*
19. *State the Clausius statement for refrigerators and heat pumps.*
20. *Solve problems related to steam power plants, refrigerators and heat pumps.*

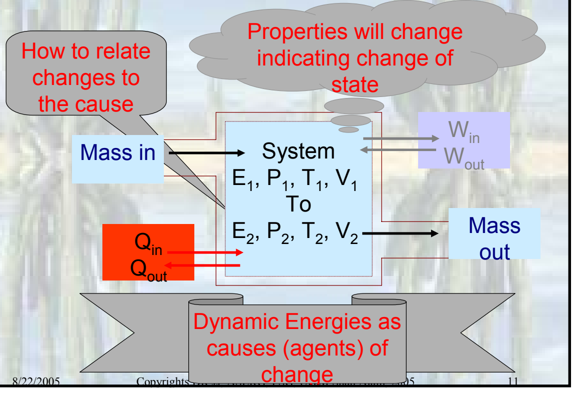
## Review - First Law

- All processes must obey energy conservation
- Processes which do not obey energy conservation cannot happen.
- Processes which do not obey mass conservation cannot happen

Piston-cylinders, rigid tanks
Turbines, compressors,
Nozzles, heat exchangers



## Review - First Law






## Review - First Law

| Energy Entering a system | - | Energy Leaving a system | = | Change of system's energy |
|---|---|---|---|---|

Energy Balance

Amount of **energy causing change** must be equal to amount of **energy change** of system

## Review - First Law

| Energy Entering a system | - | Energy Leaving a system | = | Change of system's energy |
|---|---|---|---|---|

**Energy Balance**

$E_{in} - E_{out} = \Delta E_{sys}$, kJ or

$e_{in} - e_{out} = \Delta e_{sys}$, kJ/kg or

$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{sys}$, kW



## Review - First Law

| Mass Entering a system | - | Mass Leaving a system | = | Change of system's mass |
|---|---|---|---|---|

**Mass Balance**

$m_{in} - m_{out} = \Delta m_{sys}$, kg or

$\dot{m}_{in} - \dot{m}_{out} = \Delta \dot{m}_{sys}$, kg / s



## Review - First Law

**Energy Balance – Control Volume Steady-Flow**

Steady-flow is a flow where all properties within boundary of the system remains constant with time

$\Delta E_{sys} = 0$, kJ; $\Delta e_{sys} = 0$, kJ/kg, $\Delta V_{sys} = 0$, m$^3$;
$\Delta m_{sys} = 0$ or $m_{in} = m_{out}$, kg $\Delta \dot{m}_{sys} = 0$, kg/s

$\dot{m}_{in} - \dot{m}_{out} = 0$ or $\dot{m}_{in} = \dot{m}_{out}$, kg/s



## Review - First Law

**Mass & Energy Balance–Steady-Flow CV**

Mass balance

$\Delta \dot{m}_{sys} = 0$, So, $\dot{m}_{in} = \dot{m}_{out}$ or $\sum \dot{m}_{in} = \sum \dot{m}_{out}$, kg/s

Energy balance $\Delta \dot{E}_{sys} = 0$, So, $\dot{E}_{in} = \dot{E}_{out}$ kJ/s

$$\dot{Q}_{in} + \dot{W}_{in} + \sum \left( \dot{m}\,\vartheta \right)_{in} = \dot{Q}_{out} + \dot{W}_{out} + \sum \left( \dot{m}\,\vartheta \right)_{out}, \text{kW}$$

$q_{in} + \omega_{in} + \theta_{in} = q_{out} + \omega_{out} + \theta_{out}$, kJ/kg



## Review - First Law

**Mass & Energy Balance–Steady-Flow: Single Stream**

Mass balance

$\Delta \dot{m}_{sys} = 0$. So, $\dot{m}_{in} = \dot{m}_{out} = \dot{m}$, kg/s

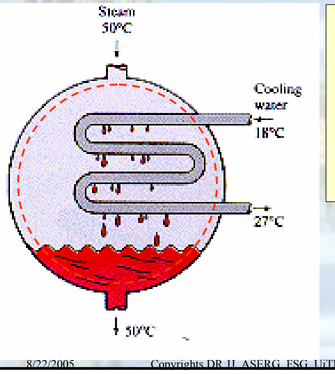
Energy balance $\Delta \dot{E}_{sys} = 0$. So, $\dot{E}_{in} = \dot{E}_{out}$, kJ/s

$$\dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} = \dot{m}(\vartheta_{out} - \vartheta_{in}), \text{kW}$$

