Chapter # 2

Energy and the First Law of Thermodynamics

OBJECTIVES

- Introduce the concept of energy and define its various forms.
- Discuss the nature of internal energy.
- Define the concept of heat and the terminology associated with energy transfer by heat.
- Discuss the three mechanisms of heat transfer: conduction, convection, and radiation.
- Define the concept of work, including electrical work and several forms of mechanical work.
- Introduce the first law of thermodynamics, energy balances, and mechanisms of energy transfer to or from a system.
- Apply energy balance on closed systems and appropriately modeling the case at hand.

ENERGY

Energy: The ability to cause changes.

- May be contained in a system
- May transfer from one system to another
- Units are Joules (J) or kilo Joules (kJ)
- Total energy of a system is the sum of different forms of energy

Forms of Energy

Total Energy E:

- Thermal
- Chemical
- Magnetic
- Electrical
- Nuclear

→ Microscopic **(Internal Energy)**

- Kinetic
- Potential

→ Macroscopic

Thermodynamics deals only with the ***change*** of the ***Total Energy***.

Total Energy contained in a system has ***two*** forms

Total Energy = Macroscopic forms + Microscopic forms

Specific Energy $e = E/m$ (J/kg) or (kJ/kg)

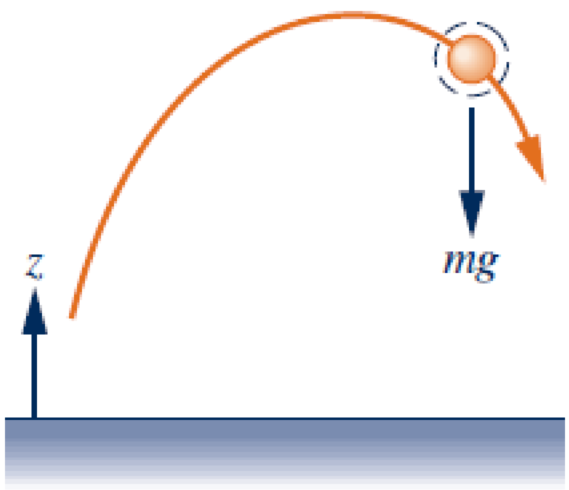
CONTAINED ENERGY

Total Energy = Macroscopic forms + Microscopic forms

Macroscopic forms

Energy related to the system as a whole with respect to some outside reference frame.

$KE = \frac{1}{2} mv^2$ and $PE = mgz$



The macroscopic energy of an object changes with velocity and elevation.

Microscopic forms

Energy related to molecular structure and degree of molecular activity

Internal energy, *U*:

The sum of all the microscopic forms of energy.

- Sensible Energy
- Latent Energy

} Thermal Energy

Sensible energy: The portion of the internal energy of a system associated with the kinetic energies of the molecules.

Latent energy: The internal energy associated with the phase of a system.

