Internal energy:

The form of energy that is 'internal' to the system.

This energy is due to atoms or molecules contained in the system

There are processes where changes in kinetic energy or potential energy (due to gravity or any other external field) are negligible

Such processes result in changes of internal energy

State postulate :

We will consider processes in which system remains at rest. Such processes involve change of ‘(internal) state’ of the system.

We will usually consider processes in which the work done on the system results in changes in volume. The effect of external Fields (electrical or magnetic) and the surface tension effects are Negligible. Such systems are termed as ‘**simple compressible**’.

It is found empirically that if two variables of a simple compressible system consisting of a single homogeneous phase are specified, all other properties are also completely defined, i.e., all other state properties have unique values.

This is known as ‘**state postulate**’

State postulate :

State of water (which is a simple compressible substance) can be specified by 2 variables. E.g. (P,T) or (T,v) as per the state postulate

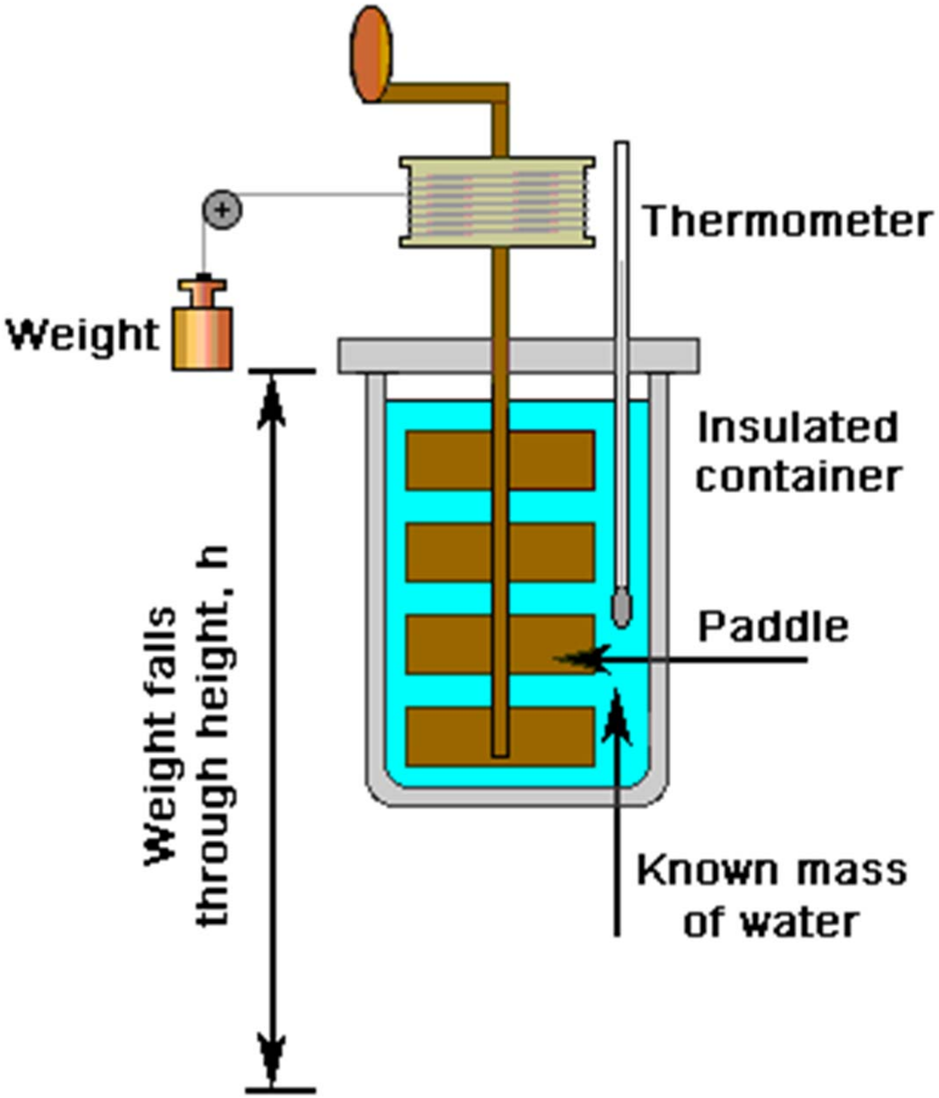
Here v is the specific volume.

Note that for 'state' is specified by intensive variables.

Properties of water at (1 atm., 20^0C).

