The First Law of Thermodynamics

Meeting 6

Section 4-1

So far we've studied two forms of energy transfer

Work Energy (W)

***Equivalent to raising a weight**

Heat (Thermal) Energy (Q)

***Caused by a temperature difference**

(W) and (Q) are path dependent!

$$\int_1^2 \delta W = W_{12} \text{ or } W, \text{ but not } W_2 - W_1$$

and

$$\int_1^2 \delta Q = Q_{12} \text{ or } Q, \text{ but not } Q_2 - Q_1$$

- **Work and Heat are forms of energy transfers that happens at the boundary of a system.**

- **As Work and Heat cross the boundary, the system Energy changes.**

- **Work and Heat are not stored on the system but the Energy yes.**

The Business of the First Law:

$$ {}_1Q_2 - {}_1W_2 = E_2 - E_1 $$

- Energy is ***not destroyed*** but it ***is conserved***. In fact during a thermodynamic process it is ***transformed from one type in to another***.

- The ***first law*** expresses a ***energy balance*** of the system:the energy fluxes in a system (**Work** and **Heat**) is equal to the **Energy** change in a system.

The Energy Forms of the System

- **To state the 'First Law' is necessary to define the energy forms of the system;**

- **We will deal with 'only' three types of Energy:**
  - ***Internal Energy U***
  - ***Kinetic Energy KE***
  - ***Potential Energy PE***

- **The System energy change (*the deltas*) is, therefore:**

$$\boxed{\Delta E = \Delta U + \Delta KE + \Delta PE}$$

Internal Energy…..

Internal energy is the energy a molecule possesses, mostly as a result of:

Translation

Rotation

Vibration

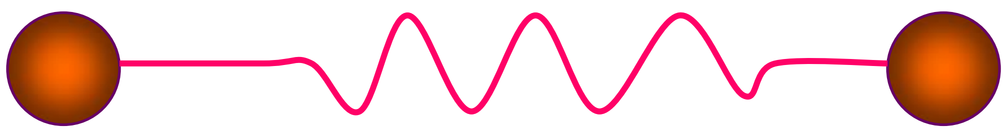
All these are forms of kinetic energy. We will neglect other forms of molecular energy which exist on the atomic level.

Internal Energy: Molecular Translation

- **The energy possessed by a molecule as it moves through space is the Kinetic Energy.**
- **The molecules collisions transfer kinetic energy by <u>linear momentum</u> changes.**
- **The temperature measurement by a thermometer is a manifestation of the molecules collisions against the sensor.**

Internal Energy: Molecular Vibration

- **Molecules (not atoms) also vibrate along their intermolecular bonds.**



The molecule has vibrational (kinetic) energy in this mode.

Internal Energy: Molecular Rotation

- **Molecules (and atoms) can also rotate and they possess kinetic energy in this rotational mode. They have <u>angular momentum</u> which can be changed to add or remove energy.**

We will not worry about the <u>microscopic</u> details of Internal Energy

- Internal energy is a <u>property</u> of the system.
- Often it shows up as a change in Temperature or Pressure of the system …
- But it can also show up as a change in composition if it's a mixture.

The System Kinetic Energy

- **It is the macroscopic kinetic energy associated with the *system mass* and *the velocity* of its mass center:**

$$\Delta KE = \frac{1}{2} m(V_f^2 - V_i^2)$$

$$= \frac{1}{2} m(V_2^2 - V_1^2)$$

The KE change in accelerating a mass of 10 kg from $V_i = 0$ to $V_f = 10$ m/s is?

$$\Delta KE = \frac{1}{2} m (V_f^2 - V_i^2)$$

$$= \frac{1}{2}\left(10\,\text{kg} \cdot 100\,\frac{\text{m}^2}{\text{s}^2}\right) \cdot \left(1\,\frac{\text{N}}{\text{kg} \cdot \frac{\text{m}}{\text{s}^2}}\right) = 500\,\text{N} \cdot \text{m}$$

$$= 500\,\text{N} \cdot \text{m} \times \left(\frac{\text{J}}{\text{N} \cdot \text{m}}\right) \times \left(\frac{\text{kJ}}{1{,}000\,\text{J}}\right) = 0.5\,\text{kJ}$$

Gravity is another force acting on our system. It shows up in the potential energy change.

$$\Delta PE = mg(z_f - z_i) = mg(z_2 - z_1)$$

Work can be done by a change in elevation of the system

TEAMPLAY

Let's say we have a 10 kg mass that we drop 100 m. We also have a device that will convert all the potential energy into kinetic energy of an object. If the object's mass is 1 kg and it is initially at rest, what would be it's final velocity from absorbing the potential from a 100 m drop?

Some comments about the First Law

$$\boxed{{}_1Q_2 - {}_1W_2 = E_2 - E_1}$$

- All terms on the left hand side are forms of energy that ***cross the boundary of the system***
- Q in is positive, W out is positive
- Right hand side is the change on system energy
- Algebraic form of first law

The right hand side of the energy equation consists of three terms:

$$\boxed{\Delta E = \Delta U + \Delta KE + \Delta PE}$$

- **ΔKE - Motion of the system <u>as a whole</u> with respect to some fixed reference frame.**
- **ΔPE - Position change of the system <u>as a whole</u> in the earth's gravity field.**
- **ΔU - Internal energy of the molecule--translation, rotation, vibration, [and energy stored in electronic orbital states, nuclear spin, and others].**

We previously had conservation of energy

- $\Delta E = \Delta U + \Delta PE + \Delta KE$, we can change the total energy E of a system by:

1. Changing the internal energy, perhaps best exemplified by heating.
2. Changing the PE by raising or lowering.
3. Changing the KE by accelerating or decelerating.