$q_{in} - q_{out} + \omega_{in} - \omega_{out} = \theta_{out} - \theta_{in}$, kJ/kg
$= h_{out} - h_{in} + ke_{out} - ke_{in} + pe_{out} - pe_{in}$, kJ/kg

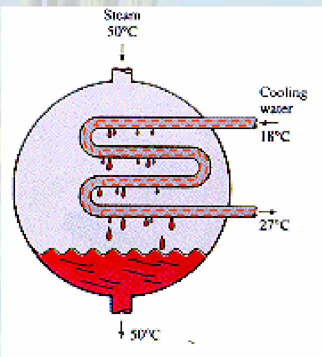


## First Law – Heat Exchanger




Heat Exchanger Boundary has 2 inlets and 2 exits

## First Law – Heat Exchanger

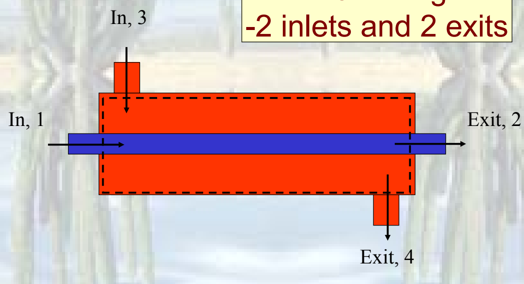



Heat Exchanger Boundary has 1 inlet and 1 exit



## First Law of Thermodynamics

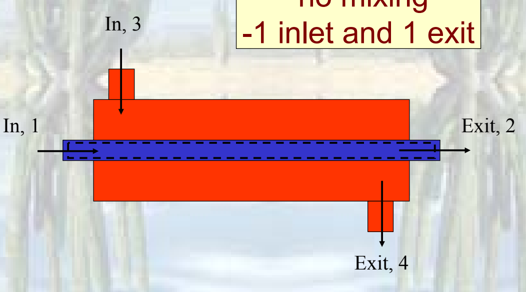
Heat Exchanger
-no mixing
-2 inlets and 2 exits






## First Law of Thermodynamics

Heat Exchanger
-no mixing
-1 inlet and 1 exit

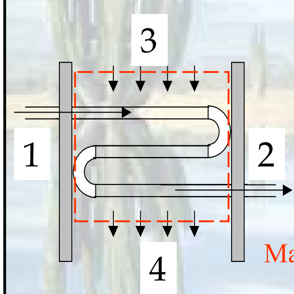





## First Law of Thermodynamics

Heat Exchanger

Case 1




Energy balance

$$0 = \vartheta_4 - \vartheta_3 + \vartheta_2 - \vartheta_1$$

where $\vartheta = h + ke + pe$

Mass balance

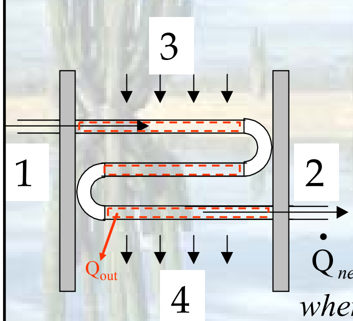
$$\dot{m}_1 = \dot{m}_2,\ \dot{m}_3 = \dot{m}_4,\ kg/s$$