- Density (998.2 kg/m^3)
- Viscosity (0.001 Pa.s)
- Refractive index (1.33)
- Speed of sound (1461 m/s)
  -- This is almost 4.2 times the speed of sound in air (344 m/s)

Joule's experiments (Adiabatic process):



Schematic diagram

Parts of the Original apparatus used by Joule

Joule's experiments :

Joule measured the energy 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

The measure value of energy required was approximately the **same** in all 4 methods.

When converted to SI units, results of paddle wheel experiments (see images on last slide) showed that 4.16 J of energy is required to raise temperature of 1 g 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 in adiabatic process 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.

$U = f(T,P)$ for a fixed mass system.

In Joule's experiment, $U_1 = f(P_{atm}, T_1)$, $U_2 = f(P_{atm}, T_2)$,

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 (as heat) is equal to increase internal energy

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.

More on internal energy:

Internal energy is equal to average of instantaneous energy (which is also known as the Hamiltonian) of the system.

$$
\begin{aligned}
U &= \langle H \rangle \\
&= \langle K.E. \rangle + \langle P.E. \rangle
\end{aligned}
$$

It can be shown (through Joule's experiments) that U is extensive.

From a molecular level perspective, U is extensive because the energy associated with interfaces is negligible as compared to the energy associated with the bulk

Since energy associated with interface is negligible, U of a fluid or a stress-free solid is independent of shape.

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

First law of thermodynamics :
(Generalized form)

A process may involve change of internal energy, kinetic energy as well as potential energy.

Thus, for a finite change between equilibrium states of a control mass (closed system)

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

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 <u>control mass</u> 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 <u>control mass</u> :

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

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***

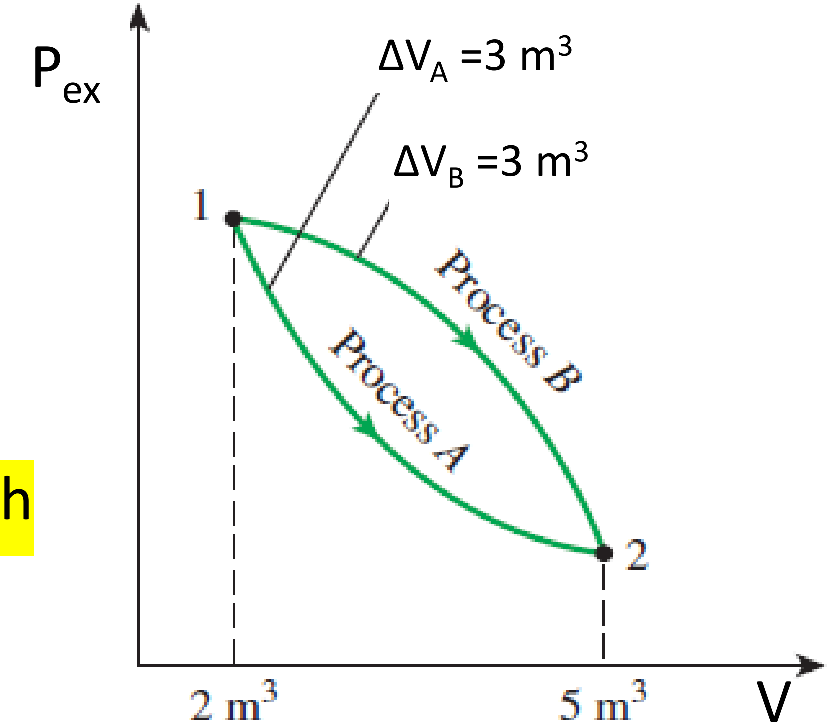
For a gas expansion process in a piston-cylinder device

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

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

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

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



Work due to change of volume :