Conservation of Energy for Stationary System

- **Stationary** means not moving -so ΔPE and ΔKE are zero and the first law becomes

$$ {}_1Q_2 - {}_1W_2 = \Delta U $$

First Law Forms for <u>Stationary</u> Systems

- **Differential Form:** $$\boxed{\delta Q - \delta W = dU}$$

- **Rate Form:** $$\boxed{\dot{Q} - \dot{W} = \frac{dU}{dt}}$$

  Where: $\dot{Q} = \frac{\delta Q}{dt}$ $\dot{W} = \frac{\delta W}{dt}$

- **Integrated Form:** $$\boxed{{}_1Q_2 - {}_1W_2 = U_2 - U_1}$$

Hints to set up a problem

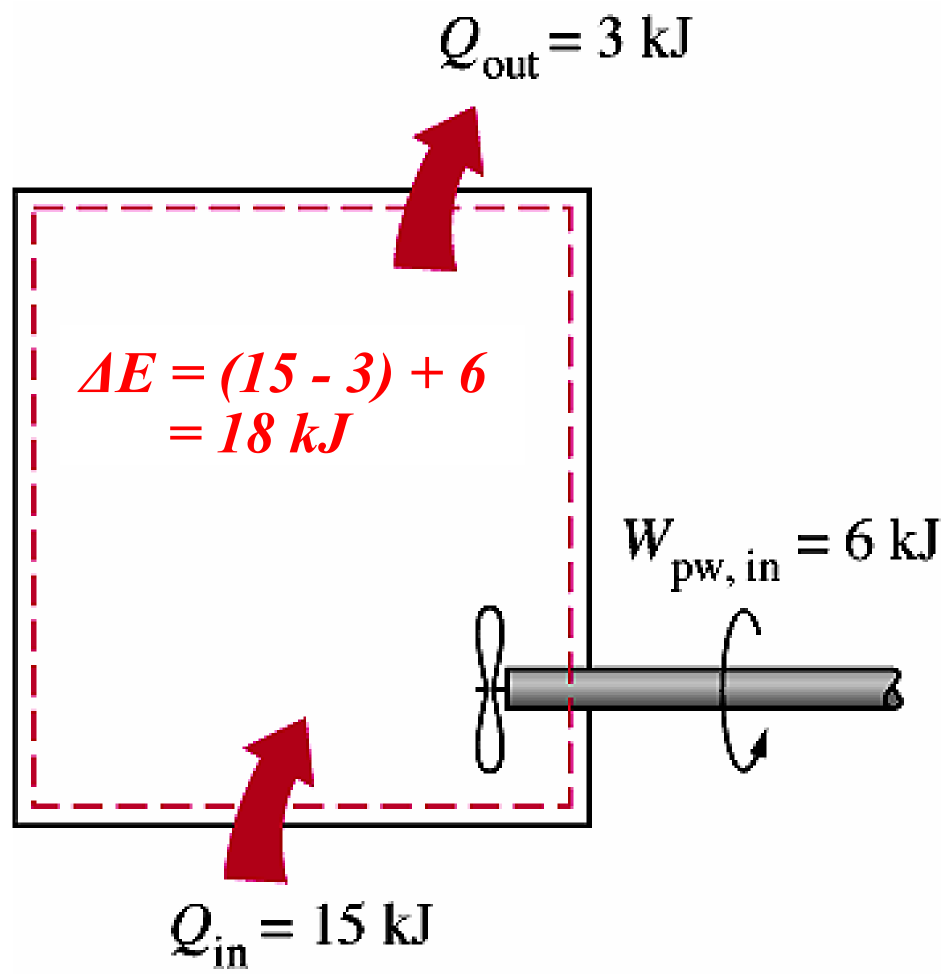
1. Define the system carefully indicating clearly its boundaries.
2. Enroll all the simplifying hypothesis to the case.
3. Draw the heat and work fluxes at the boundaries including their signals.
4. Sketch a process representation on a thermodynamic diagram Pv or Tv.

Evaluate the System Energy Change given Q and W

$$\Delta E = Q - W$$

$$= (Q_{in} - Q_{out})$$

$$- (W_{out} - W_{in})$$



Example 4-1

0.01 kg of air is compressed in a piston-cylinder. Find the rate of temperature rise at an instant of time when T = 400K. Work is being done at a rate of 8.165 KW and Heat is being removed at a rate of 1.0 KW.

Solution on the black board

Example 4-2
Isothermal Process

An ideal gas is compressed reversibly and isothermally from a volume of 0.01 m^3 and a pressure of 0.1 MPa to a pressure of 1 MPa. How much heat is transferred during this process?

Solution on the black board

Isobaric Process

For a *constant-pressure process*,

$$W_b + \Delta U = P\Delta V + \Delta U$$
$$= \Delta(U+PV) = \Delta H$$

Thus,

$${}_1Q_2 = H_2 - H_1 + \Delta KE + \Delta PE \quad (kJ)$$

Example: Boil water at constant pressure

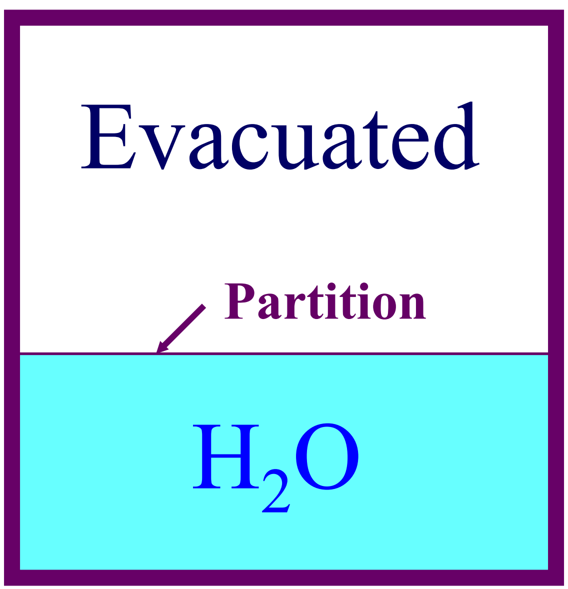
Example 4-3 Isobaric Process

The volume below a weighted piston contains 0.01 kg of water. The piston area is of 0.01 m^2 and the piston mass is of 102 kg. The top face of the piston is at atmospheric pressure, 0.1 MPa. Initially liquid water is at 25 ^oC and the final state is saturated vapor ($x = 1$). How much heat and work are done on or by the water?

