ESO201A : THERMODYNAMICS
2021-22 Ist semester
IIT Kanpur

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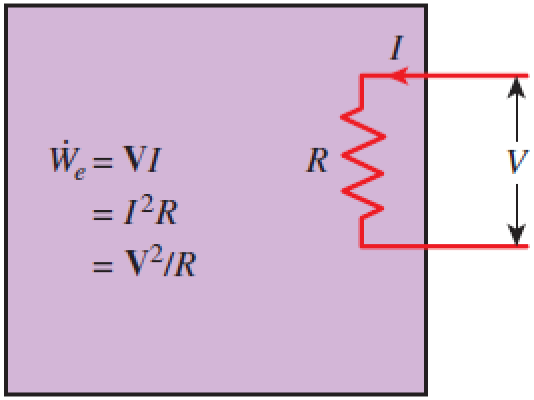
Lecture 3

Non-mechanical forms of work:

(a) Electrical work : When charged particles move across a potential difference

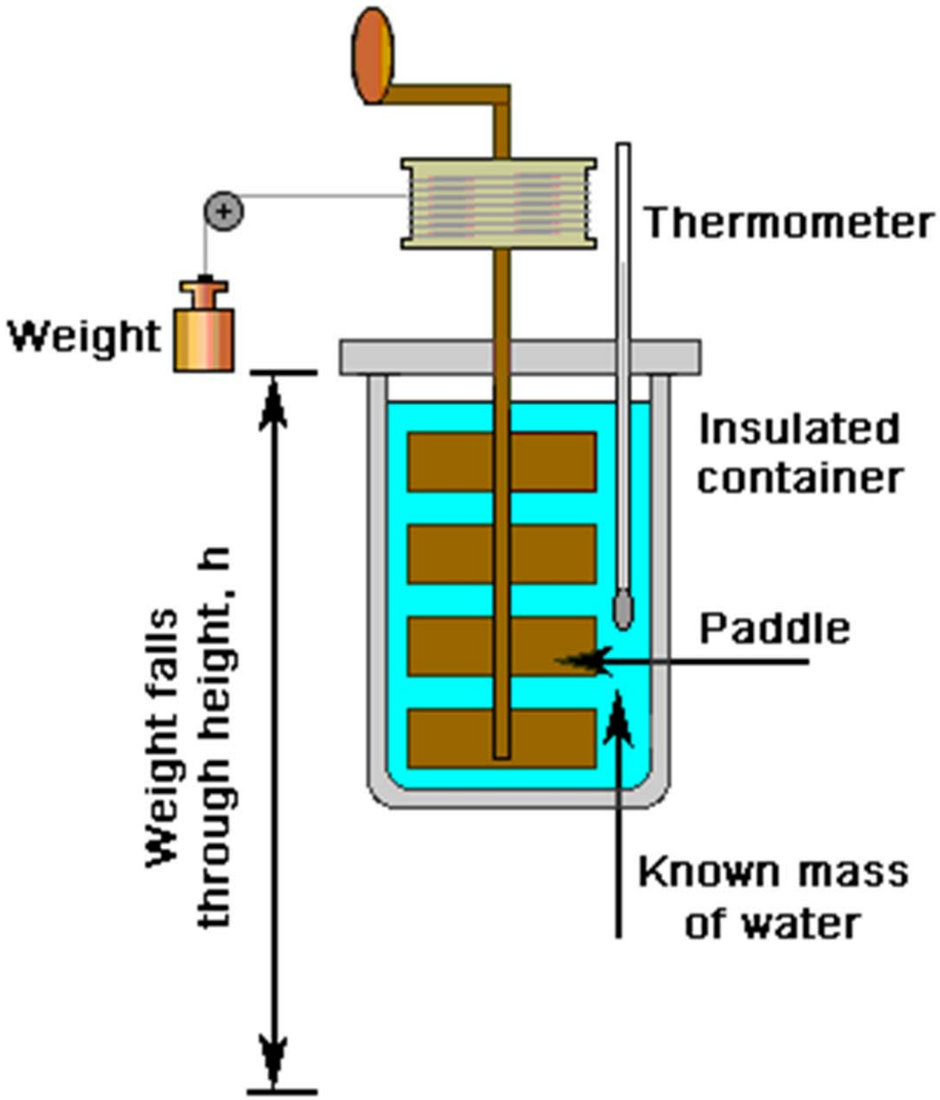


(b) Magnetic work : When we deal with a paramagnetic material in a magnetic force field