## First Law of Thermodynamics

Heat Exchanger

Case 2




Mass balance

$$\dot{m}_1 = \dot{m}_2 = \dot{m},\ \text{kg/s}$$

Energy balance

$$\dot{Q}_{net,in} + 0 = \dot{m}(\vartheta_2 - \vartheta_1)$$

where $\vartheta = h + ke + pe$



## First Law of Thermodynamics

Heat Exchanger

Purpose: Remove or add heat

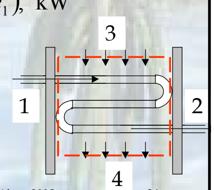
Energy balance: Case 1

$$0 - 0 + 0 - 0 = \dot{m}_4(h_4 + ke_4 + pe_4) - \dot{m}_3(h_3 + ke_3 + pe_3)$$
$$+ \dot{m}_2(h_2 + ke_2 + pe_2) - \dot{m}_1(h_1 + ke_1 + pe_1),\ \text{kW}$$

Mass balance: $\dot{m}_1 = \dot{m}_2,\ \dot{m}_3 = \dot{m}_4,\ kg/s$

$$\dot{m}_1(h_1 - h_2 + ke_1 - ke_2 + pe_1 - pe_2)$$
$$= \dot{m}_3(h_4 - h_3 + ke_4 - ke_3 + pe_4 - pe_3)$$

where $\Delta ke = \Delta pe \cong 0$





## First Law of Thermodynamics

### Heat Exchanger

Purpose: Remove or add heat

Mass balance:

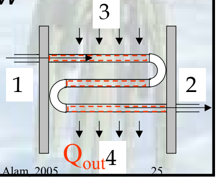
$$\dot{m}_1 = \dot{m}_2 = \dot{m},\ \text{kg/s}$$

Energy balance: Case 2

$$\dot{Q}_{in} - \dot{Q}_{out} + 0 - 0 = \dot{m}_2 h_2 - \dot{m}_1 h_1,\ kW$$

$$-\dot{Q}_{out} + 0 - 0 = \dot{m}(h_2 - h_1),\ \text{kW}$$

where $(h_2 - h_1) = \dfrac{\dot{m}_3 (h_3 - h_4)}{\dot{m}_1}$






## First Law of Thermodynamics

### Heat Exchanger

Purpose: Remove or add heat

Mass balance:

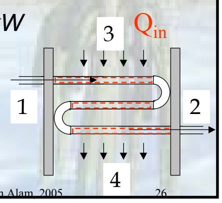
$$\dot{m}_1 = \dot{m}_2,\ \dot{m}_3 = \dot{m}_4,\ kg/s$$

Energy balance: Case 2

$$\dot{Q}_{in} - \dot{Q}_{out} + 0 - 0 = \dot{m}_2 h_2 - \dot{m}_1 h_1,\ kW$$

$$\dot{Q}_{in} - 0 + 0 - 0 = \dot{m}_2 (h_2 - h_1),\ kW$$

where $(h_2 - h_1) = \dfrac{\dot{m}_3 (h_3 - h_4)}{\dot{m}_1}$

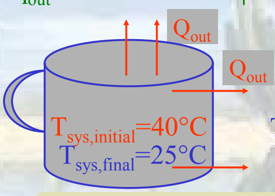





## Second Law

$0 - q_{out} + 0 - 0 = -\Delta u = u_1 - u_2$, kJ/kg

- First Law involves quantity or amount of energy to be conserved in processes




•OK for this cup

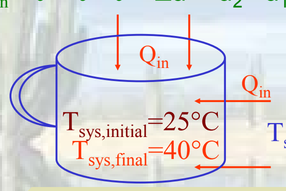
$T_{surr}$=25°C

This is a natural process!!! Q flows from high T to low T medium until thermal equilibrium is reached



## Second Law

$q_{in} - 0 + 0 - 0 = \Delta u = u_2 - u_1$, kJ/kg



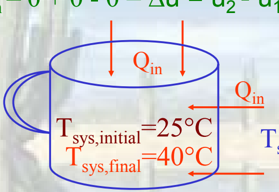

$T_{surr}$=25°C

This is NOT a natural process!!! Q does not flow from low T to high T medium. Never will the coffee return to its initial state.



## Second Law

$q_{in} - 0 + 0 - 0 = \Delta u = u_2 - u_1$, kJ/kg




$T_{surr}$=25°C

This is NOT a natural process!!! Q does not flow from low T to high T medium. Never will the coffee return to its initial state.