Solution on the black board

Example

An insulated tank is divided into two parts by a partition. One part of the tank contains 2.5 kg of compressed liquid water at 60°C and 600 kPa while the other part is evacuated. The partition is now removed, and the water expands to fill the entire tank. Determine the final temperature of the water and the volume of the tank for a final pressure of 10 kPa.



$m = 2.5\ kg$

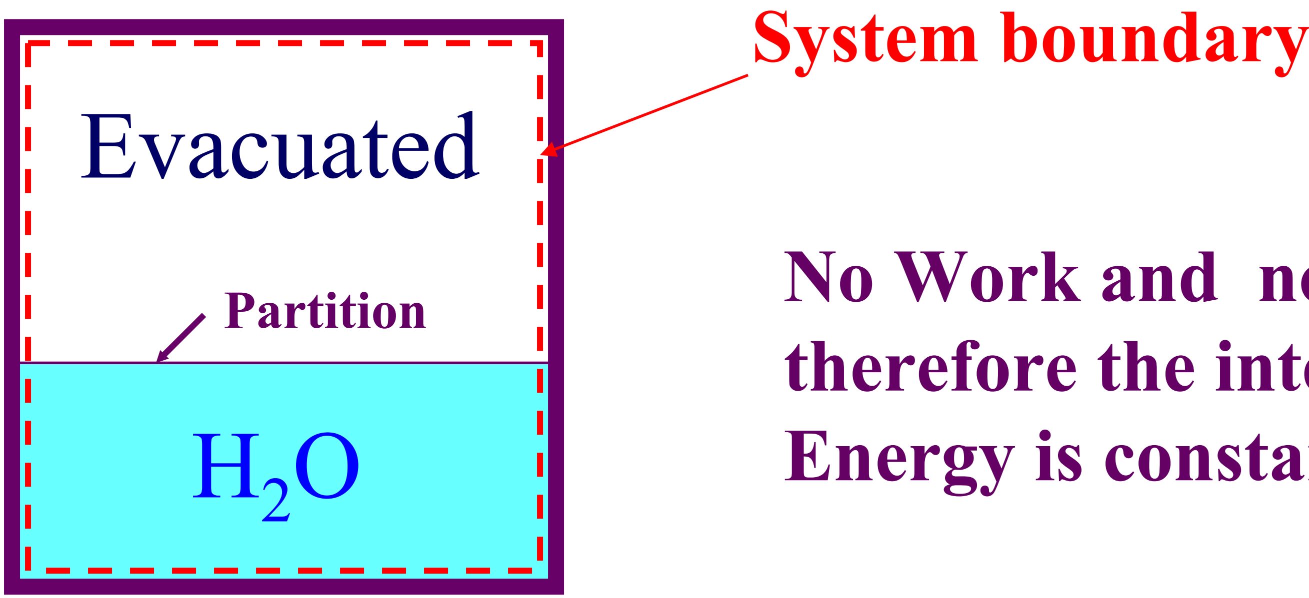
$T_1 = 60^oC$

$P_1 = 600\ kPa$

$P_2 = 10\ kPa$

$\boxed{\Delta E = Q - W}$

Solution - page 1



No Work and no Heat therefore the internal Energy is constant!

First Law: $Q - W = \Delta E$

$$Q = W = \Delta KE = \Delta PE = 0$$

$$\Delta E = \Delta U = m(u_2 - u_1) = 0$$

$$u_1 = u_2$$

Solution - page 2

State 1: compressed liquid

$P_1 = 600$ kPa, $T_1 = 60^oC$

$v_l = v_{l@60^oC} = 0.001017$ m³/kg

$u_l = u_{l@60^oC} = 251.11$ kJ/kg

State 2: we know $u_2 = u_1 = 251$ kJ/kg

$P_2 = 10$ kPa,

$u_l = 191.82$ kJ/Kg, $u_{lv} = 2246.1$ kJ/kg

As $u_{l2} < u_2 < u_{v2}$, saturated liquid-vapor mixture

$$x_2 = \frac{u_2 - u_l}{u_{lv}} = \frac{251.11 - 191.82}{2246.1} = 0.0264$$

Solution - page 3

Thus, $T_2 = T_{sat@10\ kPa} = 45.81^oC$

$v_2 = v_l + x_2 v_{lv}$

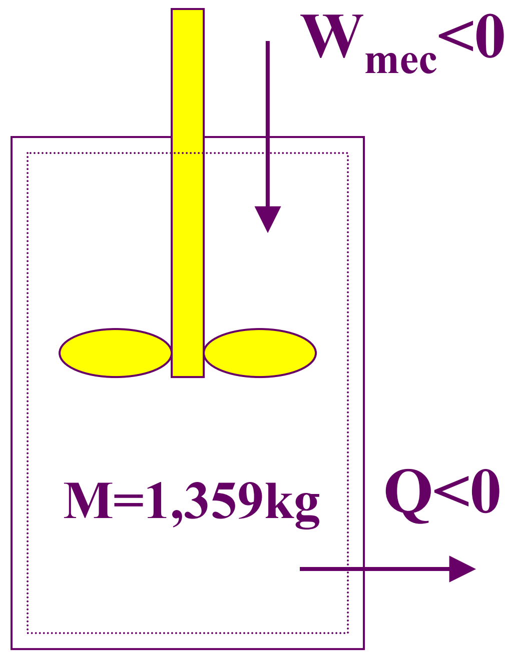
$= [0.00101+0.0264*(14.67 - 0.00101)]\ m^3/kg$

$= \ 0.388\ m^3/kg$

$V_2 = mv_2 = (2.5\ kg)(0.388 m^3/kg) = 0.97\ m^3$

TEAMPLAY EX. 4-7

A powerful 847W blender is used to raise the temperature from 20°C to 70°C of 1.36kg of compressed liquid water. If the water loses heat to the surroundings at the rate of 0.176 W, how much time the process will take?