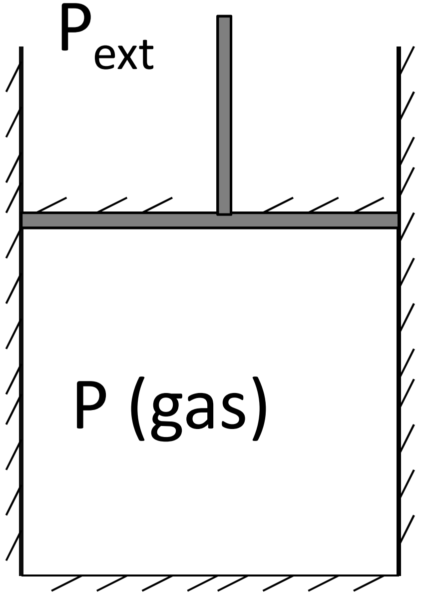
$$W_{in} = -\int_1^2 P_{ext}\, dV$$

For a sufficiently slow expansion

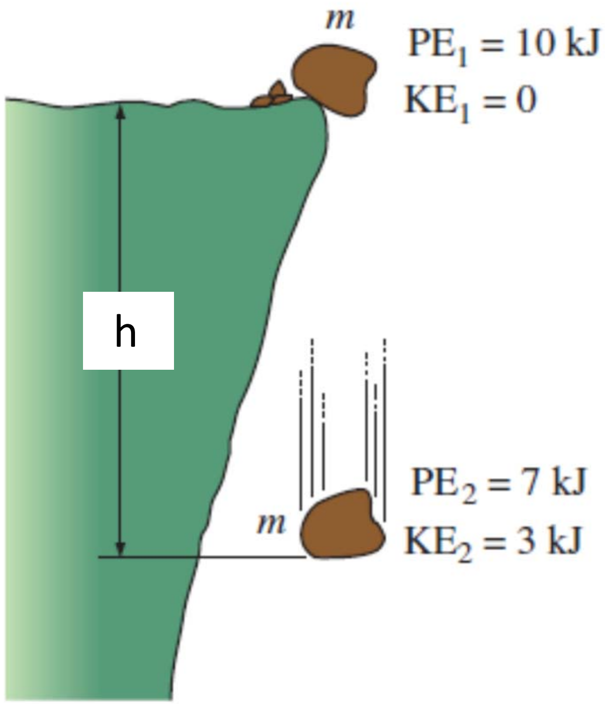
$$P_{ext} = P + dP$$

Substituting in above equation,
and neglecting the term involving dP
we get,

$$W_{in} = -\int_1^2 P\, dV$$



Application of first law :



As an example, consider object falling through some height. We solve this question through 2 ways :

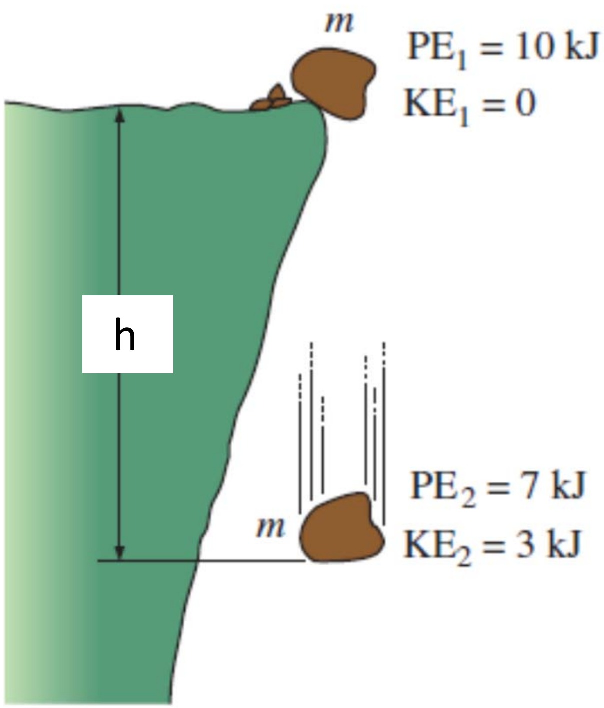
(I) Considering just the 'object' as the system

and

(II) considering '(object + earth)' as our system.

Both of these approaches yield the same final equation. This is explained in the following slides.

Case I : considering (object) as our system



If we neglect air friction, no heat loss occurs. This implies that

$$Q_{in} = 0$$

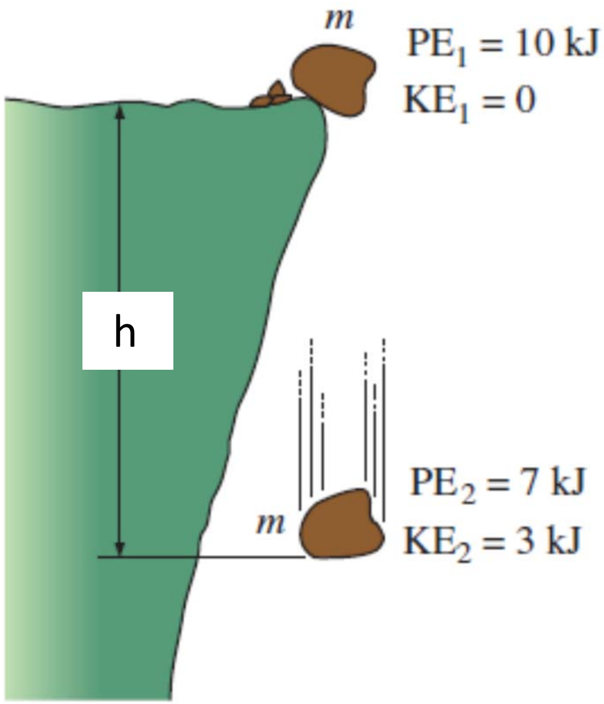
Due to lack of friction, there will not be any change in internal energy of the object.