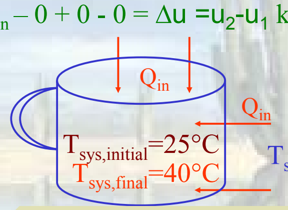


## Second Law

$q_{in} - 0 + 0 - 0 = \Delta u = u_2 - u_1$ kJ/kg

- First Law involves quantity or amount of energy to be conserved in processes

But is the process in this cup possible??




$T_{surr}$=25°C

This is a NOT a natural process!!! Q does not flow from low T to high T medium. Never will equilibrium be reached

## Second Law

- First Law is not sufficient to determine if a process can or cannot proceed



## Second Law

- First Law is not sufficient to determine if a process can or cannot proceed

•Introduce the second law of thermodynamics – processes occur in its natural direction.

- ➢ Heat (thermal energy) flows from high temperature medium to low temperature medium.
- ➢ Energy has quality & quality is higher with higher temperature. More work can be done.



## Second Law

### Considerations:

•Work can be converted to heat directly & totally.

•Heat cannot be converted to work directly & totally.

- ➢ Requires a special device – heat engine.



## Second Law

### Heat Engine Characteristics:

•Receive heat from a high T source.

•Convert part of the heat into work.

•Reject excess heat into a low T sink.

•Operates in a cycle.



## Second Law

### Heat Engines

•Thermodynamics heat engines – external combustion: steam power plants

Combustion outside system

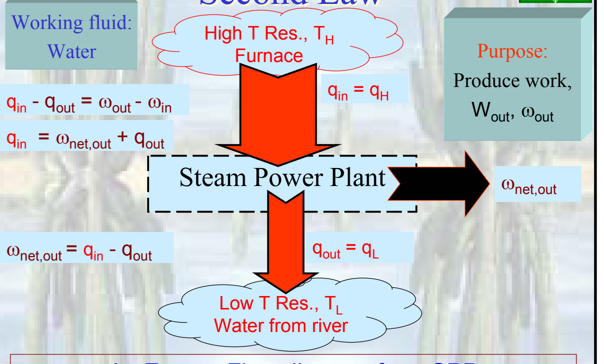
•Mechanical heat engines – internal combustion: jets, cars, motorcycles

Combustion inside system

Performance = Desired output / Required input

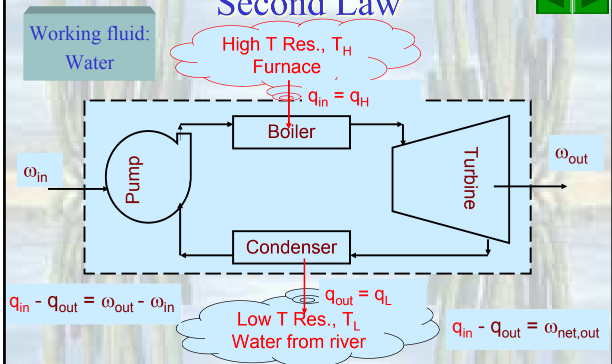


## Second Law




An Energy-Flow diagram for a SPP

## Second Law




A Schematic diagram for a Steam Power Plant



## Second Law

Thermal Efficiency for steam power plants

$$\eta = \frac{desired\ \ output}{required\ \ input} = \frac{\omega_{net,out}}{q_{in}}$$

$$\eta = \frac{\omega_{net,out}}{q_{in}} = \frac{q_{in} - q_{out}}{q_{in}} = \frac{q_{in}}{q_{in}} - \frac{q_{out}}{q_{in}}$$

$$= 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{q_L}{q_H}$$



## Second Law

Thermal Efficiency for steam power plants

$$\eta = \frac{desired\ \ output}{required\ \ input} = \frac{\dot{W}_{net,out}}{\dot{Q}_{in}}$$

$$\eta = \frac{\dot{W}_{net,out}}{\dot{Q}_{in}} = \frac{\dot{Q}_{in} - \dot{Q}_{out}}{\dot{Q}_{in}} = \frac{\dot{Q}_{in}}{\dot{Q}_{in}} - \frac{\dot{Q}_{out}}{\dot{Q}_{in}}$$

$$= 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}} = 1 - \frac{\dot{Q}_L}{\dot{Q}_H}$$