Note: Microscopic KE of molecules does not turn a wheel… Macroscopic KE does

CONTAINED ENERGY

Total Energy = Macroscopic forms + Microscopic forms

Kinetic energy

$$KE = m\frac{V^2}{2} \qquad \text{(kJ)}$$

Potential energy

$$PE = mgz \qquad \text{(kJ)}$$

Internal Energy U =

Sensible Energy + Latent Energy

Total energy of a system

$$E = U + KE + PE = U + m\frac{V^2}{2} + mgz \qquad \text{(kJ)}$$

Energy per unit mass $e = E/m$ **(kJ/kg)**

Kinetic energy per unit mass

$$ke = \frac{V^2}{2} \qquad \text{(kJ/ kg)}$$

Potential energy per unit mass

$$pe = gz \qquad \text{(kJ/ kg)}$$

Internal Energy per unit mass

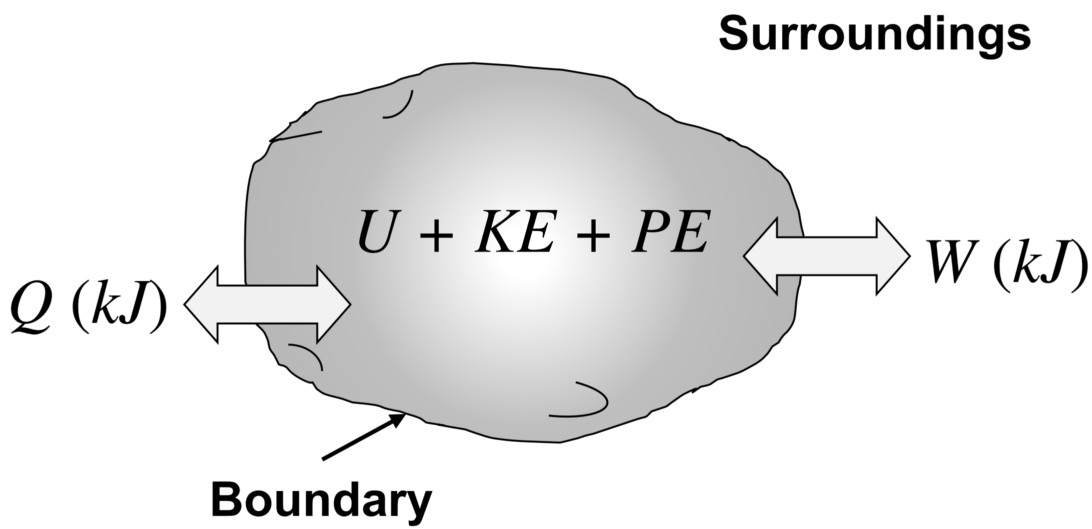
$u = U/m$

Energy of a system per unit mass

$$e = u + ke + pe = u + \frac{V^2}{2} + gz \qquad \text{(kJ/ kg)}$$

ENERGY TRANSFER

Energy contained in a system (as $U + KE + PE$) can be transferred at the system boundary as ***Heat*** (Q) or ***Work*** (W) in general and also with ***mass flow*** for open systems



Heat and work are never contained in a system, they transfer (enter or leave) *at* the system boundary by increasing or decreasing the internal energy (U)

Remember, Heat and Work are path functions!

$$\int_1^2 \delta W = W_{12} \quad \text{not} \quad \Delta W \; or \; \left(W_2 - W_1\right)$$

ENERGY TRANSFER BY HEAT

Heat: The form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference. [Q (kJ), q (kJ/kg), $\dot{Q}$ (kW)]

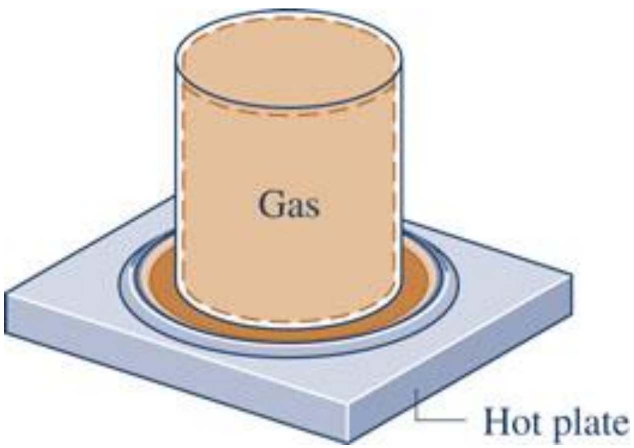
Net energy transfer by heat occurs only in the direction of decreasing temperature.

The larger the temperature difference, the higher is the rate of heat transfer.

Heat transfer into a system is taken as **positive** and heat transfer from a system is taken as **negative**:

Q* > 0**: heat transfer ***to the system

Q* < 0**: heat transfer ***from the system



If Q = 30 kJ, m = 2kg, Δt = 5s, what is q and $\dot{Q}$?

ENERGY TRANSFER BY HEAT

Three Mechanisms of Heat Transfer

1. **Conduction Heat Transfer**

   Energy transfer occurs through molecular motion.

2. **Convection Heat Transfer**

   Energy transfer occurs through bulk fluid motion over a surface.

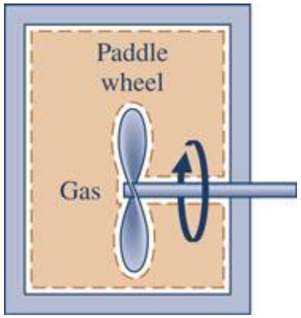
3. **Radiation Heat Transfer**

   Energy transfer occurs through electromagnetic waves.

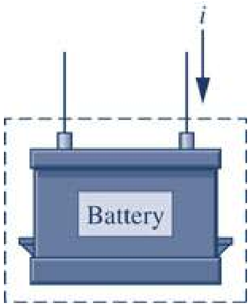
ENERGY TRANSFER BY WORK

Work: The energy transfer associated with a force acting through a distance.

- **A rotating shaft, an electric wire crossing the system boundaries and a moving piston,** are all associated with work interactions.



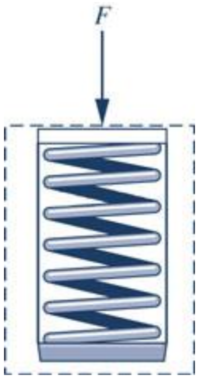
Rotating shaft work (W_s)



Electrical work (W_e)

Moving boundary work (W_b)