$$\Delta U = 0$$

Since system is just the object, gravity is an **external force** acting on the system. Thus, work is being done by gravitational force. This work is given as

$$W_{in} = mgh$$

Case I : considering (object) as our system (contd.)



substituting above values in general equation for first law :

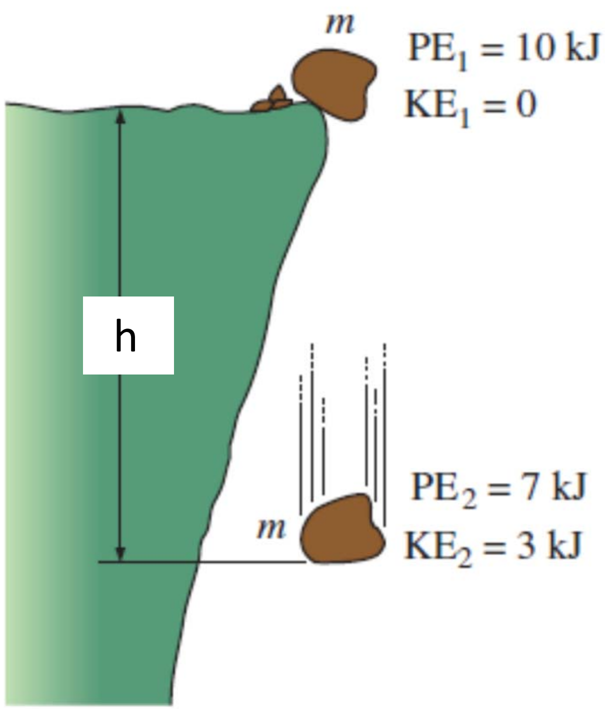
$$\cancelto{0}{Q_{in}} + mgh = \cancelto{0}{\Delta U} + \Delta(\mathrm{K.E.}) + \cancelto{0}{\Delta(\mathrm{P.E.})}$$

This leads to the following equation

$$\boxed{\begin{aligned} mgh &= \Delta(\mathrm{K.E.}) \\ &= 3\ \mathrm{kJ} \end{aligned}}$$

Note that the change in potential energy is **zero**. This is because there are no other binding forces 'within' the 'system' (i.e. object) other than the inter and intra-molecular binding forces. The potential energy change due these later type of binding forces is already included in the internal energy change.

Case II : considering (object + earth) as our system



If we consider (object + earth) as our system, no external force is acting on this system. Hence work term is zero

$$W_{in} = 0$$

If we neglect air friction, no heat loss occurs. This implies that $Q_{in} = 0$

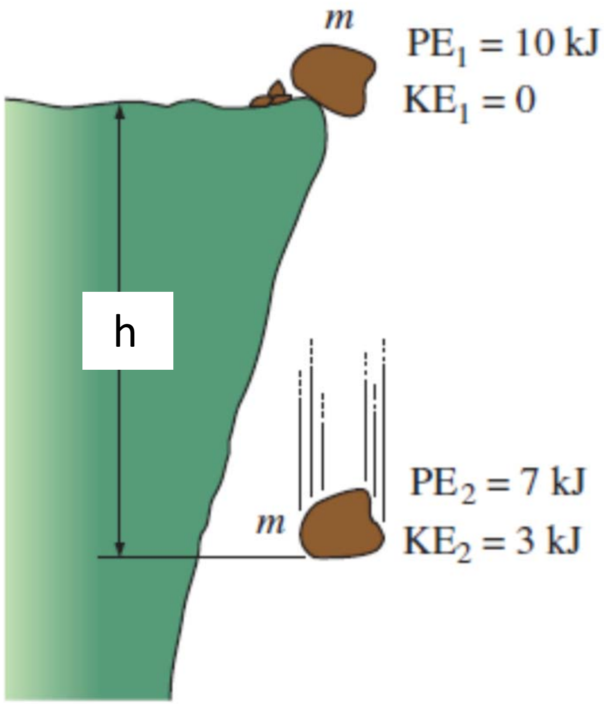
Due to lack of friction, change in internal energy of object is zero. Further, change in internal energy of earth is zero since this process does not influence the earth.