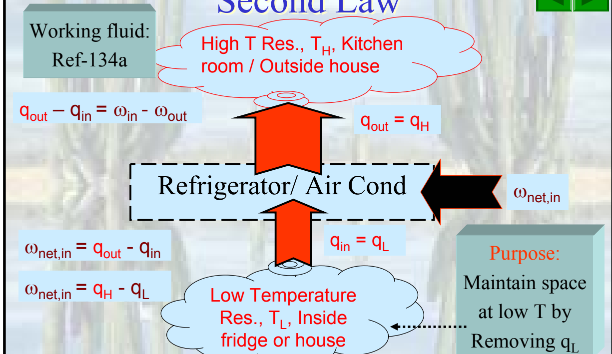
## Second Law

Kelvin Planck Statement for steam power plants

- It is impossible for engines operating in a cycle to receive heat from a single reservoir and convert all of the heat into work.
- Heat engines cannot be 100% efficient.



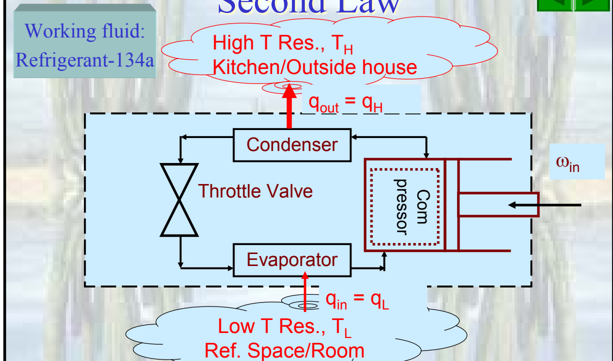
## Second Law




An Energy-Flow diagram for a Refrigerator/Air Cond.



## Second Law




A Schematic diagram for a Refrigerator/Air Cond.

## Second Law

Coefficient of Performance for a Refrigerator

$$COP_R = \frac{desired\ \ output}{required\ \ input} = \frac{q_{in}}{\omega_{net,in}}$$

$$COP_R = \frac{q_{in}}{\omega_{net,in}} = \frac{q_{in}}{q_{out} - q_{in}}$$

Divide top and bottom by $q_{in}$

$$= \frac{1}{\frac{q_{out}}{q_{in}} - \frac{q_{in}}{q_{in}}} = \frac{1}{\frac{q_{out}}{q_{in}} - 1} = \frac{1}{\frac{q_H}{q_L} - 1}$$

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## Second Law

Coefficient of Performance for a Refrigerator

$$COP_R = \frac{desired\ \ output}{required\ \ input} = \frac{\dot{Q}_{in}}{\dot{W}_{net,in}}$$

$$COP_R = \frac{\dot{Q}_{in}}{\dot{W}_{net,in}} = \frac{\dot{Q}_{in}}{\dot{Q}_{out} - \dot{Q}_{in}}$$

$$= \frac{1}{\frac{\dot{Q}_{out}}{\dot{Q}_{in}} - \frac{\dot{Q}_{in}}{\dot{Q}_{in}}} = \frac{1}{\frac{\dot{Q}_{out}}{\dot{Q}_{in}} - 1} = \frac{1}{\frac{\dot{Q}_H}{\dot{Q}_L} - 1}$$

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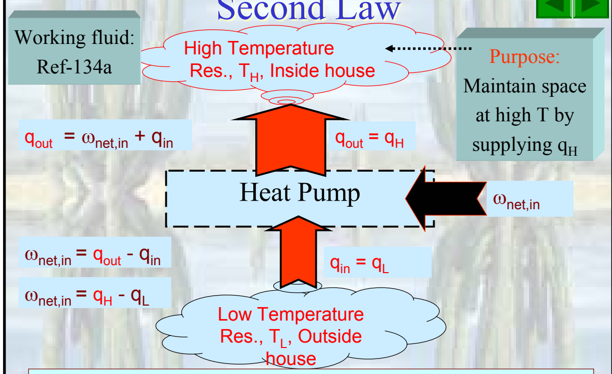
## Second Law