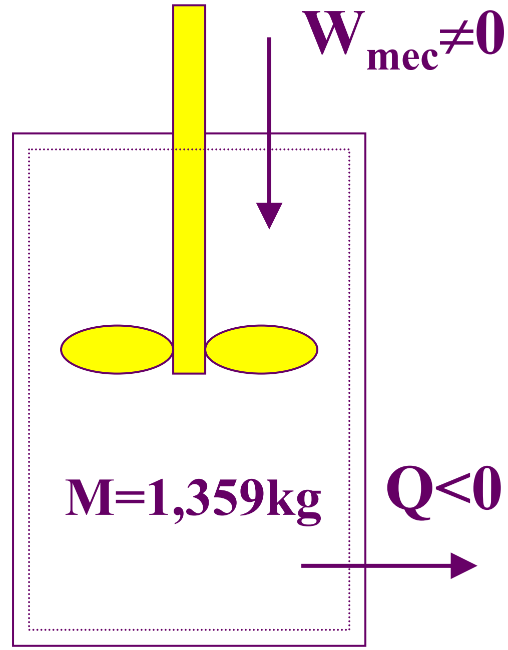
Problem originally in english units. Use the conversion factors:

1HP=745W
1lbm=0,453kg
°C=(°F-32)/1,8
1Btu=1,055J

Ex4.7)

W_{mec}=1,2HP=894W
68ºF=20ºC (água no estado líquido)
158ºF=70ºC (água no estado líquido)
Q=10Btu/min=0,176W
3lbm=1,359kg
$c_v=c_p$=4,180KJ/kgºC

For compressible liquid
Cp=Cv nearly constant,



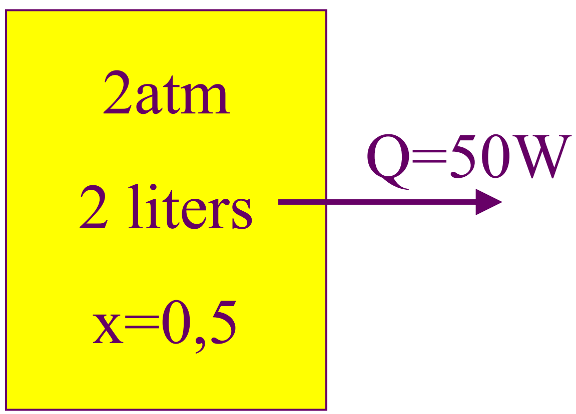
$$\dot{Q}-\dot{W}=\frac{dU}{dt}=MC_v\frac{dT}{dt}$$

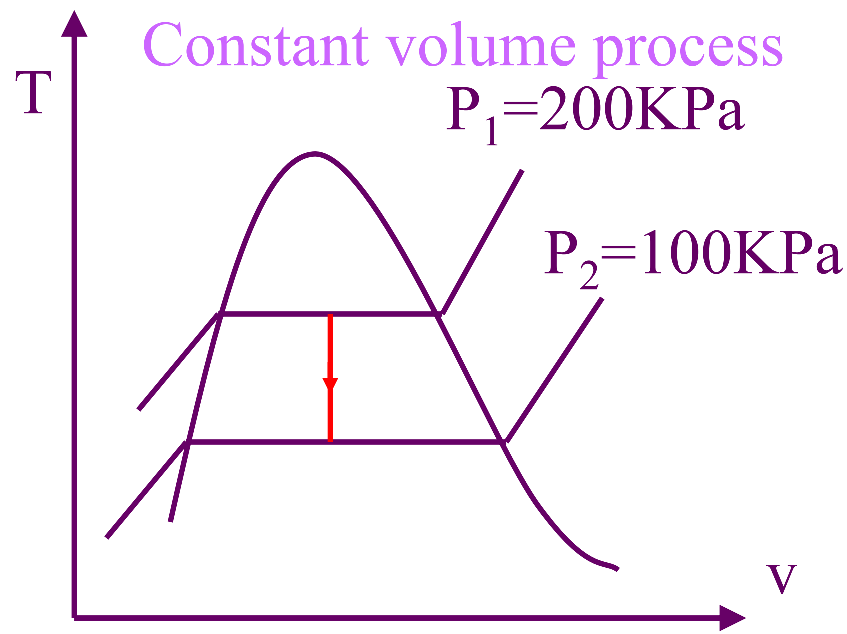
$$\frac{dT}{dt}=\frac{-0{,}176-(-894)}{1{,}359\times 4{,}180\times 10^3}=+0{,}157\frac{^oC}{s}$$