(c) Electrical polarization work : When an electric force field distorts eletron clouds around atomic nuclei

Ref. : Cengel and Boles, 8th Edition (2015)

Joule's experiments (Adiabatic process):



Schematic diagram

Parts of the Original apparatus used by Joule

Joule's experiments :

Joule measured the work required to raise 1 lb of water by 1 ^{0}F in adiabatic process by the following methods

1. Turbulent motion of water (paddle wheel experiments)

2. Electrical current

3. Compression of gas

4. Friction of iron blocks

Work measured was approximately the **same** in all 4 methods.

When converted to SI units, results of paddle wheel experiments (see images on last slide) imply that 4.16 kJ of energy is required to raise temperature of 1 kg of water by 1 ^{0}C

Presently accepted value at (15 ^{0}C) is 4.184 kJ for raising temperature of 1 kg of water by 1 ^{0}C (i.e., from 14.5 to 15.5 ^{0}C).

Conclusions based on Joule's experiments:

The change of a body in an adiabatic enclosure from a given initial state to a given final state involves the same amount of work by whatever means the process is carried out.

This leads to the conclusions that

(i) there exists a quantity called as internal energy (U) which depends <u>ONLY</u> upon the internal state (as determined by temperature, pressure, and composition) of the body (or a control mass) .

(ii) work done on the body is equal to increase in U.

U is similar to the Gravitation potential energy (mgZ)
Change in gravitational potential energy between two fixed points is the SAME, independent of the path.

First law of thermodynamics :
(for adiabatic processes)

The work done on a body in an adiabatic process, not involving changes of the body's kinetic and potential energies, is equal to increase in a quantity U which is a function of the state of a body.

Thus amount of work (in an adiabatic process) for change of state of a body from '1' to '2' is given as :

$$W_{in} = U_2 - U_1$$

Heat:

The same change of state can be brought about without doing work on the body. For example, by bringing body in contact with another body at a higher temperature.

The change of internal energy must be the same ($U_2 - U_1$)

The energy transferred in the process (which does not involve work) is called as Heat

Thus, $Q_{in} = U_2 - U_1$

Estimation of heat transferred in a process :

The heat transferred to a body can only be determined by measuring the amount of work which causes the same change of state.

Change in energy due to bulk motion:

In a process, there can be bulk motion of the body, which results in changes in kinetic energy and potential energy.

Kinetic energy due to bulk motion is given by $K.E. = \frac{1}{2}MV^2$

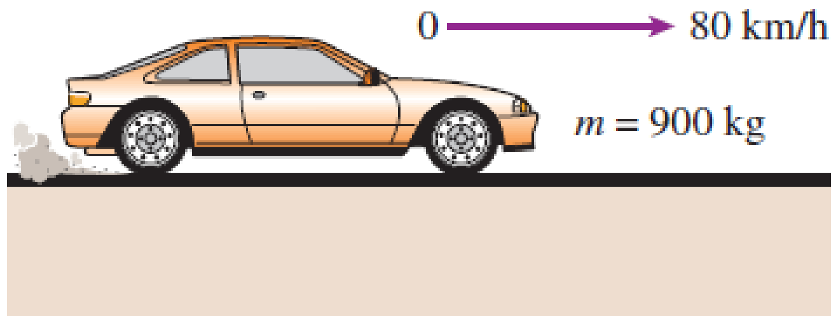
M = total mass, V = center of mass velocity of the body

Potential energy in a gravitational force field is $P.E. = MgH$

H = height of the center of mass above ground level

Change in energy due to bulk motion:

Power required for a 800-kg car to accelerate from 0 to 80 km/h in 20 s



$$W = \int_1^2 \vec{F}.d\vec{R}$$

W = Work done by the car engine

$\vec{F}$ = Force generated by car engine

$\vec{R}$ = Position vector of center of mass of the car

According to Newton's second law of motion: $\vec{F}_{total} = M \frac{d\vec{V}}{dt}$

