CAE 208 / MMAE 320: Thermodynamics

Fall 2023

October 31, 2023

Mass & energy analysis of control volumes (5) and intro to second law (1)

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ANNOUNCEMENTS

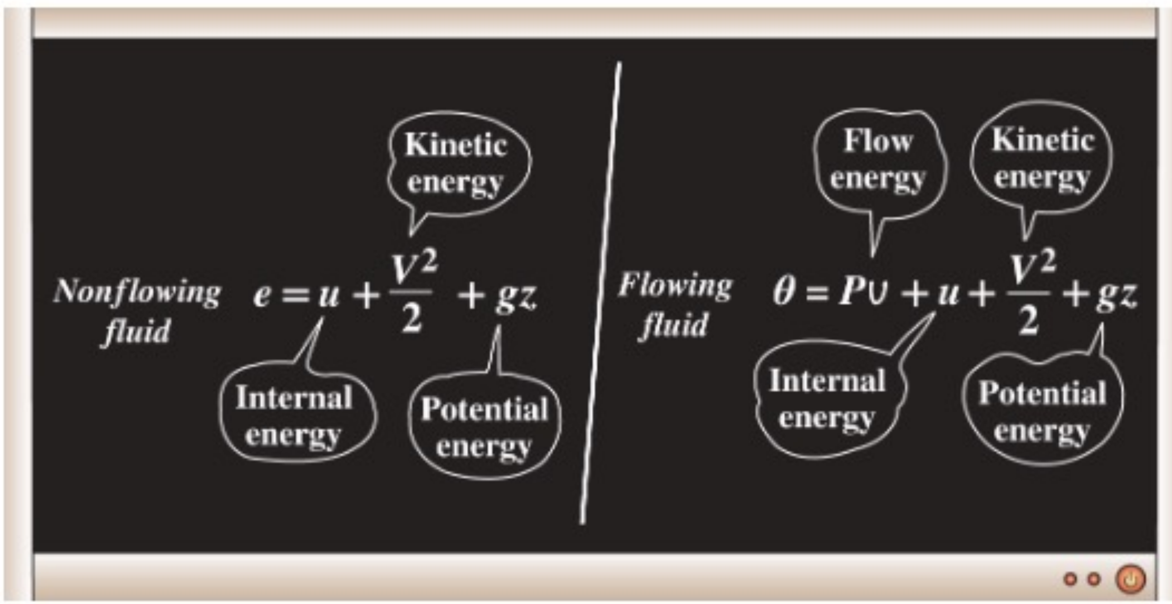
Announcements

- The solution to Assignment 6 is posted
- Assignment 7 is due this Thursday

RECAP

Recap

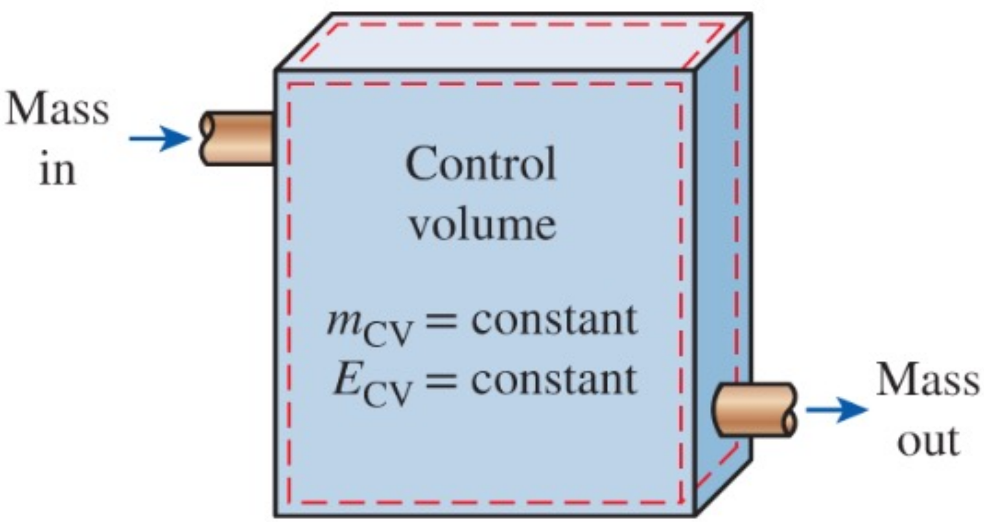
- Total energy of a flowing fluid is:



$$\theta = Pv + e = Pv + (u + ke + pe) = (u + Pv) + ke + pe$$

Recap

- Steady-flow process:
  - ❑ No intensive or extensive properties within the control volume change with time
  - ❑ Boundary work is zero
  - ❑ $\Delta E_{CV} = 0$



Recap

- Steady-flow process:

$$\sum_{in} \dot{m} = \sum_{out} \dot{m}$$

Recap

- Steady-flow process:

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{system}}{dt} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}\theta = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}\theta$$

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}(h + \frac{V^2}{2} + gz) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}(h + \frac{V^2}{2} + gz)$$

Recap

- Steady flow applications

Application	Energy Equations
Nozzles and diffusers	$\dot{Q} \cong 0$; $\dot{W} = 0$ $(most\ times)$; $\Delta pe \cong 0$; $\Delta ke \neq 0$; enthalpy exits
Throttling valves / capillary tubes	$\dot{Q} \cong 0$; $\dot{W} = 0$; $\Delta pe \cong 0$; $\Delta ke = 0$; $h_2 \cong h_1$
Mixing streams	$\dot{Q} \cong 0$; $\dot{W} \cong 0$; $\Delta ke \cong 0$; $\Delta pe \cong 0$; enthalpy exits
Heat exchangers	$\dot{W} \cong 0$; $\Delta ke \cong 0$; $\Delta pe \cong 0$; $\dot{Q}$ depends!; enthalpy exists
Pipe flow	$\Delta \mathrm{ke} = 0$; $\Delta pe = 0$; $\dot{Q}$ and $\dot{W}$ depend; enthalpy exists

- Don’t forget about your mass balance equation as the second equation!
- The formulation of mass and energy equations could vary for for a given application based on the system selection (e.g., heat exchangers)!

Recap

QUIZ

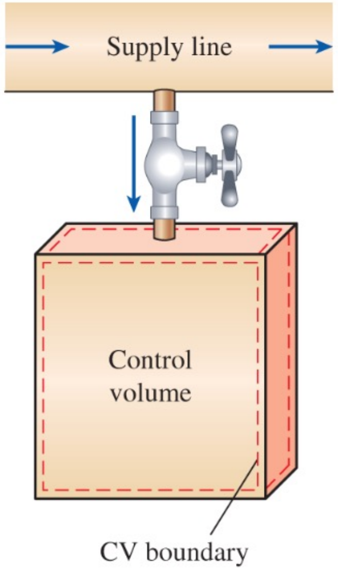
Quiz

ENERGY ANALYSIS O UNSTEADY-FLOW PROCESSES

Energy Analysis of Unsteady-Flow Processes

- During a steady-flow process, no changes occur within the control volume, so one does not need to be concerned about what is going on within the boundaries

- However, many processes involve change within the control volume with respect to time, which we call them *unsteady-flow* or *transient-flow* processes



Energy Analysis of Unsteady-Flow Processes

- We deal with changes that occur over some time interval Δt instead of with the rate of changes

- At unsteady-flow system in some respects is similar to a closed system, except that the mass within the system boundaries does not remain constant during a process

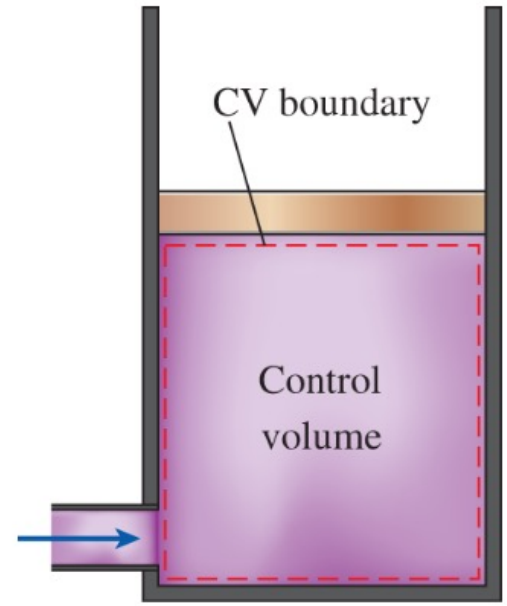
- Steady-flow systems are fixed in space, size, and shape while unsteady-flow systems are not. They are usually stationary that is they are fixed in space, but they may involve moving boundaries and thus boundary work