$$\Delta t=\frac{(70-20)}{0{,}157}=317s=5'17''$$

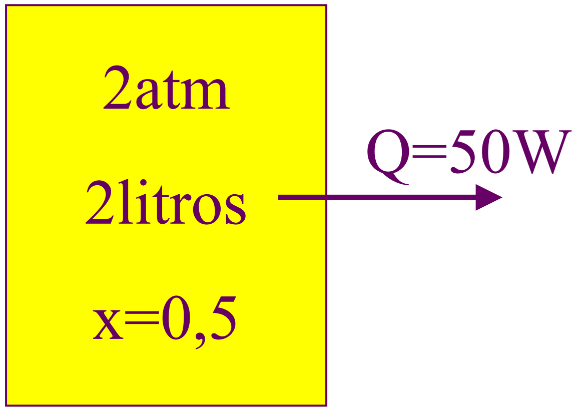
TEAMPLAY EX. 4-6

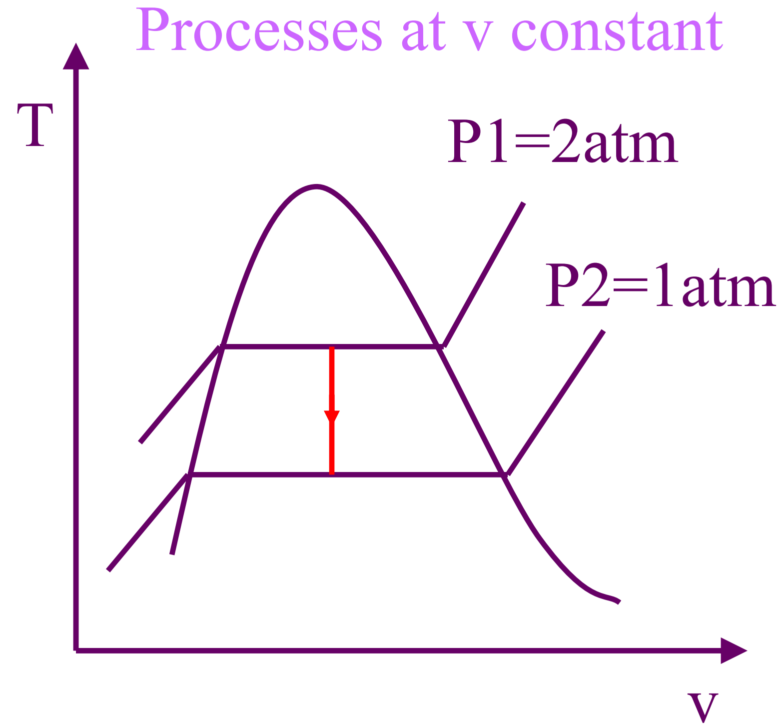
A pressure cooker with volume of 2 liters operates at 0.2 MPa with water at x = 0.5. After operation the pressure cooker is left aside allowing its contents to cool. The rate of heat loss is 50 watts, how long does it take for the pressure drop to 0.1 MPa? What is the state of the water at this point? Indicate the process on a T-v diagram.





Ex4.6)





$$1^{o}\ \mathbf{Lei}: \frac{dQ}{dt} - \cancelto{0}{\frac{dW}{dt}} = \frac{dU}{dt}$$

$$\frac{dU}{dt} = \dot{Q} \rightarrow M\Delta u = \dot{Q}\Delta t$$

$$M(u_2 - u_1) = \dot{Q}\Delta t$$

$$\Rightarrow \Delta t = \frac{M(u_2 - u_1)}{\dot{Q}}$$

One has to find u_2 and u_1 using the thermodynamic tables!

Steam Properties

State (1)

$P_1=0,2MPa$
$T_{sat}=120^oC$
$v_{1L}=0,001m^3/kg$
$v_{1G}=0,8919m^3/kg$
$u_{1L}=503,5KJ/kg$
$u_{1G}=2025,8KJ/kg$
$x=0,5$

Internal Energy:
u1=(1-x)u1L+xu1G
u1=0,5*503+0,5*2025,8
u1=1264KJ/kg

Specific volume, v
v1 = v2
$v=(1-x)v_L+xv_G$
v=0,5*0,001+0,5*0,8919
$v_1=v_2=0,446m^3/kg$

Steam Properties

State (2)

P_2=0,1MPa
T_{sat}=100°C
v2=0,446m3/kg
v_{2L}=0,001m^3/kg
v_{2G}=1,6729m^3/kg
u_{2L}=418,9KJ/kg
u_{2G}=2087,5KJ/kg

quality (2)

$$x_2 = \frac{v - v_L}{v_G - v_L} = \frac{0,446 - 0,001}{1,672} = 0,266$$

Internal Energy (2):

$u_2 = (1\text{-}x)u_{2L} + xu_{2G}$
$u_2 = 0,734*418+0,266*2087,5$
$u_2 = 862$KJ/kg

Mass of water: v=V/M→M=V/v

M = 2*10^{-3}/0,446 = 0,004kg

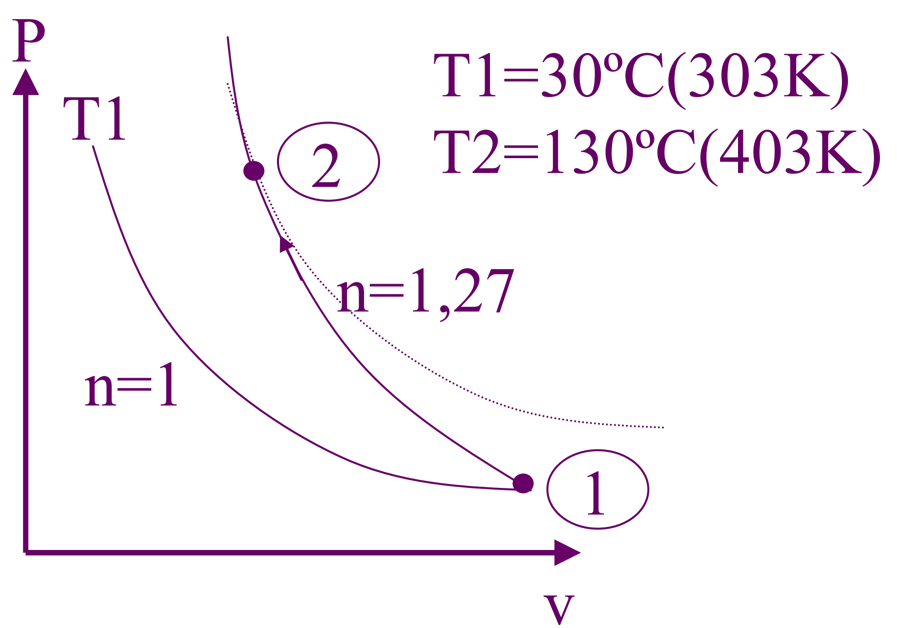
1ºLaw:

$$\Delta t = \frac{-M(u_2 - u_1)}{\dot{Q}} = \frac{4\times10^{-3}(1264-862)10^3}{50}$$

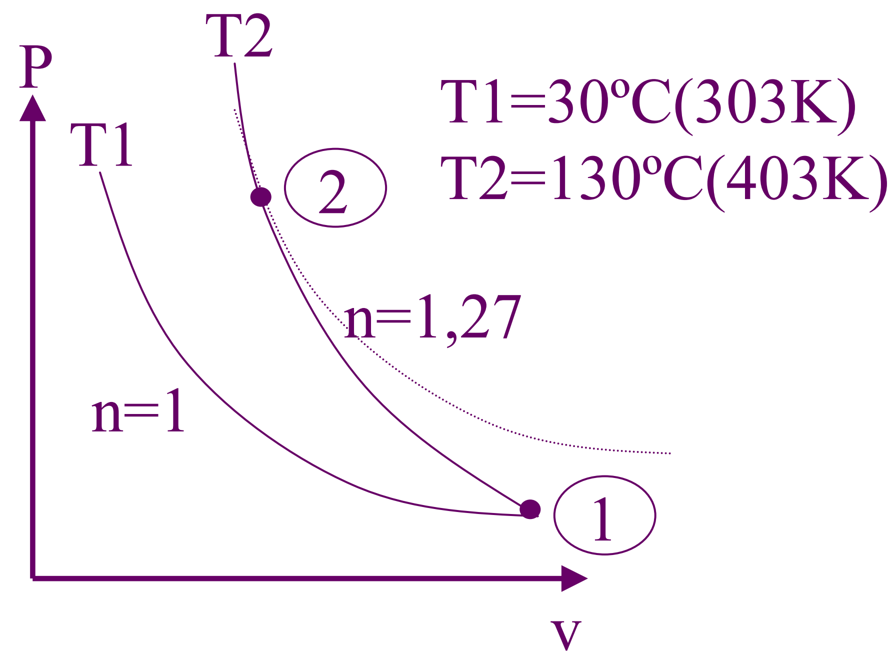
$$\Delta t = 32s$$

TEAMPLAY EX. 4-10

Air, assumed to be ideal gas with constant specific heats, is compressed in a closed piston-cylinder device in a reversible polytropic process with n = 1.27. The air temperature before compression is 30°C and after compression is 130°C. Compute the heat transferred on the compression process.



Ex4.10)



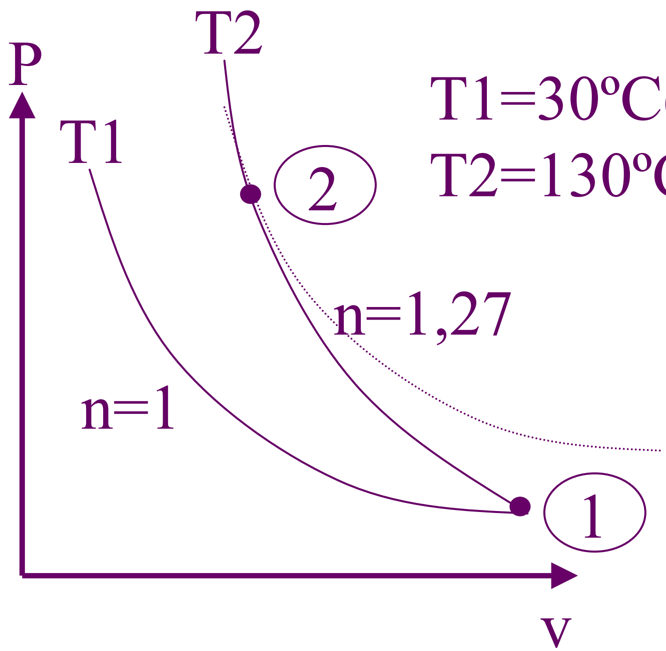
$$\text{Calor} \rightarrow 1^{o}\,\text{Lei}$$

$$_1q_2 - {}_1w_2 = (u_2 - u_1)$$

$$_1q_2 = C_v\Delta T + {}_1w_2$$

To get the <u>heat</u> is necessary to know the work done on the system, $_1w_2$.