An Energy-Flow diagram for a Heat Pump

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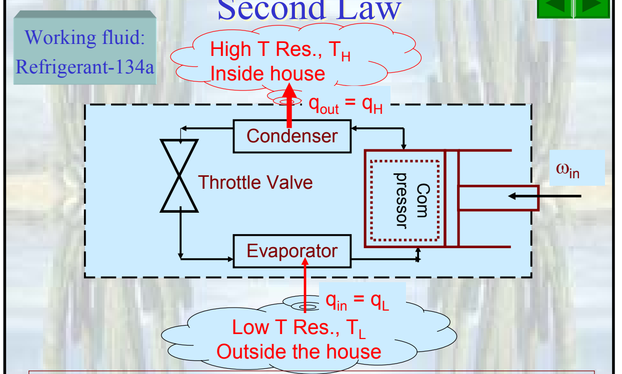
## Second Law




A Schematic diagram for a Heat Pump

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## Second Law

Coefficient of Performance for a Heat Pump

$$COP_{HP} = \frac{desired\ \ output}{required\ \ input} = \frac{q_{out}}{\omega_{net,in}}$$

$$COP_{HP} = \frac{q_{out}}{\omega_{net,in}} = \frac{q_{out}}{q_{out} - q_{in}}$$

$$= \frac{1}{\frac{q_{out}}{q_{out}} - \frac{q_{in}}{q_{out}}} = \frac{1}{1 - \frac{q_{in}}{q_{out}}} = \frac{1}{1 - \frac{q_L}{q_H}}$$

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## Second Law

Clausius Statement on Refrigerators/Heat Pump

- It is impossible to construct a device operating in a cycle and produces no effect other than the transfer of heat from a low T to a high T medium.
- Must do external work to the device to make it function. Hence more energy removed to the surrounding.

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# Second Law – Energy Degrade

What is the maximum performance of real engines if it can never achieve 100%??

Factors of irreversibilities

- less heat can be converted to work
  - Friction between 2 moving surfaces
  - Processes happen too fast
  - Non-isothermal heat transfer



# Second Law – Dream Engine

Carnot Cycle

- **Isothermal expansion**
  - ❖Slow adding of Q resulting in work done by system (system expand)
  - ❖$Q_{in} – W_{out} = \Delta U = 0$. So, $Q_{in} = W_{out}$ . Pressure drops.
- **Adiabatic expansion**
  - ❖$0 – W_{out} = \Delta U$. Final U smaller than initial U.
  - ❖T & P drops.



# Second Law – Dream Engine

Carnot Cycle

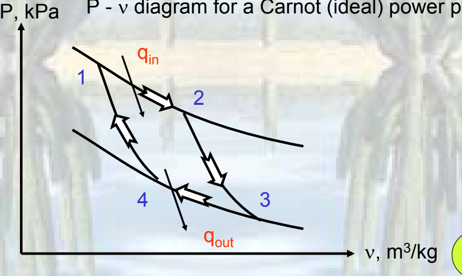
- Isothermal compression
  - ❖Work done on the system
  - ❖Slow rejection of Q
  - ❖$- Q_{out} + W_{in} = \Delta U = 0$. So, $Q_{out} = W_{in}$ .
  - ❖Pressure increases.
- Adiabatic compression
  - ❖$0 + W_{in} = \Delta U$. Final U higher than initial U.
  - ❖T & P increases.