Spring Work is also encountered in thermodynamic problems



W* > 0**: Work done ***by the system

W* < 0**: Work done ***on the system

ELECTRICAL FORM OF WORK

Electrical Work

Electrical power

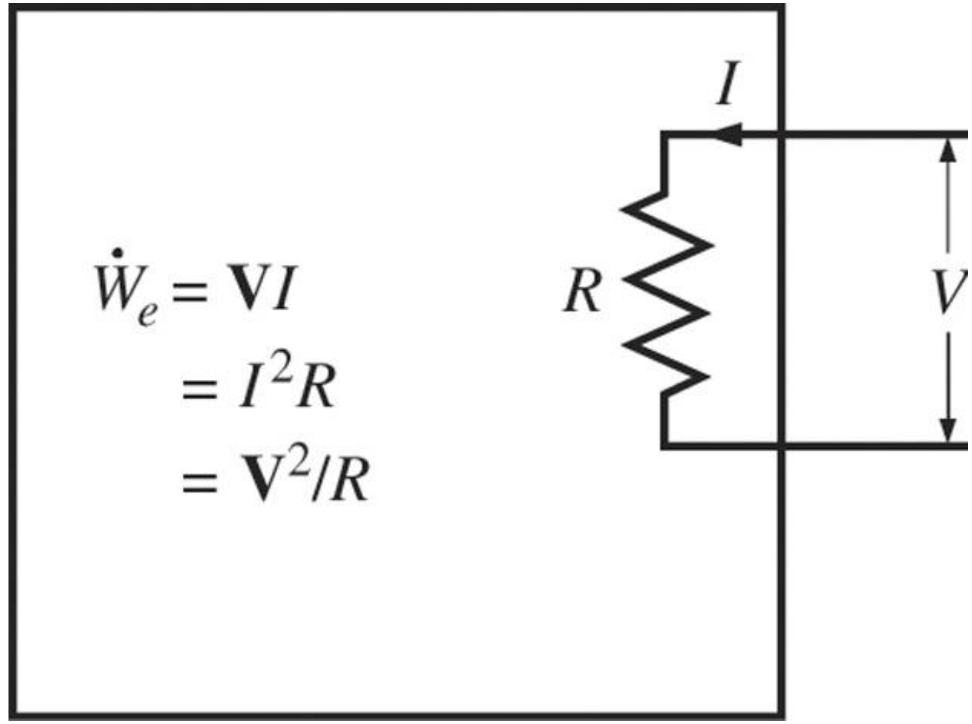
$$\dot{W}_e = VI \qquad (W)$$

When potential difference and current change with time

$$W_e = \int_1^2 (VI)\,dt \qquad (kJ)$$

When potential difference and current remain constant

$$W_e = VI\,\Delta t \qquad (kJ)$$

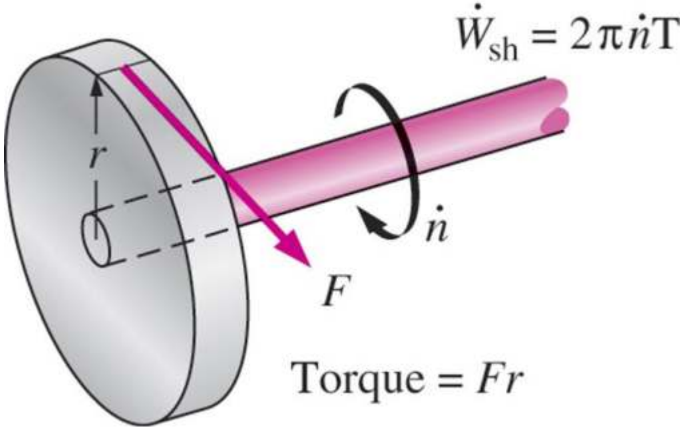


Electrical power in terms of resistance *R*, current *I*, and potential difference **V**.

MECHANICAL FORMS OF WORK

Rotating shaft Work (W_{sh}) and Power ($\dot{W}_{sh}$)

Work (W) = Force (F) × Displacement (s)

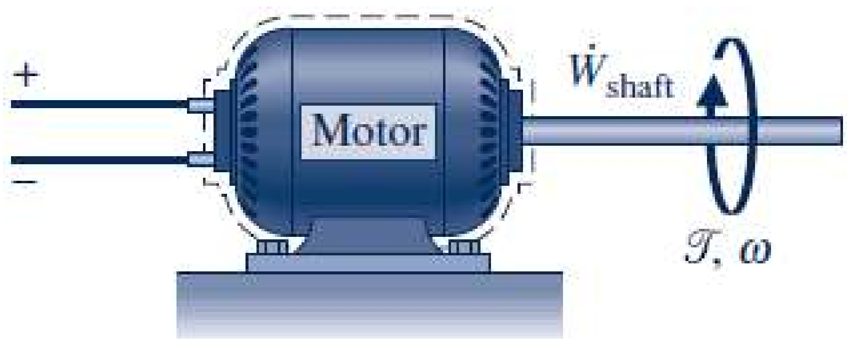


A force F acting through a moment arm r generates a torque T

$$T = Fr \quad \rightarrow \quad F = \frac{T}{r}$$

For rotating shaft, the force acts through a distance s

$$s = (2\pi r)n$$



Shaft work

$$W_{sh} = 2\pi nT \quad (kJ)$$

Shaft power

$$\dot{W}_{sh} = 2\pi\dot{n}T \quad (kW) \qquad \text{with} \qquad \dot{n} \equiv rev/s$$

MECHANICAL FORMS OF WORK

Spring work

Work = Force × Displacement

For linear elastic springs, the force applied is proportional to the displacement x

$$F = kx \qquad (kN)$$

k: spring constant (kN/m)