Ex4.10)



T1=30ºC(303K)
T2=130ºC(403K)

$$W = \int P dv$$

$$Pv^n = const.$$

$$W = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{MR(T_2 - T_1)}{1-n}$$

Trabalho – específico

$$_1w_2 = \frac{R(T_2 - T_1)}{1-n} = \frac{-297 \times 100}{0,27} = -110\frac{KJ}{kg}$$

Calor → 1º Lei

$$_1q_2 - {}_1w_2 = (u_2 - u_1)$$

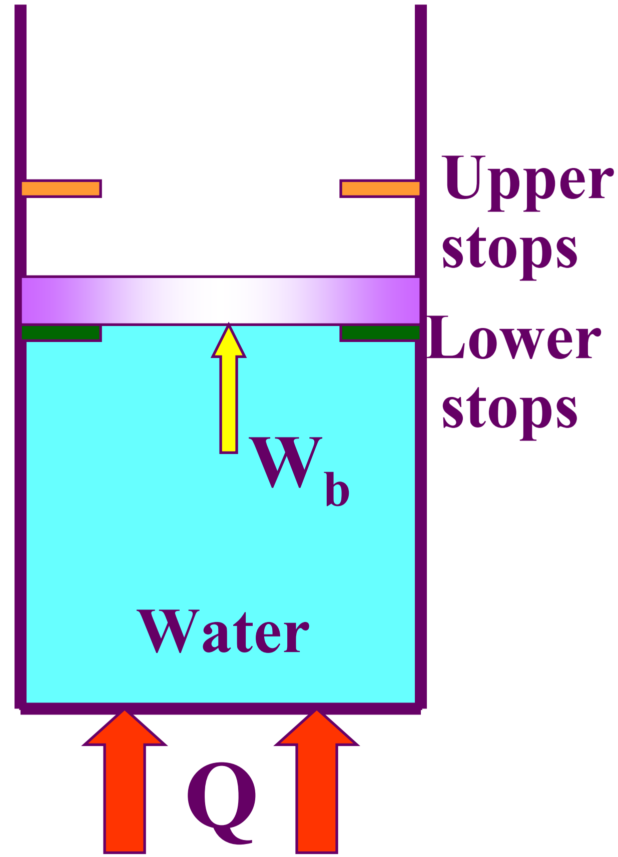
$$_1q_2 = C_v \Delta T + {}_1w_2$$

$$_1q_2 = 0,7165 \times 110 - 110 = -38,3\frac{KJ}{kg}$$

It is necessary a heat flux of -38,3 kJ/kg of air

Example

One kilogram of water is contained in a piston-cylinder device at 100°C. The piston rests on lower stops such that the volume occupied by the water is 0.835 m³. The cylinder is fitted with an upper set of stops. The volume enclosed by the piston-cylinder device is 0.841 m³ when the piston rests against the upper stops. A pressure of 200 kPa is required to support the piston. Heat is added to the water until the water exists as a saturated vapor. How much work does the water do on the piston?