# Second Law – Dream Engine

Carnot Cycle

P - ν diagram for a Carnot (ideal) power plant

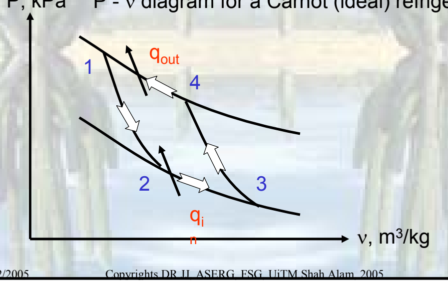





# Second Law – Dream Engine

Reverse Carnot Cycle

P - ν diagram for a Carnot (ideal) refrigerator



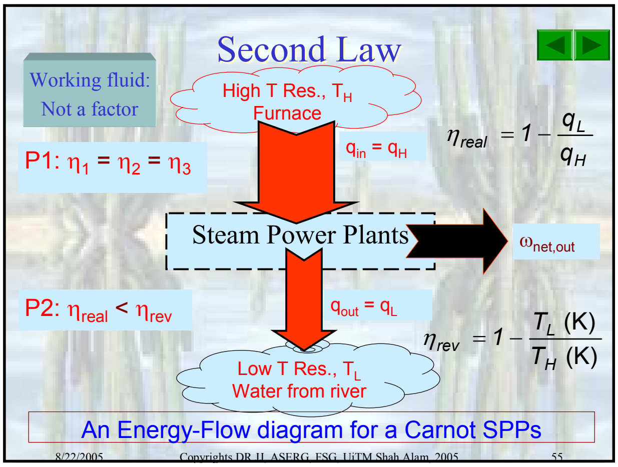



# Second Law – Dream Engine

Carnot Principles

- For heat engines in contact with the same hot and cold reservoir
  - ❖All reversible engines have the same performance.
  - ❖Real engines will have lower performance than the ideal engines.

$$\left(\frac{q_H}{q_L}\right)_{rev} = \frac{T_H\ (K)}{T_L\ (K)}$$


Second Law
Working fluid: Not a factor
P1: $\eta_1 = \eta_2 = \eta_3$
P2: $\eta_{real} < \eta_{rev}$
High T Res., $T_H$ Furnace
$q_{in} = q_H$
Steam Power Plants
$\omega_{net,out}$
$q_{out} = q_L$
Low T Res., $T_L$ Water from river
$\eta_{real} = 1 - \frac{q_L}{q_H}$
$\eta_{rev} = 1 - \frac{T_L\ (K)}{T_H\ (K)}$
An Energy-Flow diagram for a Carnot SPPs
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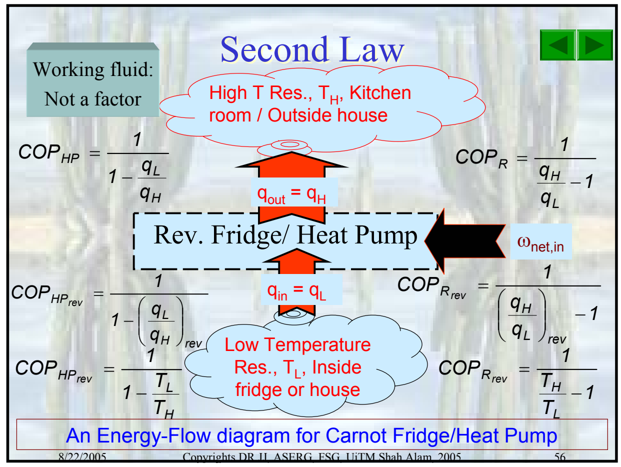
Second Law
Working fluid: Not a factor
High T Res., $T_H$, Kitchen room / Outside house
$q_{out} = q_H$
Rev. Fridge/ Heat Pump
$\omega_{net,in}$
$q_{in} = q_L$
Low Temperature Res., $T_L$, Inside fridge or house
$COP_{HP} = \frac{1}{1 - \frac{q_L}{q_H}}$
$COP_R = \frac{1}{\frac{q_H}{q_L} - 1}$
$COP_{HP_{rev}} = \frac{1}{1 - \left(\frac{q_L}{q_H}\right)_{rev}}$
$COP_{R_{rev}} = \frac{1}{\left(\frac{q_H}{q_L}\right)_{rev} - 1}$
$COP_{HP_{rev}} = \frac{1}{1 - \frac{T_L}{T_H}}$
$COP_{R_{rev}} = \frac{1}{\frac{T_H}{T_L} - 1}$
An Energy-Flow diagram for Carnot Fridge/Heat Pump
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