Energy Analysis of Unsteady-Flow Processes

- Let's look at unsteady flow processes:

$$m_{in} - m_{out} = \Delta m_{system}$$

$$\Delta m_{system} = m_{final} - m_{initial}$$



subscripts:
- "i" = inlet
- "e" = exit
- "1" = initial state
- "2" = final state

Energy Analysis of Unsteady-Flow Processes

- Let's look at unsteady flow processes and a few cases for mass change:

$$m_i - m_e = (m_2 - m_1)_{CV}$$

Empty CV (no initial mass):

CV with mass (initial mass exists):

Energy Analysis of Unsteady-Flow Processes

- Let's look at unsteady flow processes and a few cases for mass change:

$$m_i - m_e = (m_2 - m_1)_{CV}$$

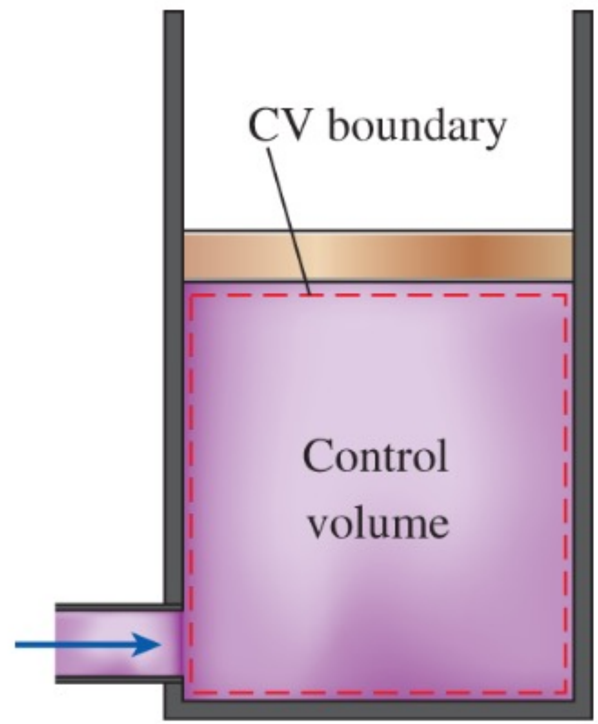
Inlet flow (mass in the inlet)

Exit flow (mass in the exit)

Energy Analysis of Unsteady-Flow Processes

- Let's look at unsteady energy balance:

$$E_{in} - E_{out} = \Delta E_{system}$$



Energy Analysis of Unsteady-Flow Processes

- Let's look at unsteady flow process energy balance
  - It is difficult to solve
  - Sometimes we can use uniform-flow process

$$\left(Q_{in} + W_{in} + \sum_{in} m\theta\right) - \left(Q_{out} + W_{out} + \sum_{out} m\theta\right) = (m_2 e_2 - m_1 e_1)_{system}$$

Energy Analysis of Unsteady-Flow Processes

- Let's look at unsteady flow process energy balance
  - A few simplified cases (kinetic and potential energy changes associated with the control volume and fluid streams are negligible):

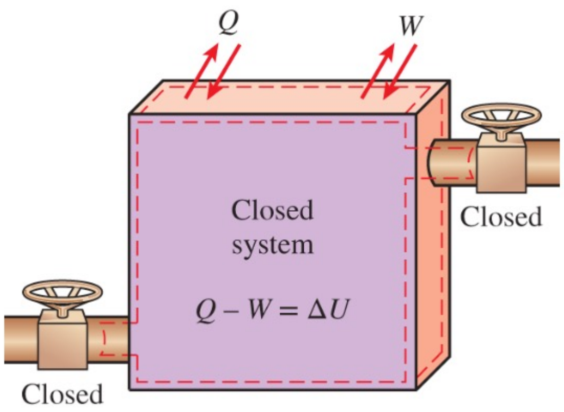
$$Q - W = \sum_{out} mh - \sum_{in} mh + (m_2 u_2 - m_1 u_1)_{system}$$

$$Q = Q_{net,in} = Q_{in} - Q_{out}$$

$$W = W_{net,in} = W_{in} - W_{out}$$

Energy Analysis of Unsteady-Flow Processes

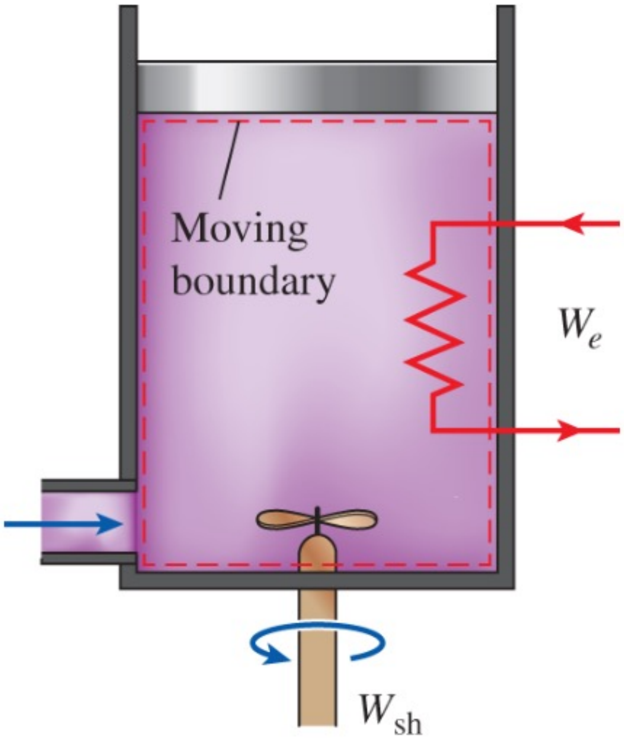
- Let's look at unsteady flow process energy balance
  - If no mass enters or leaves the control during a process ($m_i = m_e = 0$ and $m_1 = m_2 = m$), the equation reduces to the energy balance relation for closed systems



$$(Q_{in} + W_{in} + \sum_{in} m\theta) - (Q_{out} + W_{out} + \sum_{out} m\theta) = (m_2e_2 - m_1e_1)_{system}$$

Energy Analysis of Unsteady-Flow Processes

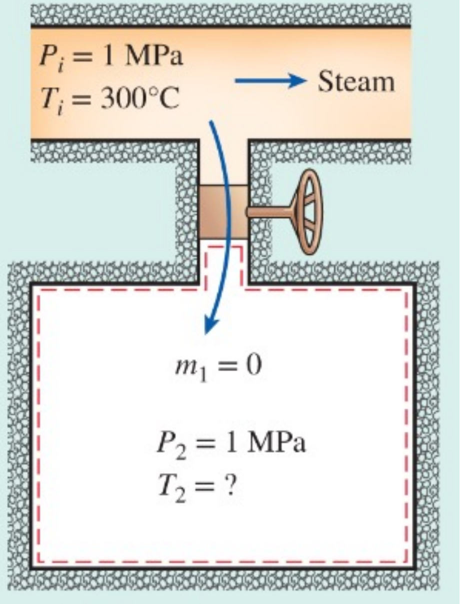
- Let's look at unsteady flow process energy balance
  - It can also involve work:



CLASS ACTIVITY

Class Activity

- A rigid, insulated tank that is initially evacuated is connected through a valve to a supply line that carries at 1 MPa and 300 °C. Now the valve is opened, and steam is allowed to flow slowly into the tank until the pressure reaches 1 MPa, at which the valve is closed. Determine the final temperature of the steam in the tank.