$\vec{F}_{total}$ = total Force acting on the car

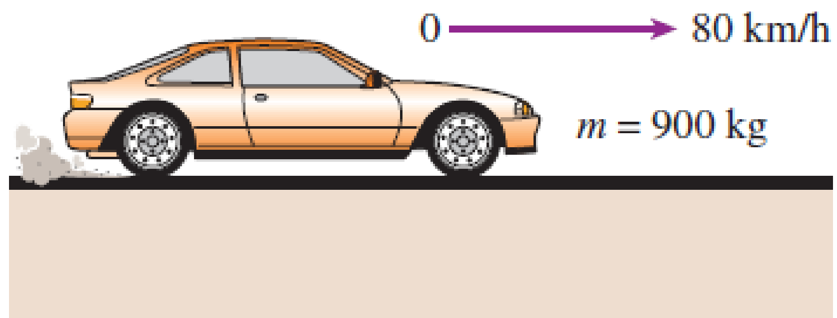
$\vec{V}$ = velocity of the center of mass of the car

M = total mass of the car

Ref. : Cengel and Boles, 8th Edition (2015)

Change in energy due to bulk motion:

Neglecting friction and drag forces, total force acting on car is given by



$$\vec{F}_{total} = \cancel{M\vec{g}} + \vec{F} + \cancel{\vec{N}}$$

$\vec{N}$ = Normal reaction of the road surface on the car.

Substituting Newton's second law on the left hand side of the above equation, we get

$$M\frac{d\vec{V}}{dt} = \vec{F}$$

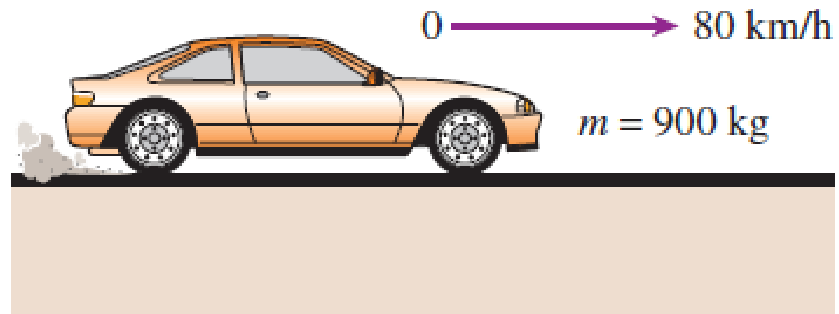
Substituting above equation in Work expression (last slide),

$$W = \int_{1}^{2} \left(M\frac{d\vec{V}}{dt}\right). d\vec{R}$$

Ref. : Cengel and Boles, 8th Edition (2015)

Change in energy due to bulk motion:

Substituting $d\vec{R} = \vec{V}\,dt$



$$W = \int_1^2 \left(M \frac{d\vec{V}}{dt} . \vec{V} dt \right)$$

$$= \frac{1}{2} \int_1^2 \frac{d}{dt} \left(M \vec{V} . \vec{V} \right) dt$$

$$= \left(\frac{1}{2} M V_2^2 \right) - \left(\frac{1}{2} M V_1^2 \right)$$

Substituting values M = 900 kg, $V_1 = 0$, $V_2 = 80$ km/h, we get

W = 222 kJ

Average power required = $\dfrac{W}{\Delta t} = \dfrac{222\,\text{kJ}}{20\,\text{s}}$ = 11.1 kW

First law of thermodynamics :
(Generalized form)

In a process, there can be bulk motion of the body, which results in changes in kinetic energy and potential energy.

Thus, for a finite change between equilibrium states of a control mass

$$\boxed{Q_{in} + W_{in} = \Delta U + \Delta(K.E.) + \Delta(P.E.)}$$

OR

$$\boxed{Q_{in} + W_{in} = \Delta E}$$

where $E = U + K.\,E. + P.\,E.$ is the total energy of the control mass

First law of thermodynamics :
(Generalized form)

For an infinitesimal change of state of a control mass system

$$\boxed{\delta Q_{in} + \delta W_{in} = dU + d(K.E.) + d(P.E.)}$$

OR $$\boxed{\delta Q_{in} + \delta W_{in} = dE}$$

Note that δQ_{in} and δW_{in} are path-dependent.