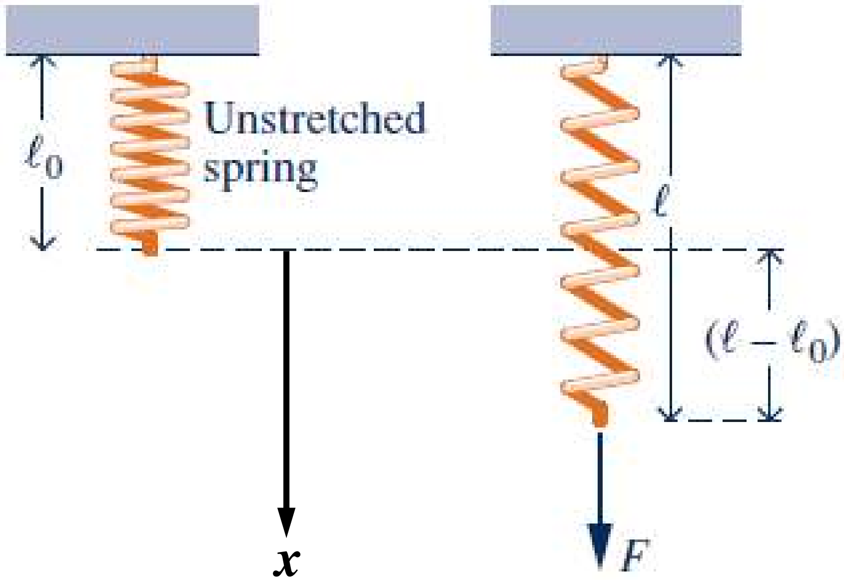
The work done for a differential amount of displacement dx is

$$\delta W_{spring} = F\,dx \qquad (kJ)$$

Substituting value of F and integrating yields:

$$W_{spring} = \frac{1}{2}k\left(x_2^2 - x_1^2\right) \qquad (kJ)$$

x_1 and x_2: The initial and the final displacements

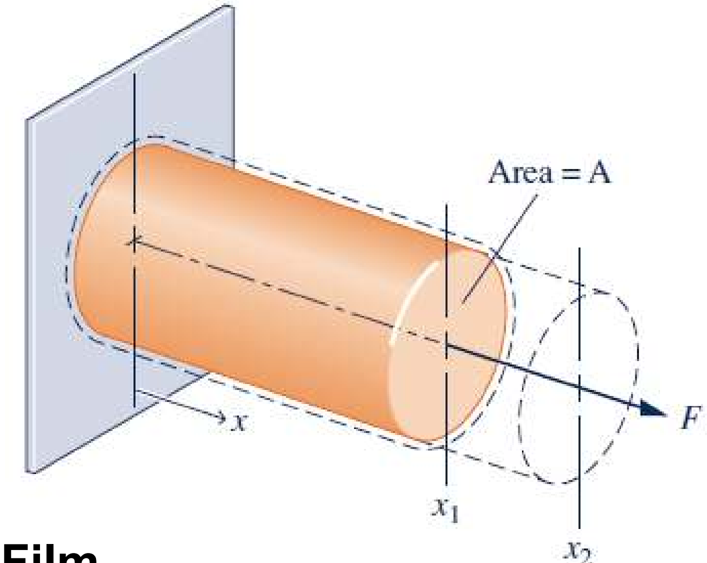


MECHANICAL FORMS OF WORK

Work Done on Elastic Solid Bars

$$W = -\int_{x_1}^{x_2} \sigma A \, dx$$

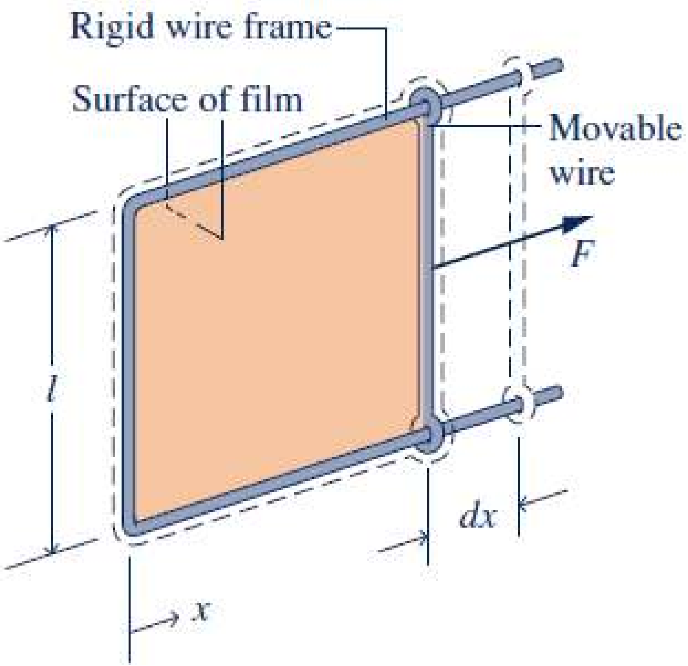
$\sigma \equiv$ *normal stress acting at the end* of the bar.