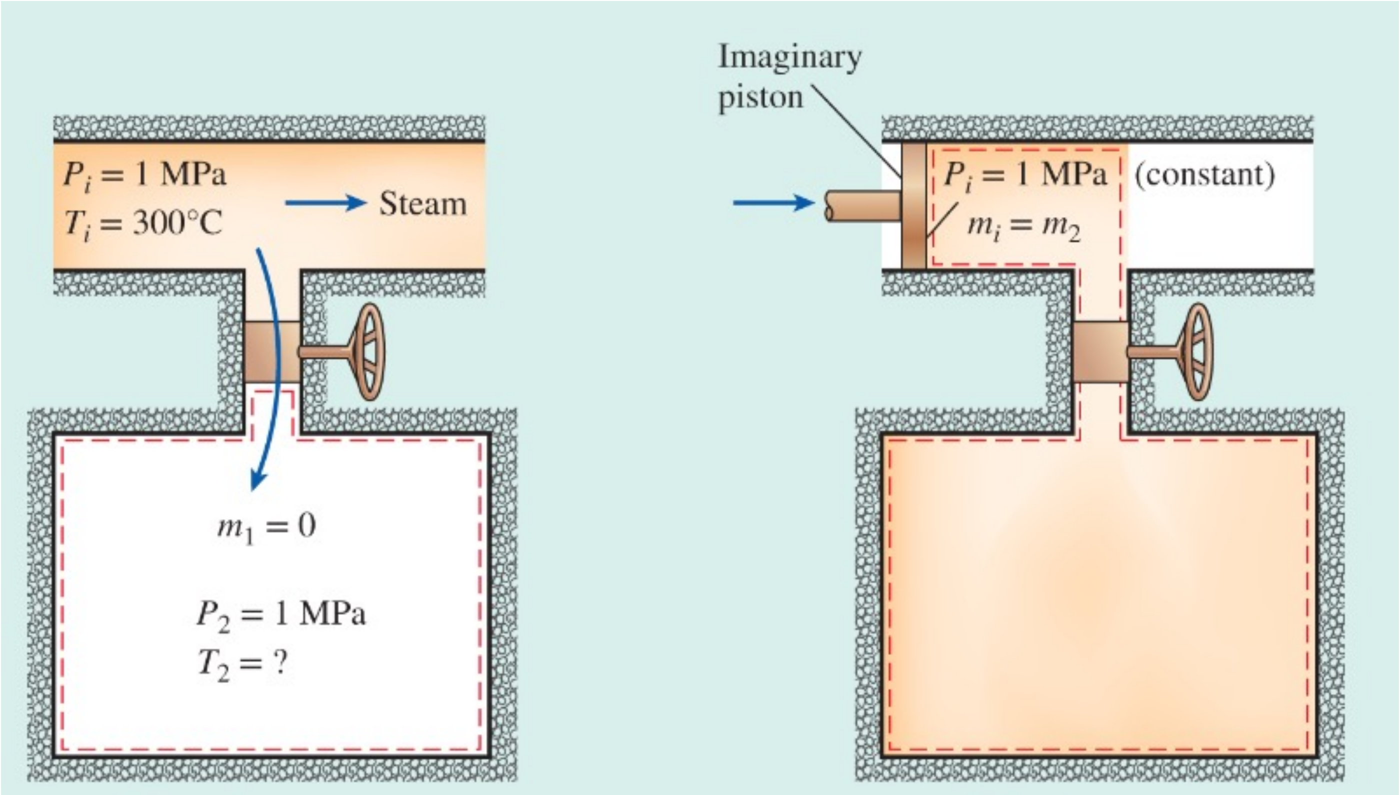
(*a*) Flow of steam into an evacuated tank

Class Activity

- Solution (assumptions):
  1. This process can be analyzed as a uniform-flow process since the properties of the steam entering the control volume remain constant during the entire process
  2. The kinetic and potential energies of the streams are negligible
  3. The tank is stationary and thus its kinetic and potential energy changes are zero $(\Delta \mathrm{KE} = \Delta PE = 0)$ and $\Delta E_{System} = \Delta U_{System}$
  4. There are no boundary, electrical, or shaft work interactions involved
  5. The tank is well-insulated and this there is no heat transfer

Class Activity

- Solution:



(*a*) Flow of steam into an evacuated tank

(*b*) The closed-system equivalence

Class Activity

- Solution (mass balance):

$$m_{in} - m_{out} = \Delta m_{system} = m_2 - m_1$$

$$m_i = m_2$$

Class Activity

- Solution (energy balance):

$$E_{in} - E_{out} = \Delta E_{system}$$

$$(Q_{in} + W_{in} + \sum_{in} m\theta) - (Q_{out} + W_{out} + \sum_{out} m\theta) = (m_2 e_2 - m_1 e_1)_{system}$$

$$m_i h_i = m_2 u_2$$

$$h_i = u_2$$

Class Activity

- Solution (finding states):

$$\left.\begin{array}{l} P_i = 1\ MPa \\ T_i = 300\ °C \end{array}\right\} \rightarrow\ h_i = 3051.6\,\frac{kJ}{kg}$$

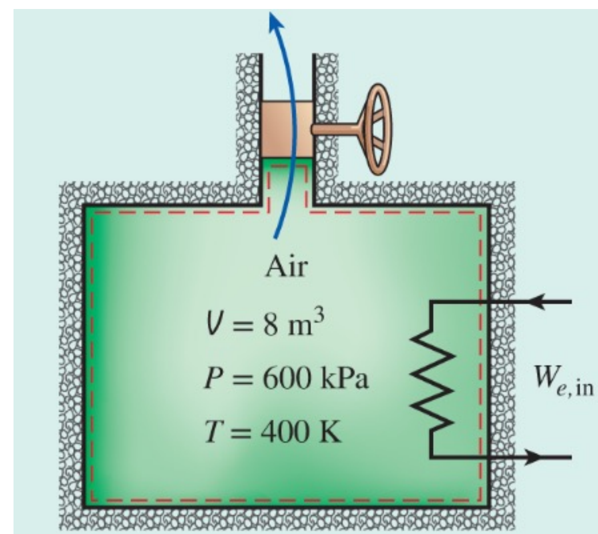
$$h_i = 3051.6\,\frac{kJ}{kg} = u_2$$

$$\left.\begin{array}{r} P_2 = 1\ MPa \\ h_2 = 3051.6\,\dfrac{kJ}{kg} \end{array}\right\} \rightarrow T_2 = 456.1\ °C$$

CLASS ACTIVITY

Class Activity

- An insulated 8 m^3 rigid tank contains air at 600 kPa and 400 K. A valve is connected to the tank is now opened, and air is allowed to escape until the pressure inside drops to 200 kPa. The air temperature during the process is maintained constant by an electric resistance heater placed in the tank. Determine the electrical energy supplied to air during this process.



Class Activity

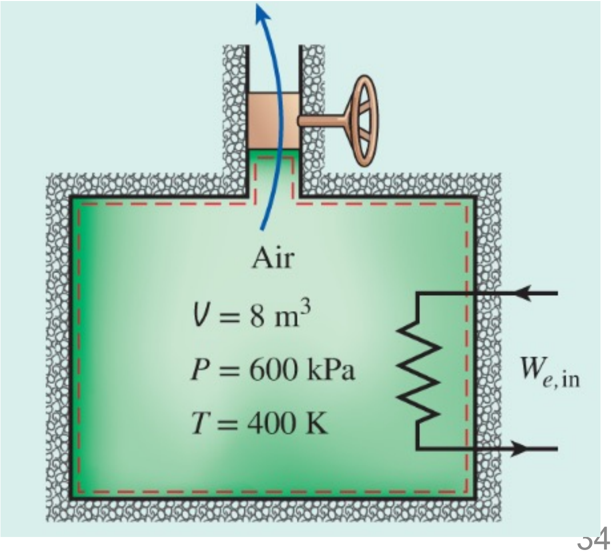
- Solution (assumptions):
  1. This process can be analyzed as a uniform-flow process since the properties of the steam entering the control volume remain constant during the entire process
  2. The kinetic and potential energies of the streams are negligible
  3. The tank is insulated, so heat transfer can be negligible
  4. Air is an ideal gas

Class Activity

- Solution (mass balance):

$$m_{in} - m_{out} = \Delta m_{system} = m_2 - m_1$$

$$m_e = m_1 - m_2$$



Class Activity

- Solution (energy balance):

$$E_{in} - E_{out} = \Delta E_{system}$$

$$(Q_{in} + W_{in} + \sum_{in} m\theta) - (Q_{out} + W_{out} + \sum_{out} m\theta) = (m_2 e_2 - m_1 e_1)_{system}$$

$$W_{e,in} - m_e h_e = m_2 u_2 - m_1 u_1$$

Class Activity

- Solution (calculating masses):

$$R = 0.287 \frac{kPa.m^3}{kg-K}$$ (Table A-1)

$$m_1 = \frac{P_1 v_1}{RT_1} = \frac{(600\ kPa)(8\ m^3)}{(0.287\ \frac{kPa - m^3}{kg - K})(400\ K)} = 41.81\ kg$$

$$m_2 = \frac{P_1 v_1}{RT_1} = \frac{(200\ kPa)(8\ m^3)}{(0.287\ \frac{kPa - m^3}{kg - K})(400\ K)} = 13.94\ kg$$

$$m_e = m_1 - m_2 = 41.81 - 13.94 = 27.87\ kg$$

Class Activity

- Solution (calculating masses):

$$at\ 400\ K\ (Table\ A-21): \begin{cases} h_e = 400.98\,\dfrac{kJ}{kg} \\ u_1 = u_2 = 286.16\,\dfrac{kJ}{kg} \end{cases}$$

$$W_{e,in} = m_e h_e + m_2 u_2 - m_1 u_1$$

$$W_{e,in} = (27.87\ kg)\left(400.98\,\frac{kJ}{kg}\right) + (13.94\ kg)\left(286.16\,\frac{kJ}{kg}\right) - (41.81\ kg)\left(286.16\,\frac{kJ}{kg}\right)$$
$$= 3200\ kJ = 0.889\ kWh$$