Rate form of first law for a control mass :

$$\boxed{\dot{Q}_{in} + \dot{W}_{in} = \frac{dE}{dt}}$$

Combined work and heat transfer:

In the absence of kinetic and potential energy changes, as per the first law : Q_{in} - W_{out} = $(U_2 – U_1)$
Note that W_{in} = - $W_{out.}$ Process 1→ 2 can be carried out in various ways. Hence, Q_{in} and W_{out} are ***path-dependent*** *or* ***process-dependent***

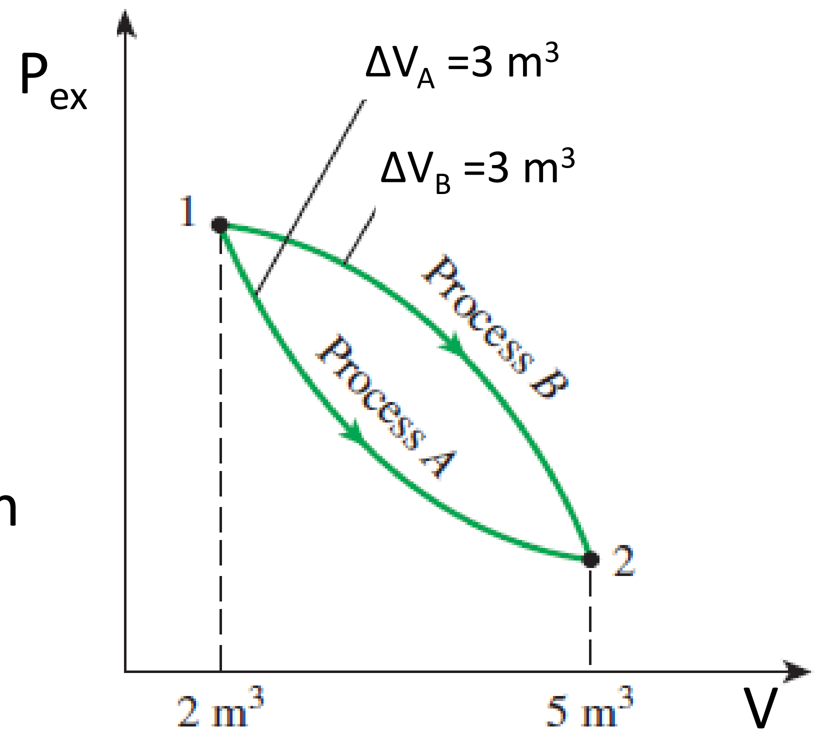
For a gas expansion process in a piston-cylinder device

$$W_{out} = \int_1^2 P_{ex}\, dV$$

$$W_{out,\ path\ A} < W_{out,\ path\ B}$$

But, $(U_2 – U_1)$ is independent of path

$$Q_{in,\ path\ A} < Q_{in,\ path\ B}$$



Ref. : Cengel and Boles, 8th Edition (2015)