Thus, $\Delta U = 0$

Substituting these values in the generalized form of first law, we get

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

Case II : considering (object + earth) as our system



The change in potential energy due to binding (gravitational) force between object and earth is

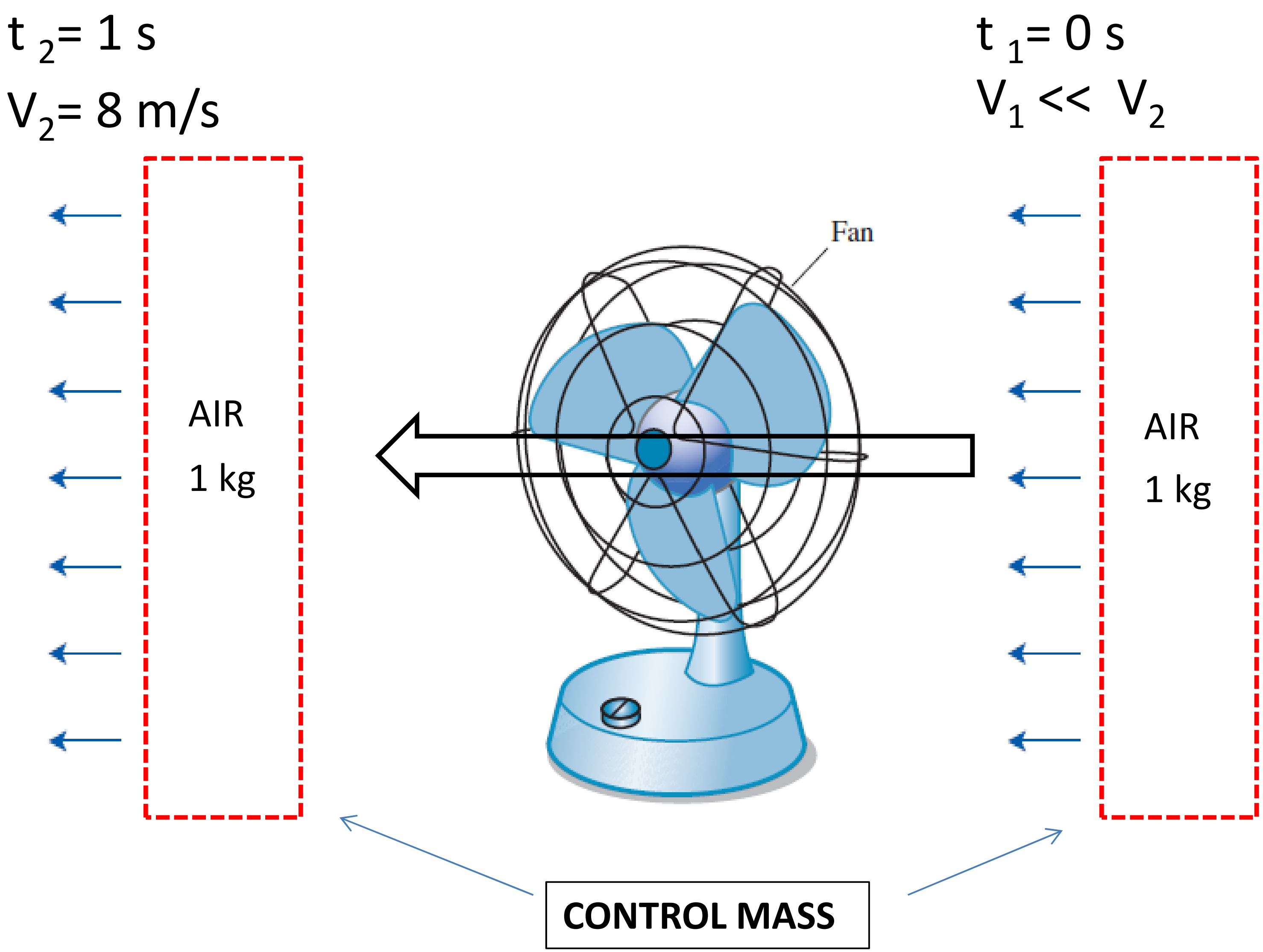
$$\Delta(\mathrm{P.E.}) = -\mathrm{mgh}$$

Substituting this in the last equation on previous slide and re-arranging we get,

$$\boxed{\begin{aligned} \mathrm{mgh} &= \Delta(\mathrm{K.E.}) \\ &= 3\ \mathrm{kJ} \end{aligned}}$$

Thus in both the cases we get the same final equation starting from the generalized equation of the first law.

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,

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

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

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

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.**