Work Associated with the Stretching of a Liquid Film

$$W = -\int_{A_1}^{A_2} \tau \, dA$$

$\tau \equiv$ surface tension *acting at the movable wire*



MECHANICAL FORMS OF WORK

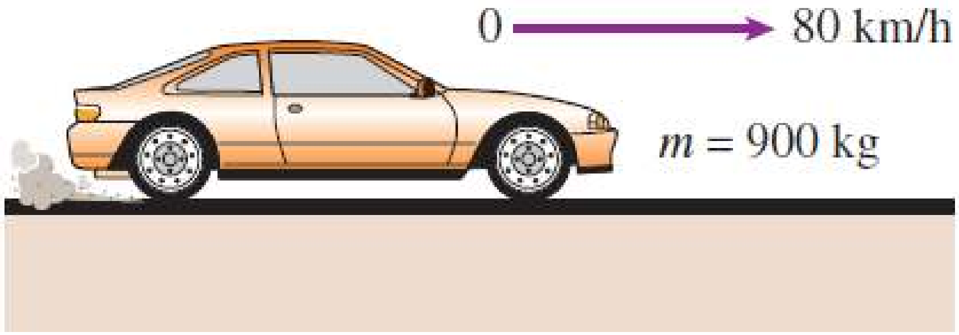
Work Done to Raise or to Accelerate a Body

1. The work transfer needed to raise a body is equal to the change in the potential energy of the body.

$$W = mg\,\Delta z$$

2. The work transfer needed to accelerate a body is equal to the change in the kinetic energy of the body.

$$W = \frac{m}{2}\left(V_f^{\,2} - V_i^{\,2}\right)$$



ENERGY BALANCE

The change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process.

$$\underbrace{\begin{pmatrix}\text{Total energy}\\ \text{entering the system}\end{pmatrix}}_{E_{in}} - \underbrace{\begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix}}_{E_{out}} = \underbrace{\begin{pmatrix}\text{Change in the total}\\ \text{energy of the system}\end{pmatrix}}_{\Delta E_{system}}$$

$$\boxed{E_{in} - E_{out} = \Delta E_{sys}}$$

For Closed System

$$E_{in} = Q_{in} + W_{in}$$

$$E_{out} = Q_{out} + W_{out}$$

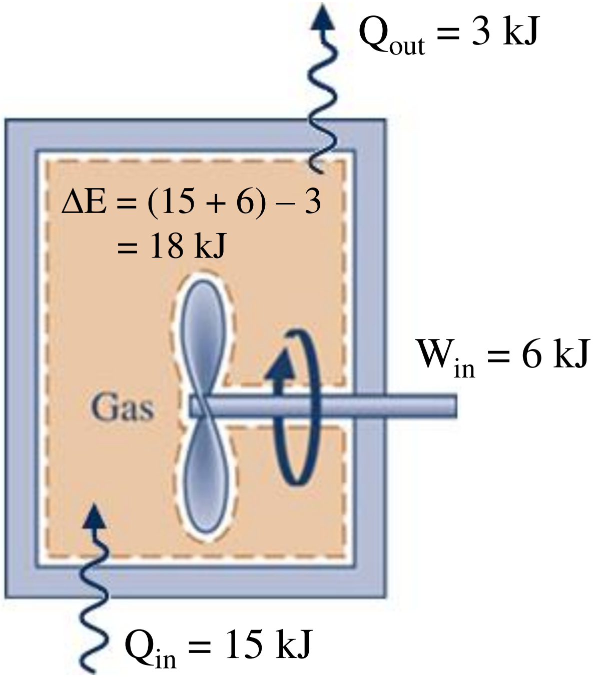
For Open System

$$E_{in} = Q_{in} + W_{in} + E_{mass,in}$$

$$E_{out} = Q_{out} + W_{out} + E_{mass,out}$$

If $\Delta E_{system} > 0$, energy is being stored in the system.

If $\Delta E_{system} < 0$, energy is being rejected from the system.



ENERGY BALANCE

Rate Form of the energy balance:

$$\dot{E}_{in} - \dot{E}_{out} = dE_{sys}/dt \qquad \text{(kW)}$$

RHS is zero for steady-state case.

Energy balance per unit mass:

$$\frac{E_{in}}{m_{sys}} - \frac{E_{out}}{m_{sys}} = \frac{\Delta E_{sys}}{m_{sys}} \quad \text{or} \quad e_{in} - e_{out} = \Delta e_{sys} \qquad \text{(kJ/ kg)}$$

Energy balance in differential form:

$$\delta E_{in} - \delta E_{out} = dE_{sys} \quad \text{or} \quad \delta e_{in} - \delta e_{out} = de_{sys}$$

The total quantities are related to the quantities per unit time as:

$$Q = \dot{Q}\,\Delta t, \qquad W = \dot{W}\,\Delta t \qquad \text{(kJ)}$$

CONSTANT PRESSURE PROCESS

Constant-pressure process (with W_b only)