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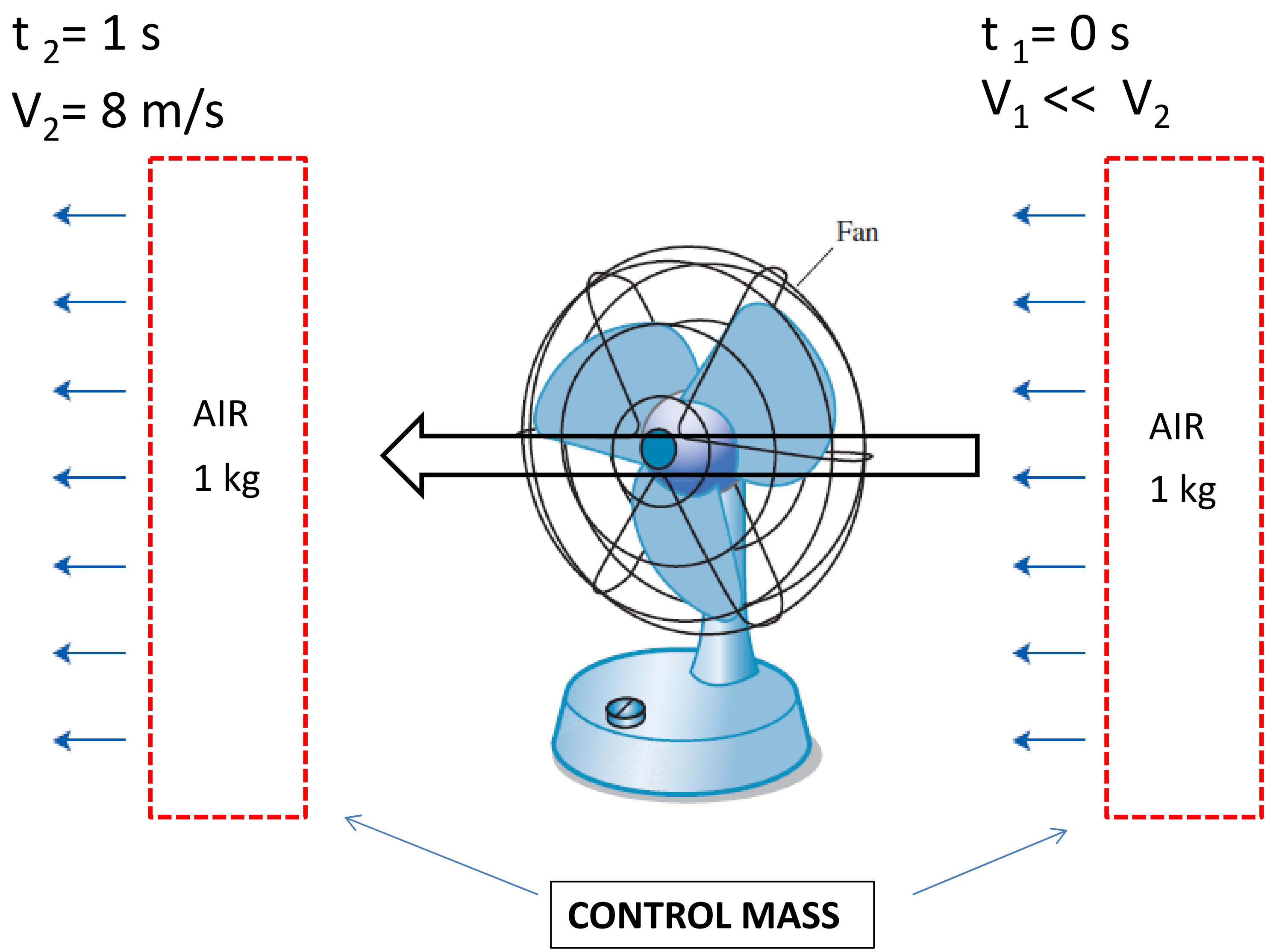
Acceleration of air by fan : A fan that consumes 20 W of electric power is claimed to discharge air at a mass flow rate of 1 kg/s with an outlet velocity of 8 m/s. **Check** if this claim is correct.



Acceleration of air by fan:

We consider mass of air (1 kg) that flows across the fan in 1 s as our system (i.e., control mass). This is enclosed by a boundary as shown in the last slide. Applying first law of thermodynamics :

$$\cancelto{0}{Q_{in}} + W_{in} = \cancelto{0}{\Delta U} + \Delta(K.E.) + \cancelto{0}{\Delta(P.E.)}$$

Note that we have neglected ΔU in comparison with Δ(K.E.) Thus,

$$W_{in} = \Delta(K.E.)$$

$$W_{in} = \text{(Fan power) (time)} = (20\ W)\ (1\ s) = 20\ J$$

$$\Delta(K.E.) = \left(\frac{1}{2}MV_2^2\right) - \left(\frac{1}{2}MV_1^2\right) = \frac{1}{2}MV_2^2 = \frac{1}{2}(1\,kg)(8\ m/s)^2 = 32\ J$$

Note that we have neglected V_1 in comparison to V_2 ($V_1 << V_2$)

Since W_{in} is not equal to Δ(K.E.) , **claim is not correct.**