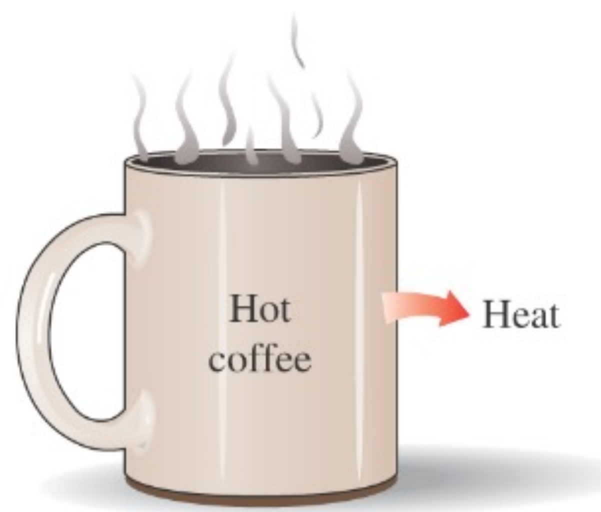
INTRO TO THE SECOND LAW

Intro to the Second Law

- We so far looked at the first law of thermodynamics or the conservation of energy principle

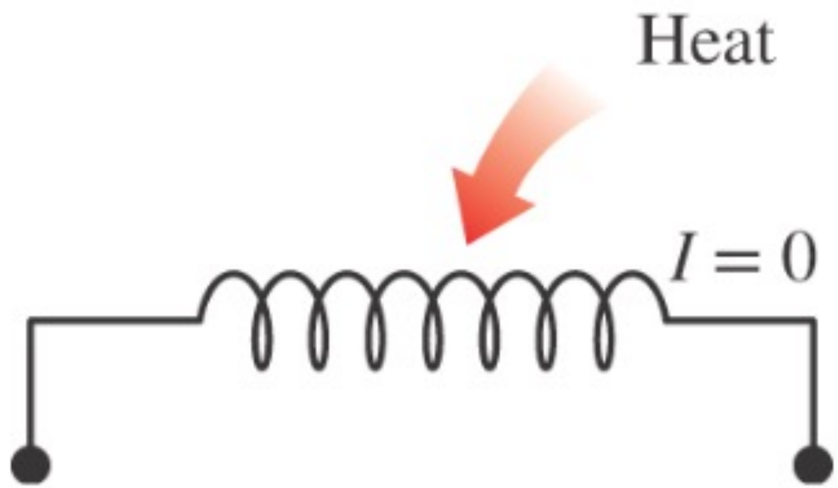
- However, satisfying the first law alone does not ensure that the process will actually take place

- Let's consider the hot coffee cup



Intro to the Second Law

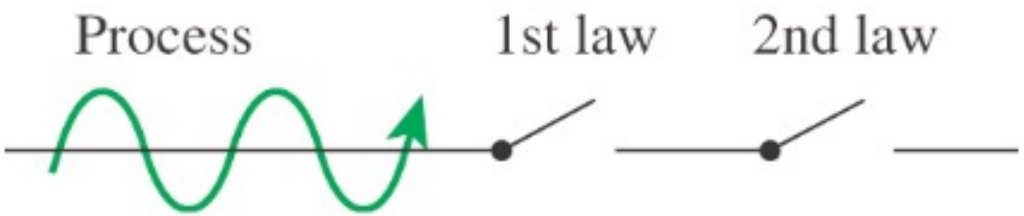
- Let's look another example:



Intro to the Second Law

- It is clear from these arguments that processes proceed in a certain direction and in the reverse direction

- The first law places no restriction on the direction of a process but satisfying the first law does not ensure that the process can actually occur



Intro to the Second Law

- The inadequacy of the first law to identify whether a process can take place is remedied by introducing another general principle, the second law of thermodynamics (the reverse processes violate the second law of thermodynamics)

- This violation is easily detected with the help of a property called entropy

- A process cannot occur unless it satisfies *both the first and the second laws of thermodynamics*

Intro to the Second Law

- We have two statements for the second law
- The use of the second law of thermodynamics is not limited to identifying the direction of processes
- The second law also asserts that energy has quality as well as quantity
- The second law provides the necessary means to determine the quality as well as the degree of degradation of energy during a process
- High temperature energy can be converted to work and thus it has a higher quality than the same amount of energy at a lower temperature

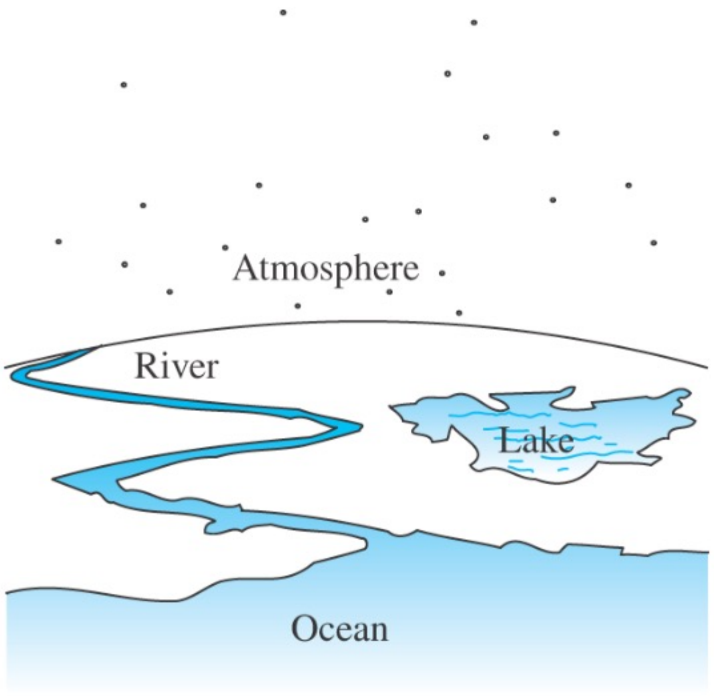
Intro to the Second Law

- The second law determine the theoretical limits for the performance of commonly used engineering systems, such as heat engines and refrigerators as well as predicting the degree of completion of chemical reactions

THERMAL ENERGY RESERVOIRS

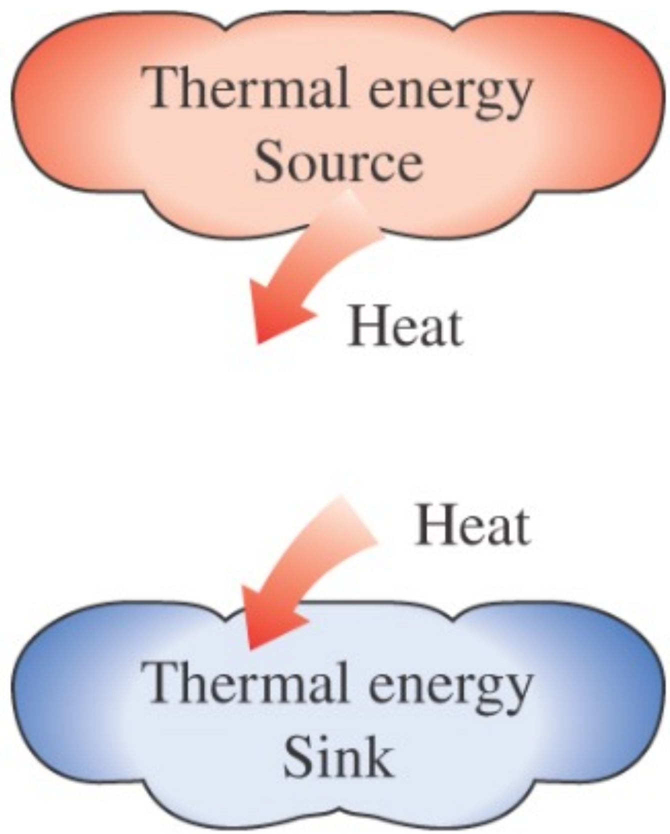
Intro to the Second Law

- We can assume a hypothetical body with a relatively large thermal capacity (mass times specific heat) that can supply or absorb finite amounts of heat without undergoing any change in temperature. Such a body is called a thermal energy reservoir, or just a reservoir.