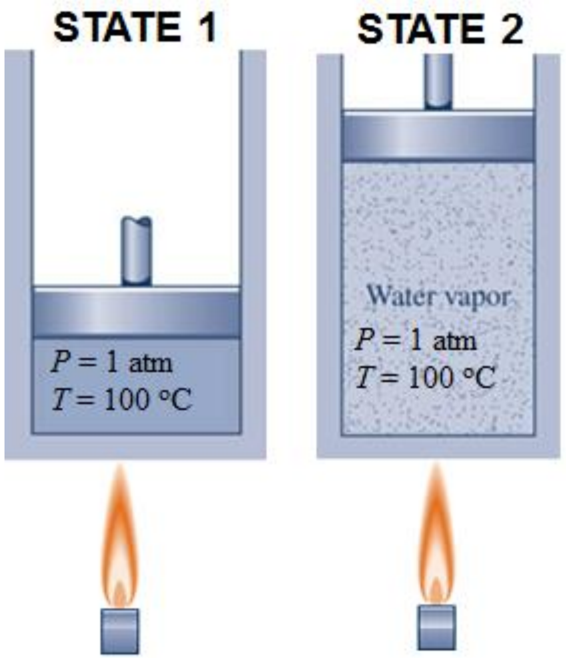
$$E_{in} - E_{out} = \Delta E_{sys}$$

$$Q_{in} - W_{b,out} = U_2 - U_1$$

$$Q_{in} - P(V_2 - V_1) = U_2 - U_1$$

$$Q_{in} = (U_2 + PV_2) - (U_1 + PV_1)$$

$$\boxed{Q_{in} = H_2 - H_1}$$



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

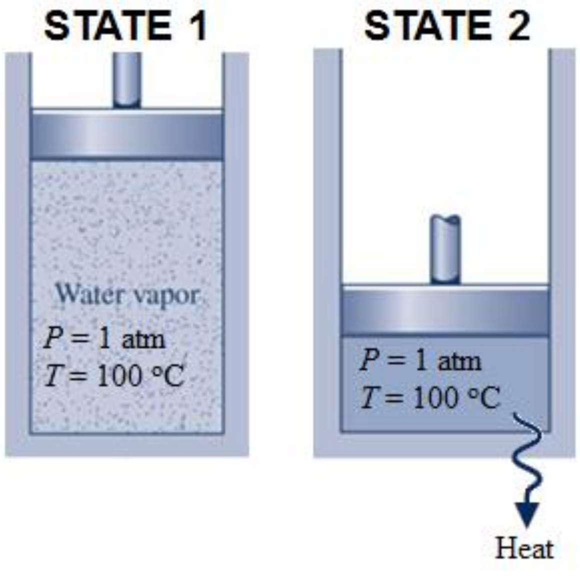
$$W_{b,in} - Q_{out} = U_2 - U_1$$

$$P(V_1 - V_2) - Q_{out} = U_2 - U_1$$

$$-P(V_2 - V_1) - Q_{out} = U_2 - U_1$$

$$-Q_{out} = (U_2 + PV_2) - (U_1 + PV_1)$$

$$\boxed{-Q_{out} = H_2 - H_1}$$



CONSTANT PRESSURE PROCESS

Therefore, we can say

$$Q = \Delta H$$

General Form

If there is some other work in addition to boundary work

$$Q + W_{other} = \Delta H$$

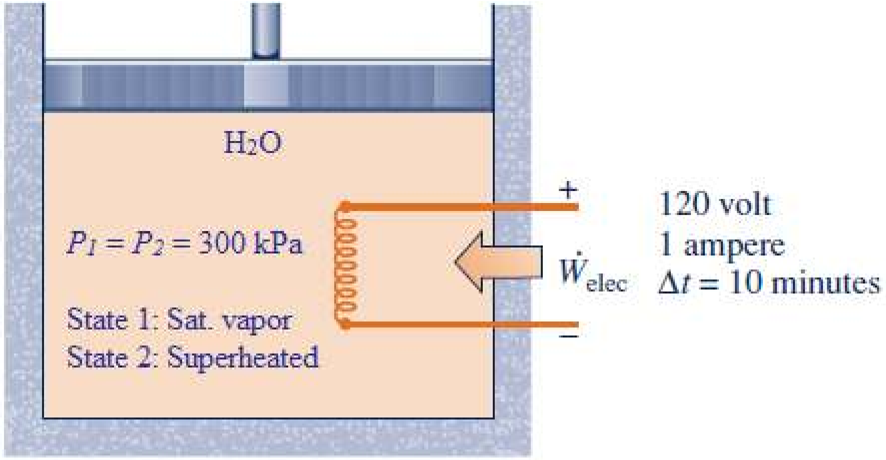
Assumes W_{other} as energy coming in

or

$$Q - W_{other} = \Delta H$$

Assumes W_{other} as energy going out

Example: Electric Work



Problem

A rigid 10-L vessel initially contains a mixture of liquid water and vapor at 100 °C with 12.3 percent quality. The mixture is then heated until its temperature is 150 °C. *Calculate the heat transfer required for this process. Also, draw the process on a T-v diagram.*

System: Closed, Water, $Q_{12}=Q_{in}=?$

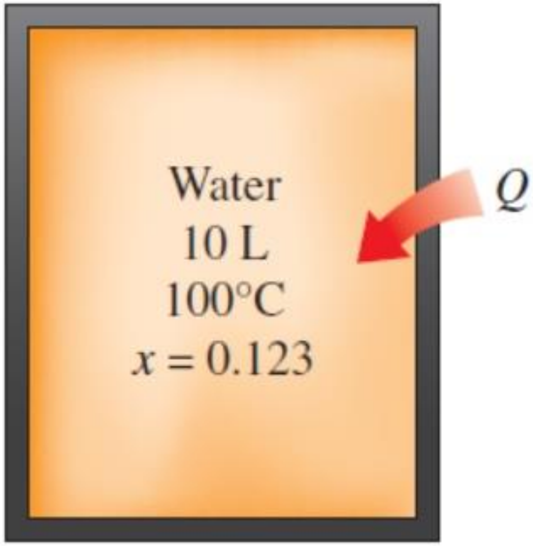
State 1		State 2	
$V_1 = 10$ L	isochoric →	$V_2 = V_1$	$v_1 = v_2$
$T_1 = 100$ °C		$m_1 = m_2$	
$x_1 = 0.123$		$T_2 = 150$ °C	