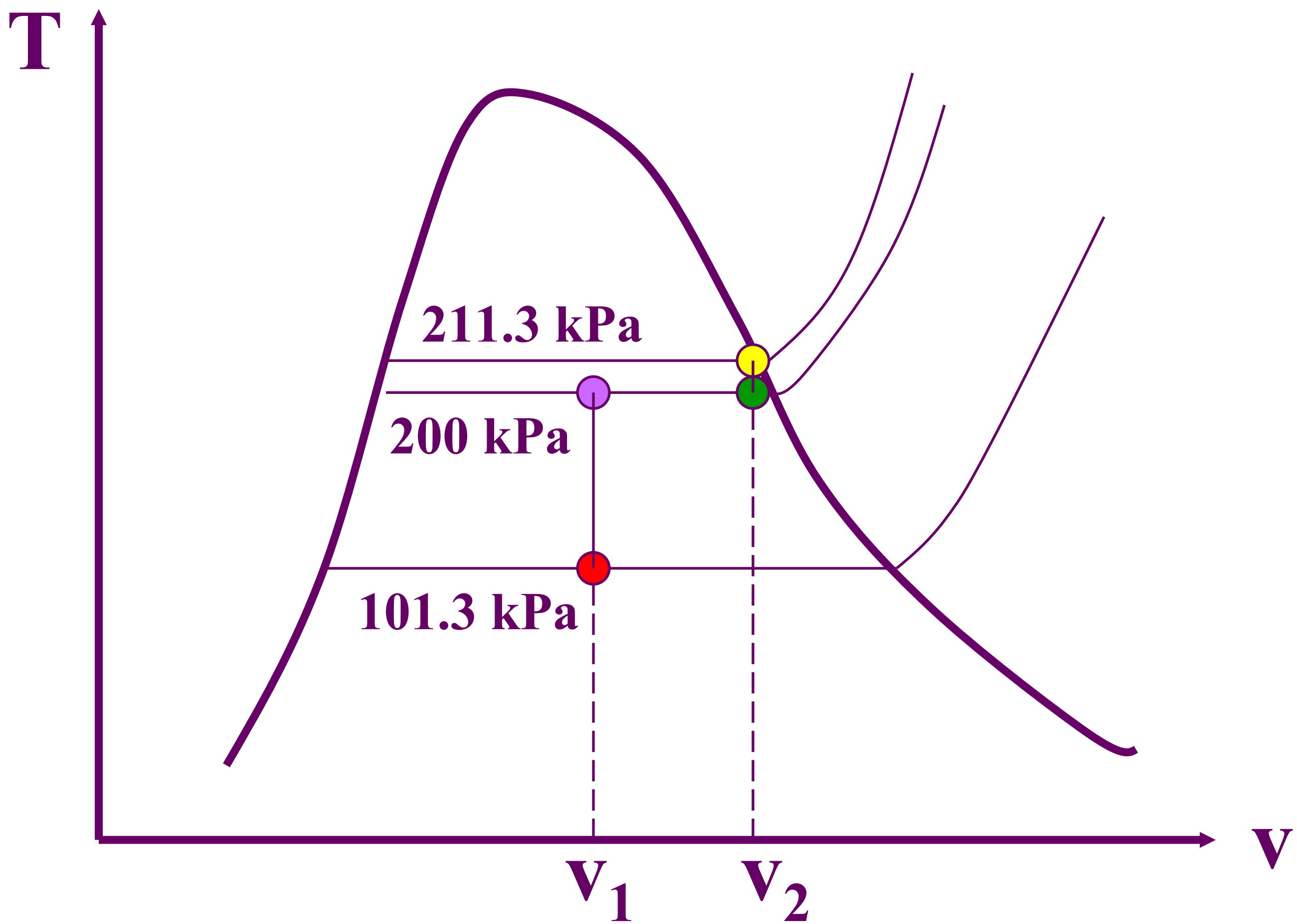
$m = 1$ kg

$T_1 = 100^oC$

$V_1 = 0.835\ m^3$

$V_2 = 0.841\ m^3$

T-v Diagram



Solution - page 1

$$v_1 = \frac{V_1}{m} = \frac{0.835\,m^3}{1\,kg} = 0.835\frac{m^3}{kg}$$

State 1: saturated liquid-vapor mixture

$T_1 = 100^oC$,

v_f=0.001044 m^3/kg , v_g=1.6729 m^3/kg

$v_f < v < v_g$ ==> saturation P_1=101.35 kPa

Solution - page 2

<u>Process 1-2</u>: **The volume stay constant until the pressure increases to 200 kPa. Then the piston will move.**

<u>Process 2-3</u>: **Piston lifts off the bottom stop while the pressure stays constant.**

<u>State 2</u>: saturated liquid-vapor mixture

$$P_2 = 200 \text{ kPa}, \; v_2 = v_1 = 0.835 \text{ m}^3$$

Does the piston hit upper stops before or after reaching the saturated vapor state?

Solution - page 3

$$v_3 = \frac{V_3}{m} = \frac{0.841\ m^3}{1\ kg} = 0.841\ \frac{m^3}{kg}$$

State 3: Saturated liquid-vapor mixture

$$P_3 = P_2 = 200\ kPa$$

$$v_f = 0.001061\ m^3/kg\ ,\ v_g = 0.8857\ m^3/kg$$

$v_f < v_3 < v_g$ ==> **piston hit the upper stops before water reaches the saturated vapor state.**

Solution - page 4

Process 3-4 : With the piston against the upper stops, the volume remains constant during the final heating to the saturated vapor state and the pressure increases.

State 4: Saturated vapor state

$$v_4 = v_3 = 0.841 \text{ m}^3/\text{kg} = v_g$$

$$P_4 = 211.3 \text{ kPa} , \ T_4 = 122^o\text{C}$$

Solution - page 5

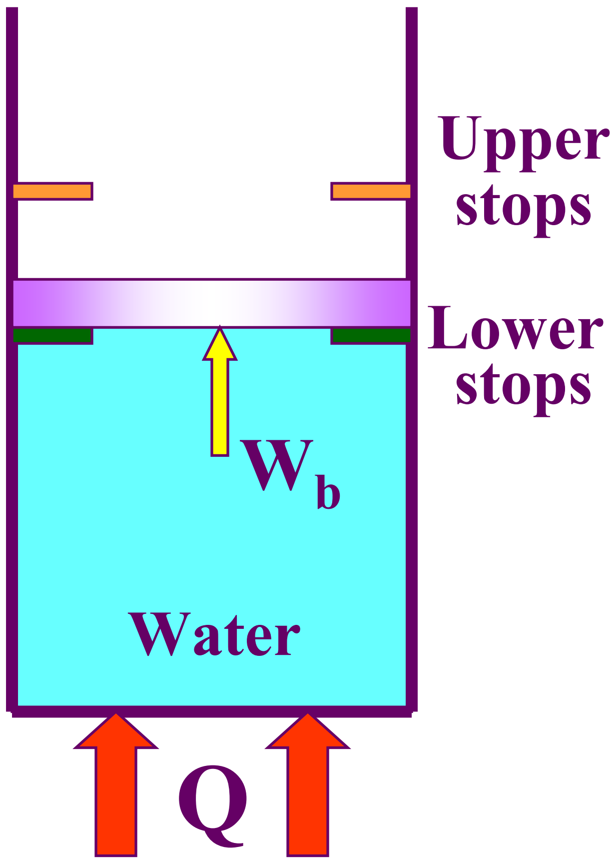
$$W_{b,14} = \int_1^4 PdV = \int_1^2 PdV + \int_2^3 PdV + \int_3^4 PdV$$

$$= 0 + mP_2(v_3 - v_2) + 0$$

$$= (1\,kg)(200\,kPa)(0.841 - 0.835)\frac{m^3}{kg}\frac{kJ}{m^3 kPa}$$

$$= 1.2\,kJ$$ (> 0, done by the system)

Example: Heat Transfer



Find the require heat transfer for the water in previous example.

Solution - page 1

First Law: Conservation of Energy

$$Q - W = \Delta E = \Delta U + \cancel{\Delta KE} + \cancel{\Delta PE}$$

$$Q_{14} = W_{b,14} + \Delta U_{14}$$

$$\Delta U_{14} = m(u_4 - u_1)$$

Solution - page 2

State 1: saturated liquid-vapor mixture

$$x_1 = \frac{v_1 - v_f}{v_g - v_f} = \frac{0.835 - 0.001044}{1.6729 - 0.001044} = 0.4988$$

$$u_1 = u_f + x_1 u_{fg}$$

$$= 418.94\frac{kJ}{kg} + 0.4988(2087.6\frac{kJ}{kg}) = 1460.23\frac{kJ}{kg}$$

Solution - page 3

State 4: saturated vapor state

$v_4 = 0.841 \text{ m}^3/\text{kg} = v_g$

$u_4 = 2531.48 \text{ kJ/kg}$ (interpolation)

$$Q_{14} = W_{b,14} + m(u_4 - u_1)$$

$$= 1.2\,\text{kJ} + (1\,\text{kg})(2531.48 - 1460.23)\frac{\text{kJ}}{\text{kg}}$$

$$= 1072.45\,\text{kJ}$$ **(> 0, added to the water)**