Intro to the Second Law

- We can define source and sink:

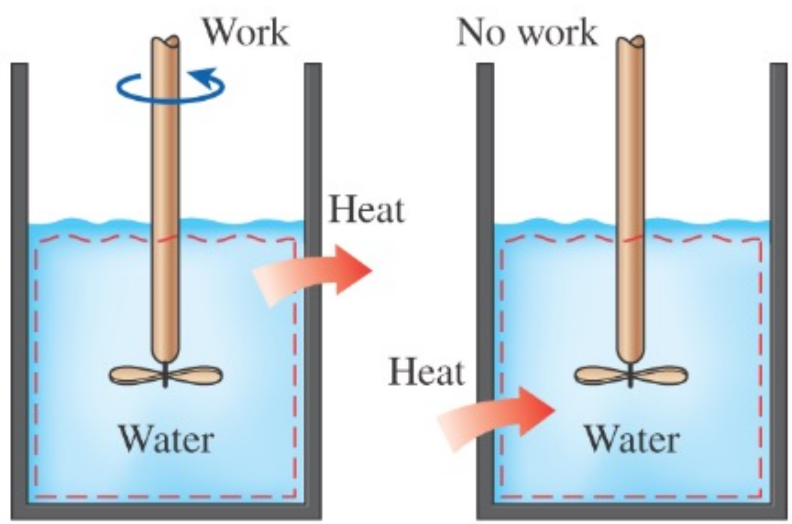


HEAT ENGINES

Heat Engines

- As we saw, work can be converted to other forms of energy, but converting other forms or energy to work is not that easy (e.g., heat leaving water)

- We can convert work to heat directly and completely but converting heat to work requires the use of some special devices named heat engines



Heat Engines

- Lighting fixtures / Electrical heaters

- Matches / internal combustion engine

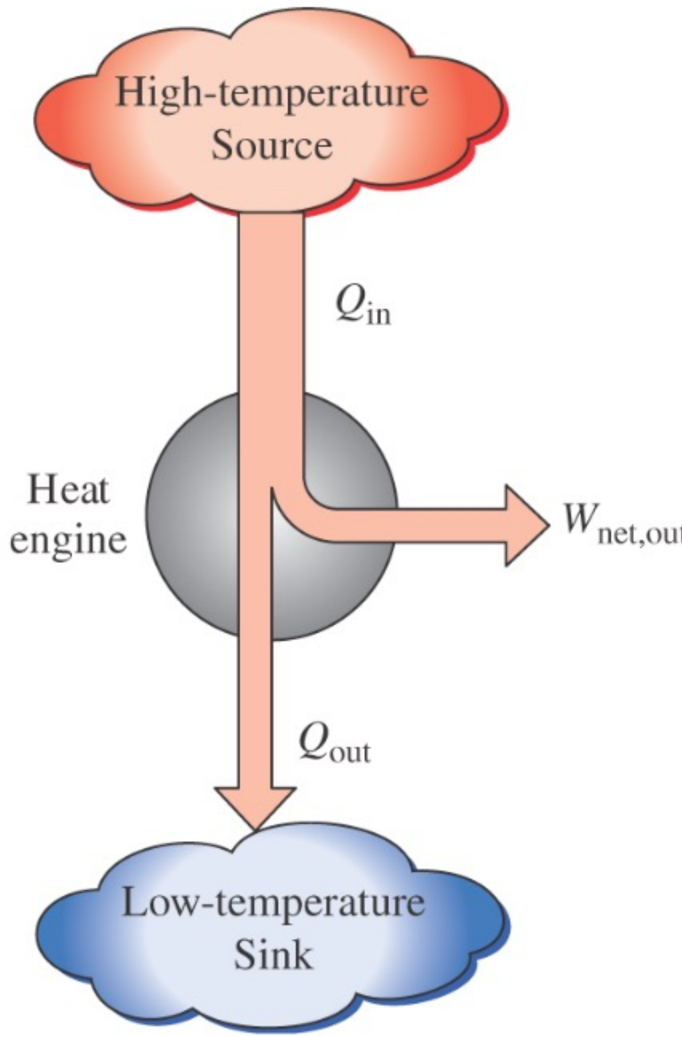
Heat Engines

- Heat engines differ considerably from one another, but all can be characterized by these criteria:
  - ❑ They receive heat from a high temperature source (e.g., solar, oil, …)
  - ❑ They convert part of this heat to work (usually in the form of a rotating shaft)
  - ❑ They reject the remaining waste heat to a low-temperature sink (e.g., the atmosphere, rivers, …)
  - ❑ They operate on a cycle

- Heat engines an other cyclic devices usually involve a fluid to and from which heat is transferred while undergoes a cycle. We call the fluid, a working fluid

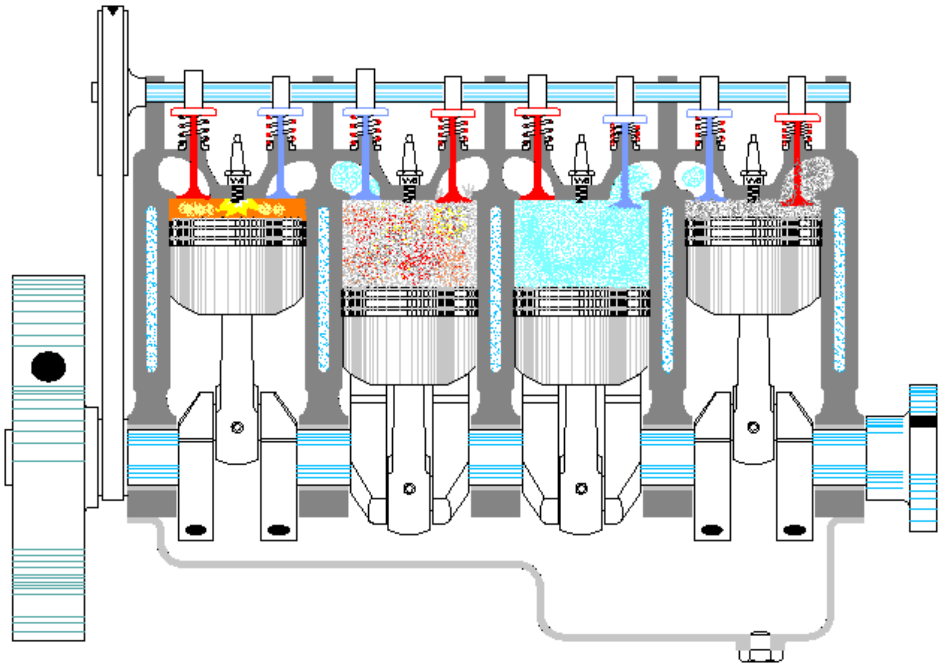
Heat Engines

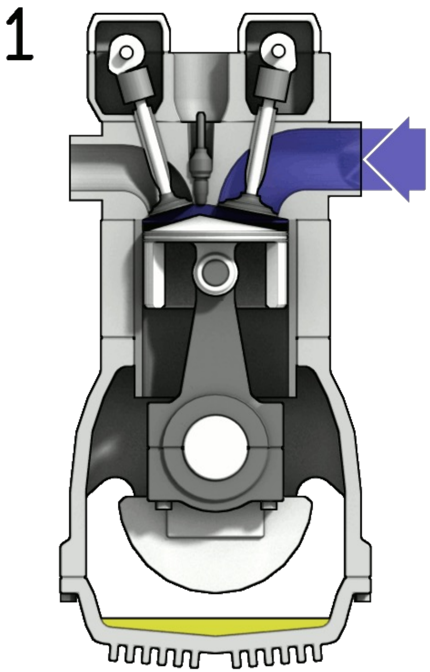
- Heat engines cycles are as following:



Heat Engines

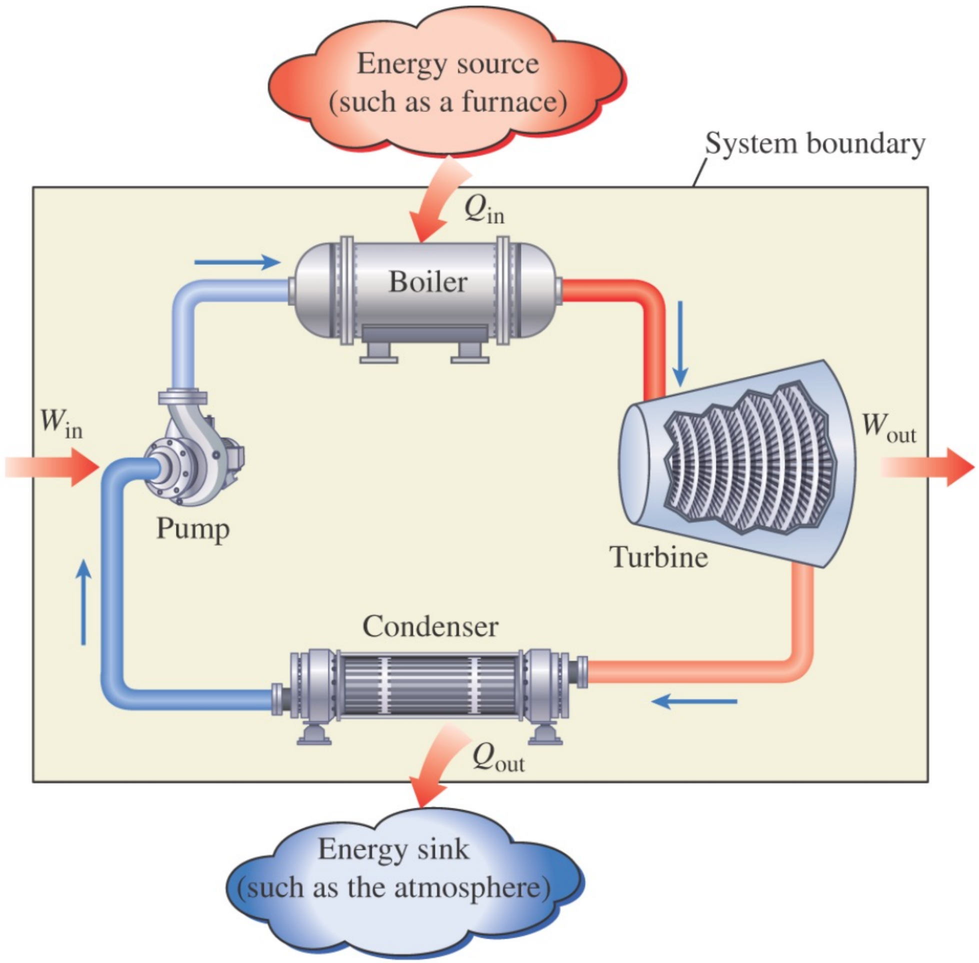
- A lot of times, heat engines are used in a broader sense to consider mechanical engines that do not undergo a complete thermodynamic cycle (e.g., internal combustion engine)





Heat Engines

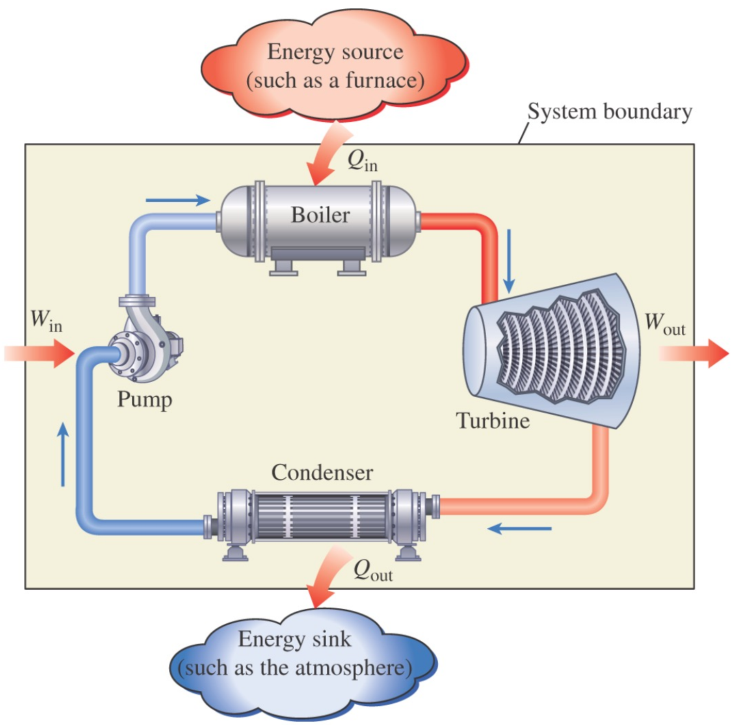
- The best example of a heat engine is the steam power plant:



Heat Engines

- The best example of a heat engine is the steam power plan:

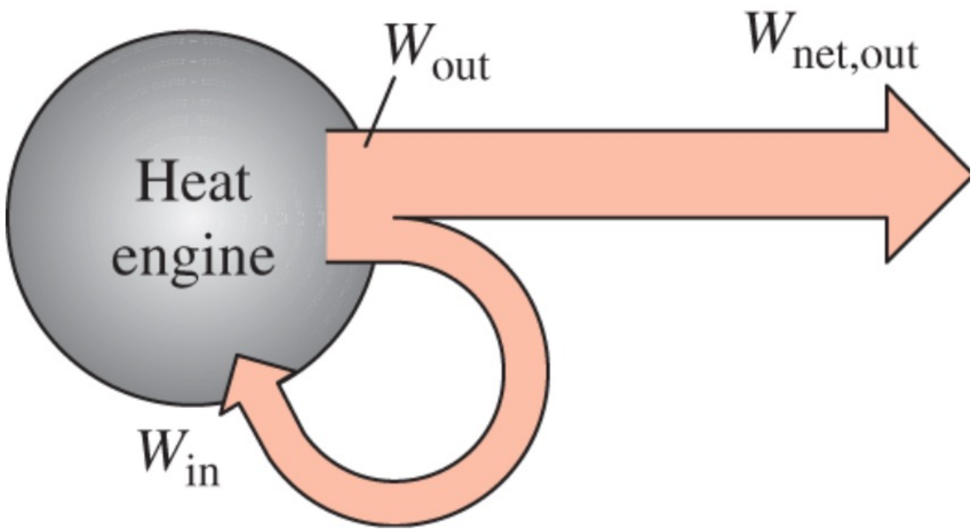
Q_{in} = amount of heat supplied to steam in boiler from a high-temperature source (furnace)
Q_{out} = amount of heat rejected from steam in condenser to a low-temperature sink (the atmosphere, a river, etc.)
W_{out} = amount of work delivered by steam as it expands in turbine
W_{in} = amount of work required to compress water to boiler pressure



Heat Engines

- What's the net work?

$$W_{net,out} = W_{out} - W_{in} \qquad \text{(kJ)}$$



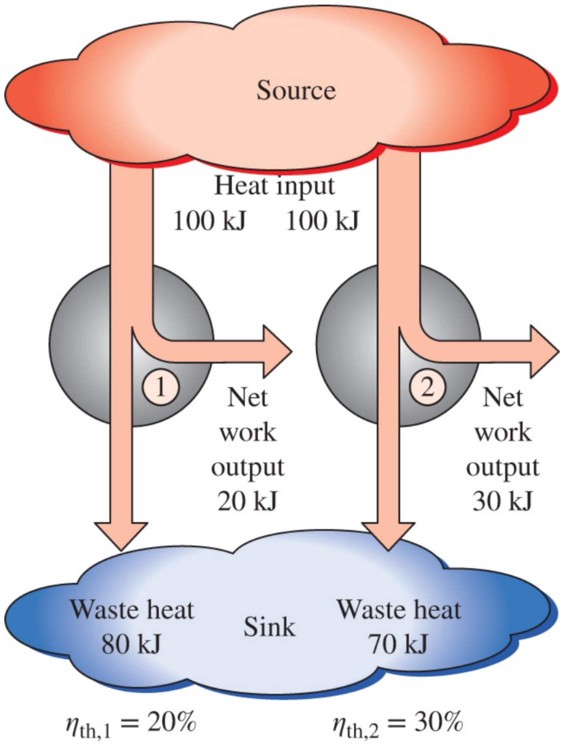
Heat Engines

- Do you remember the relation between work and heat for a cycle?