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc. energies}}}$$

$$Q_{in} = \Delta U = m(u_2 - u_1) \quad (\text{since KE} = \text{PE} = 0)$$

$$v_1 = v_f + x_1 v_{fg} = 0.0010435 + 0.123(1.673 - 0.0010435) = 0.2067\ m^3/kg$$

$$u_1 = u_f + x_1 u_{fg} = 418.94 + 0.123(2506.5 - 418.94) = 675.71\ kJ/kg$$



Problem

As $v_1 = v_2$,

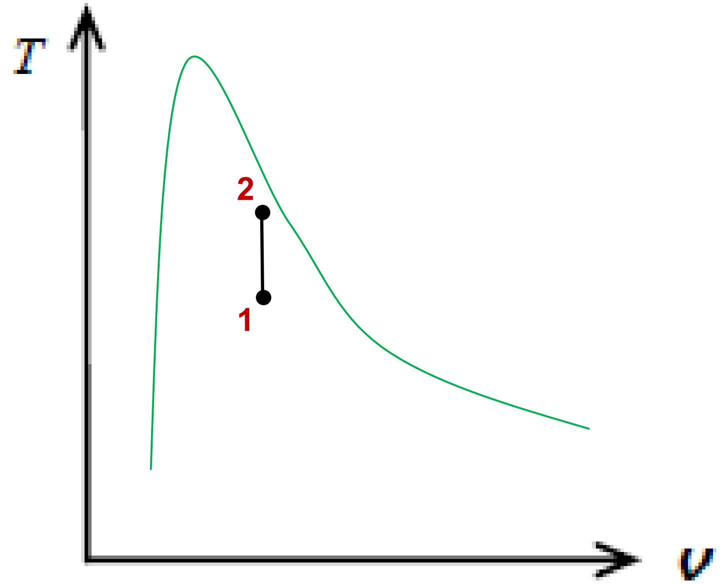
$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.2067 - 0.0010905}{0.3928 - 0.0010905} = 0.525$$

$$u_2 = u_f + x_2 u_{fg} = 631.68 + 0.525(2559.5 - 631.68) = 1643.8\ kJ/kg$$

$$m = \frac{V_1}{v_1} = \frac{0.01}{0.2067} = 0.0484\ kg$$

$$Q_{in} = m(u_2 - u_1) = 0.0484(1643.8 - 675.71)$$

$$= \boxed{46.85\ kJ}$$

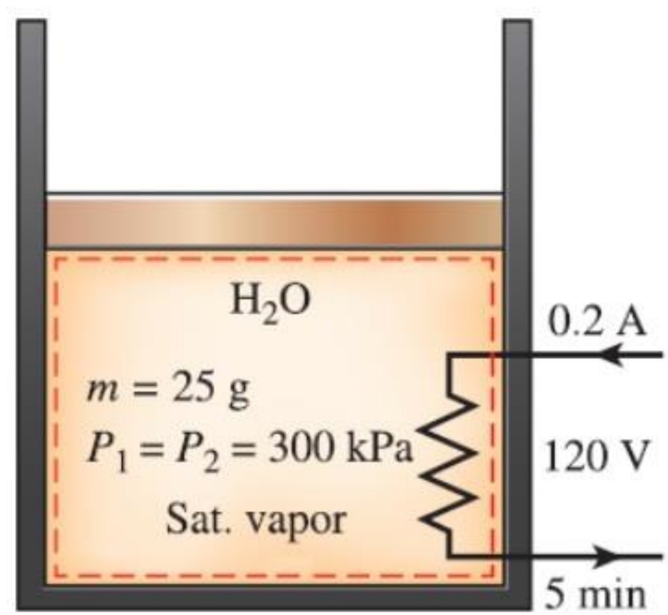


Problem

A piston–cylinder device contains 25 g of saturated water vapor that is maintained at a constant pressure of 300 kPa. A resistance heater within the cylinder is turned on and passes a current of 0.2 A for 5 min from a 120-V source. The final temperature achieved is 200 °C. *Determine the heat transferred during the process, in kJ.*

System: Closed, Water, $Q_{12}=?$

State 1		State 2
P_1 = 300 kPa	isobaric →	$P_2 = P_1$
$x_1 = 1$		$m_1 = m_2$
		T_2 = 200 °C



$$Q_{12} + W_{other} = \Delta H = m(h_2 - h_1)$$

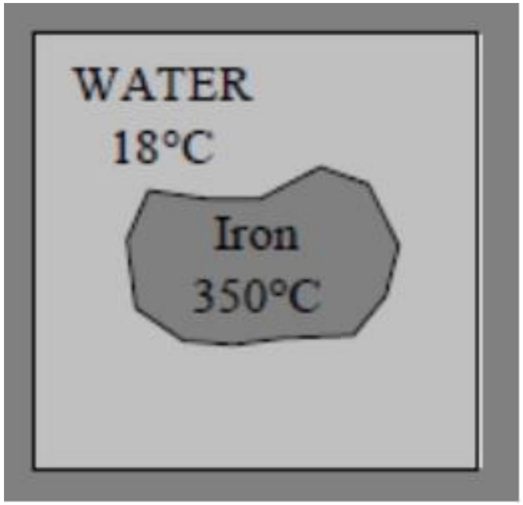
$$W_{other} = W_e = VI\Delta t = 120(0.2)(5x60) = 7200\ J$$
$$= 7.2\ kJ$$

$$h_1 = h_g = 2725.3\ kJ/kg\ ;\quad h_2 = 2865.5\ kJ/kg$$

$$\Rightarrow Q_{12} + 7.2 = 0.025(2865.5 - 2725.3) \qquad \Rightarrow Q_{12} = \boxed{-3.7\ kJ}$$

Problem

A 25-kg iron block initially at 350 °C is dropped into an insulated tank that contains 100 kg of water at 18 °C (Assume specific heats of water and iron as 4.18 kJ/kg.K and 0.45 kJ/kg.K, respectively). *The final equilibrium temperature is to be determined, in °C.*



$$E_{in} - E_{out} = \Delta E_{sys} \quad \Rightarrow 0 = \Delta U_{sys}$$

$$\Delta U_{iron} + \Delta U_{w} = 0$$

$$[mc(T_2 - T_1)]_{iron} + [mc(T_2 - T_1)]_{w} = 0$$

$$25(0.45)(T_2 - 350) + 100(4.18)(T_2 - 18) = 0$$

$$T_2 = 26.7\ ^{o}C$$

Problem

A piston–cylinder device, with a set of stops on the top, initially contains 3 kg of air at 200 kPa and 27 °C. Heat is now transferred to the air, and the piston rises until it hits the stops, at which point the volume is twice the initial volume. More heat is transferred until the pressure inside the cylinder also doubles. *Assuming air to be an ideal gas with **variable specific heat**, determine the work done and the amount of heat transfer for this process. Also, show the process on a P-v diagram.*

System: Closed, Air(ideal + var. sp. heat), Q_{in}=? , W_b=?

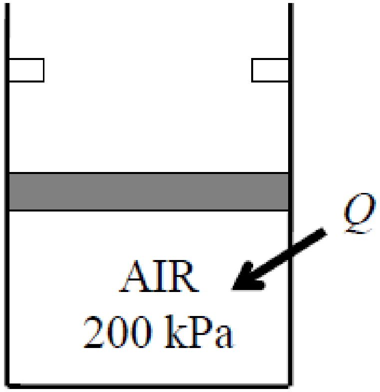
State 1		State 2		State 3
P_1 = 200 kPa	isobaric →	$P_2 = P_1$	isochoric →	$V_3 = V_2$
T_1 = 27 °C		$m_1 = m_2$		$m_2 = m_3$
m_1 = 3 kg		$V_2 = 2V_1$		$P_3 = 2P_2$

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

$$Q_{in} - W_b = m(u_3 - u_1)$$

Now, $W_b = P_2(V_2 - V_1)$

$$V_1 = \frac{mRT_1}{P_1} = \frac{3(0.287)(300)}{200} = 1.292\ m^3$$



Problem

$$V_3 = V_2 = 2V_1 = 2.584\ m^3 \Rightarrow W_b = 200(2.584 - 1.292) = \boxed{258.4\ kJ}$$

$$\frac{P_1V_1}{T_1} = \frac{P_3V_3}{T_3} \Rightarrow T_3 = \frac{P_3V_3}{P_1V_1}T_1 = 2(2)(300) = 1200\ K$$

Using **Tables A-22**, we get

$$u_1(@\,300K) = 214.07\ kJ/kg$$

$$u_3(@\,1200K) = 933.33\ kJ/kg$$

$$Q_{in} - 258.4 = 3(933.33 - 214.07)$$

$$Q_{in} = \boxed{2416.18\ kJ/kg}$$

TABLE A-22

Ideal Gas Properties of Air

T	h	u
290	290.16	206.91
295	295.17	210.49
300	300.19	214.07
305	305.22	217.67
310	310.24	221.25
1200	1277.79	933.33
1220	1301.31	951.09
1240	1324.93	968.95
1260	1348.55	986.90
1280	1372.24	1004.76

Problem

During steady-state operation, a gearbox receives 60 kW through the input shaft and delivers power through the output shaft. For the gearbox as the system, the rate of heat transfer from the system is 1.2 kW. *For the gearbox, evaluate the power delivered through the output shaft, each in kW.*

$$\dot{E}_{in} - \dot{E}_{out} = dE_{sys}/dt = 0$$

$$\dot{W}_{s1} - \dot{Q}_{out} - \dot{W}_{s2} = 0$$

$$\dot{W}_{s2} = 60 - 1.2$$

$$\dot{W}_{s2} = \boxed{58.8\ kW}$$