$$W_{net,out} = Q_{in} - Q_{out}$$

Heat Engines

- The fraction of the heat input that is converted to net work output is a measure of the performance of a heat engine is called the *thermal efficiency*



$$Thermal\ efficiency = \frac{Net\ works\ output}{Total\ heat\ input}$$

Heat Engines

- Thermal efficiency

$$Thermal\ efficiency = \frac{Net\ works\ output}{Total\ heat\ input}$$

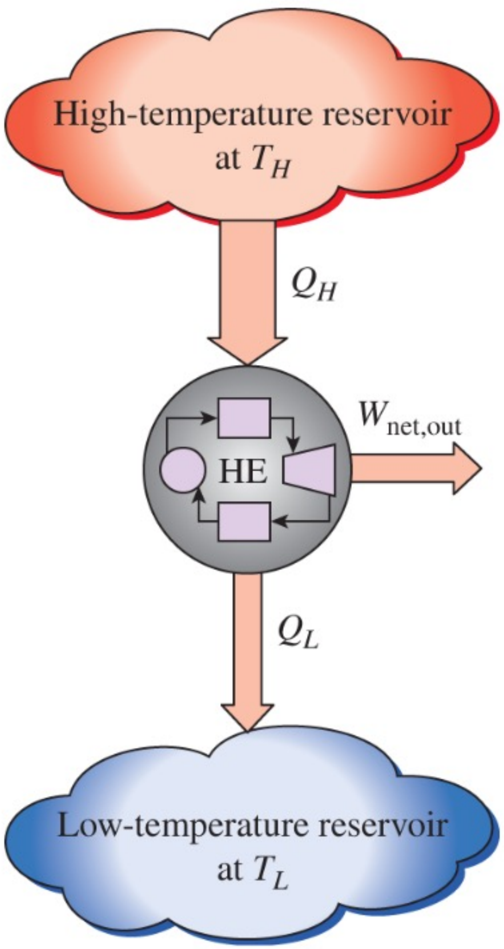
$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

Heat Engines

- Cyclic devices (e.g., heat pumps, refrigerators, heat engines) operate between a high temperature medium (or reservoir) and a low temperature medium (or reservoir)
  - ❑ Q_H: Magnitude of heat transfer between the cyclic device and the high-temperature medium at temperature T_H
  - ❑ Q_L: Magnitude of heat transfer between the cyclic device and the low-temperature medium at temperature T_L

Heat Engines

- Using this definition, we can redefine the thermal efficiency:



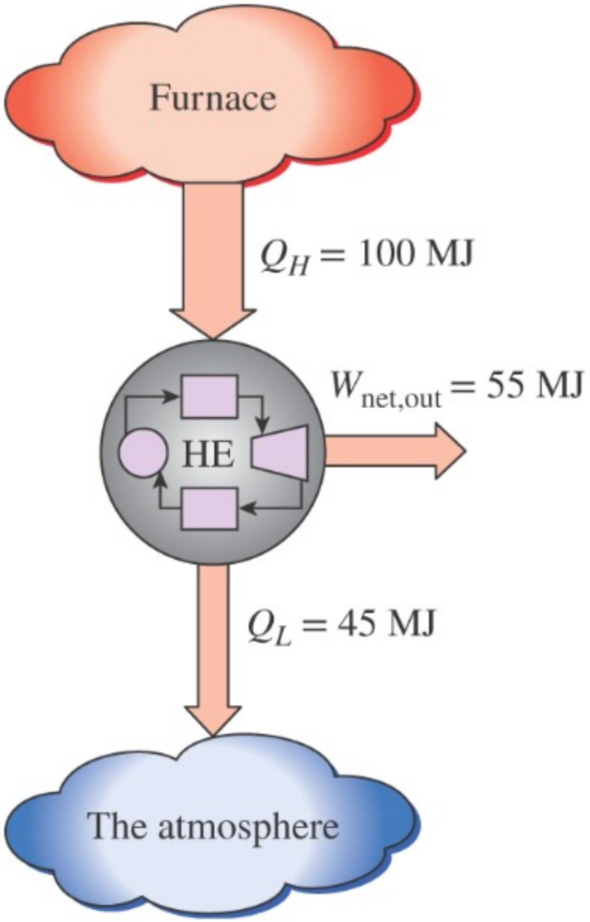
$$W_{net,out} = Q_H - Q_L$$

$$\eta_{th} = \frac{W_{net,out}}{Q_H}$$

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

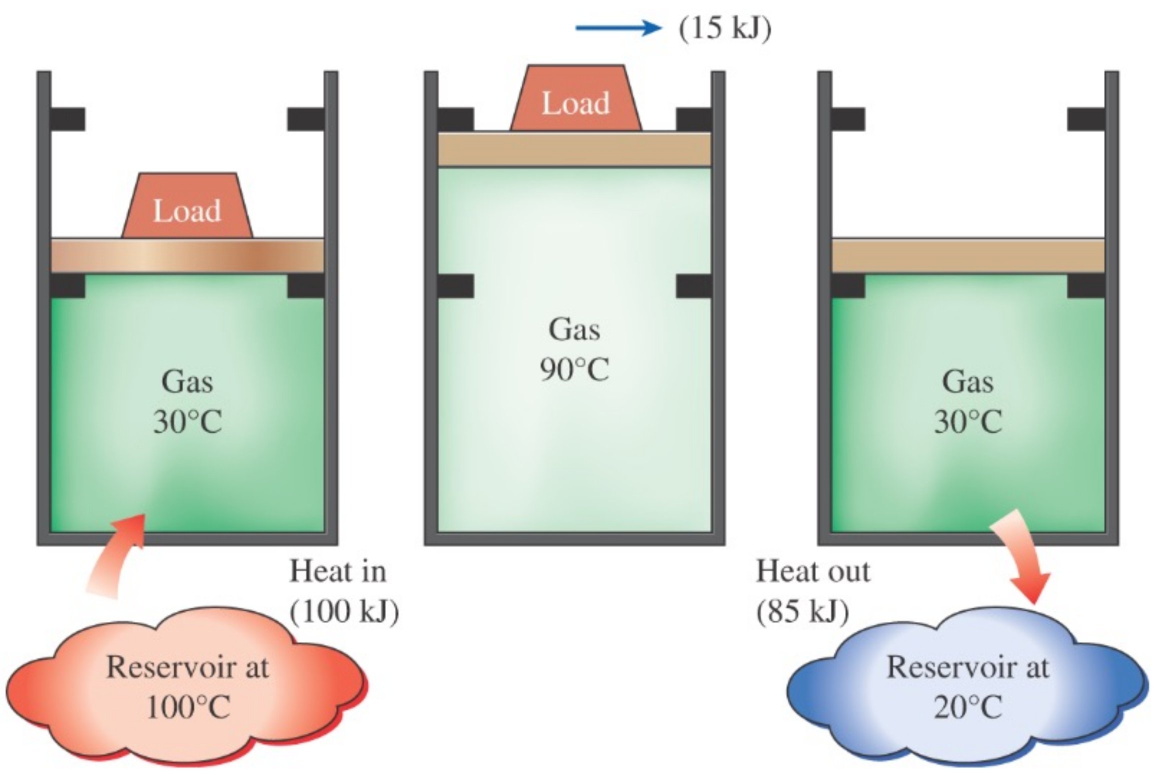
Heat Engines

- Most heat engines reject significant heat to outside



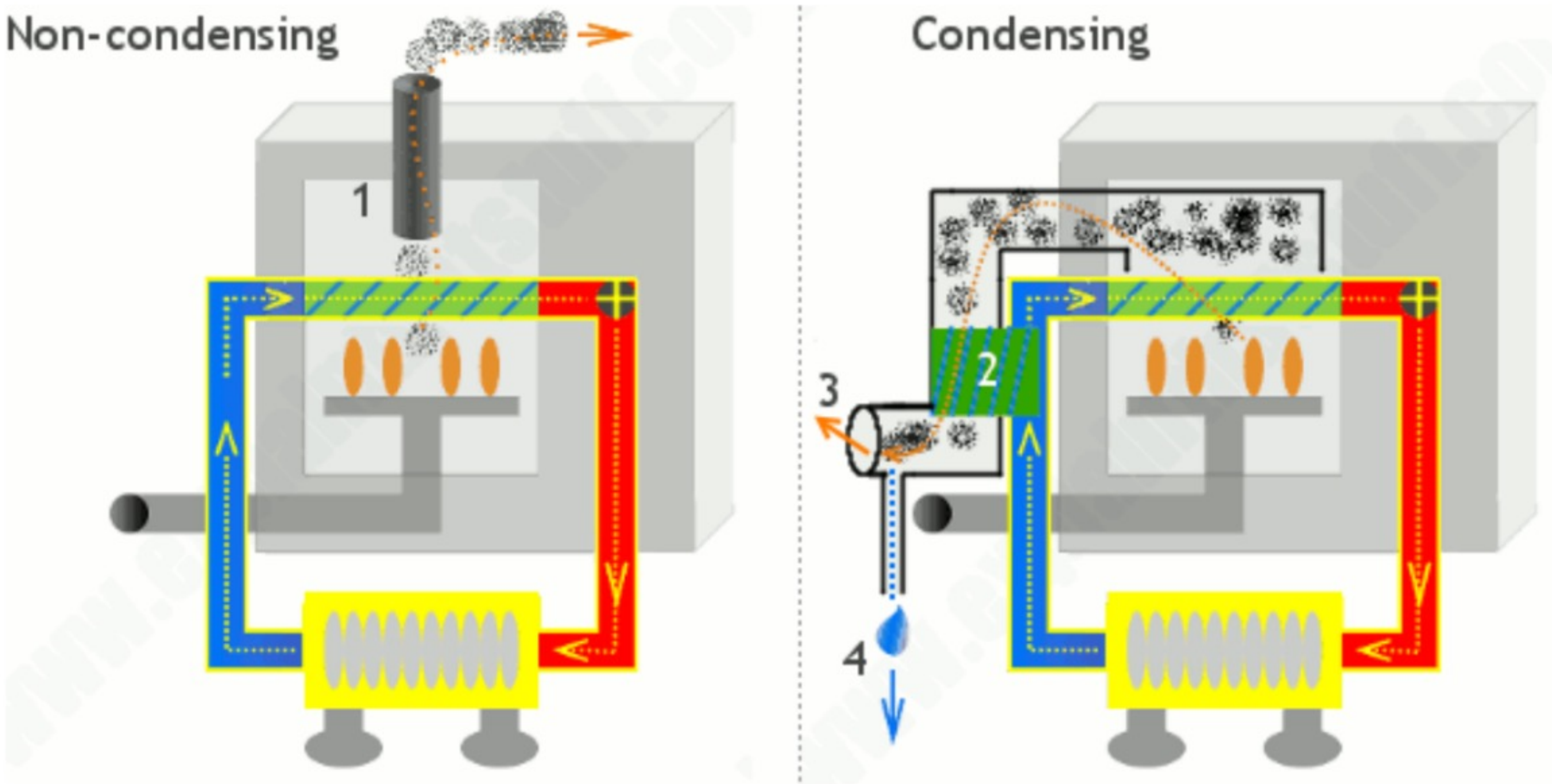
Heat Engines

- Can we save Q_{out}? Unfortunately, no, the cycle has to be completed!



Heat Engines

- We can improve the thermal efficiency:



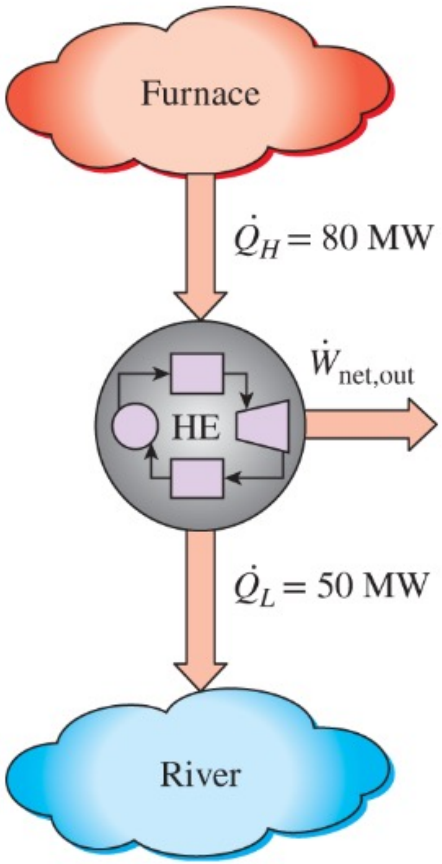
CLASS ACTIVITY

Class Activity

- Heat is transferred to a heat engine from a furnace at a rate of 80 MW. If the rate of waste heat rejection to a nearby river is 50 MW, determine net power output and the thermal efficiency for this heat engine.

Class Activity

- Solution:



Class Activity

- Solution:

$$\dot{Q}_H = 80\ MW$$

$$\dot{Q}_L = 50\ MW$$

$$\dot{W}_{net} = 80MW - 50\ MW = 30\ MW$$

$$\eta_{th} = \frac{\dot{W}_{net,out}}{\dot{Q}_H} = \frac{30\ MW}{80\ MW} = 0.375$$

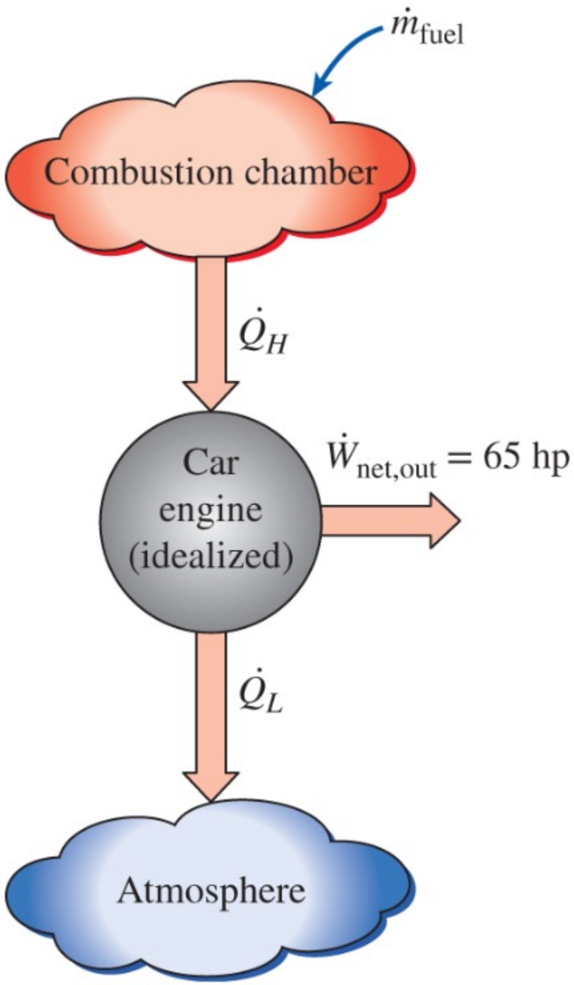
CLASS ACTIVITY

Class Activity

- A car engine with a power output of 65 hp has a thermal efficiency of 24 percent. Determine the fuel consumption rate of this car if the fuel has a heating value of 19,000 Btu/lbm (that is 19,000 Btu of energy is released for each lbm of fuel burned)

Class Activity

- Solution:



$$\dot{Q}_H = \frac{\dot{W}_{net,out}}{\eta_{th}} = \frac{65\ hp}{0.24}\left(\frac{2545\,\frac{Btu}{h}}{1\ hp}\right) = 689{,}270\ Btu/h$$

$$689{,}270\,\frac{Btu}{h} = \dot{m}_{fuel} \times 19{,}000\,\frac{Btu}{lbm}$$

$$\dot{m}_{fuel} = 36.3\,\frac{lbm}{h}$$

Heat Engines

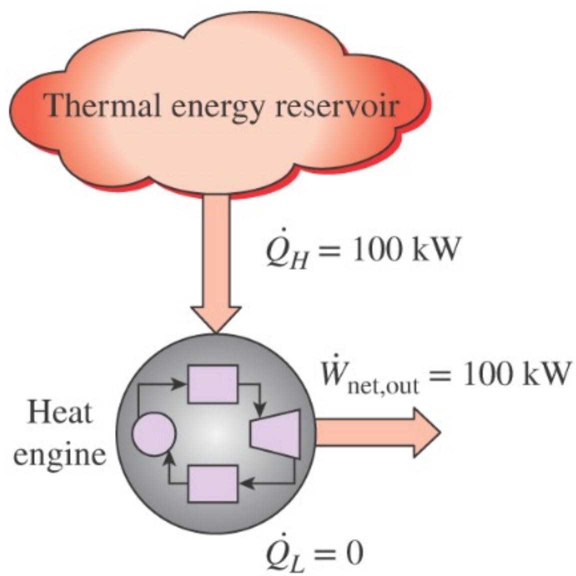
- The Second Law of Thermodynamics: Kelvin-Planck Statement:

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work

Heat Engines

- The Second Law of Thermodynamics: Kelvin-Planck Statement can be expressed as:

No heat engine can have a thermal efficiency of 100 percent



Heat Engines

- The Second Law of Thermodynamics: Kelvin-Planck Statement can be expressed as:

For a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace