ENERGY AND WORK ANALYSIS

Energy cannot be created or destroyed during a process; it can only change from one form to another.

Forms of Energy

Energy can exist in numerous forms such as thermal, electrical, mechanical, kinetic, potential, magnetic, and nuclear; their sum constitute the total energy *E* (*J*) of a system. The total energy of a system on a unit mass basis is expressed as:

$$e = \frac{E}{m}(kJ/kg)$$

In thermodynamics we deal with the change of the total energy. Therefore, the total energy of a system can be assigned a value of zero ($E = 0$) at some convenient reference point.

The total energy of a system can be categorized into two groups: macroscopic and microscopic. In most engineering applications in thermodynamics, surface tension, magnetic, and electric effects are negligible. As a result the total energy of a system can be expressed as:

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

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

where KE and PE are kinetic and potential energy, respectively. The summation of all microscopic energies of a system is called the internal energy, denoted by U (*kJ*) or in per mass basis (*kJ/kg*). Internal energy includes: sensible, latent, chemical, and atomic forces.

Mass and Energy Flow

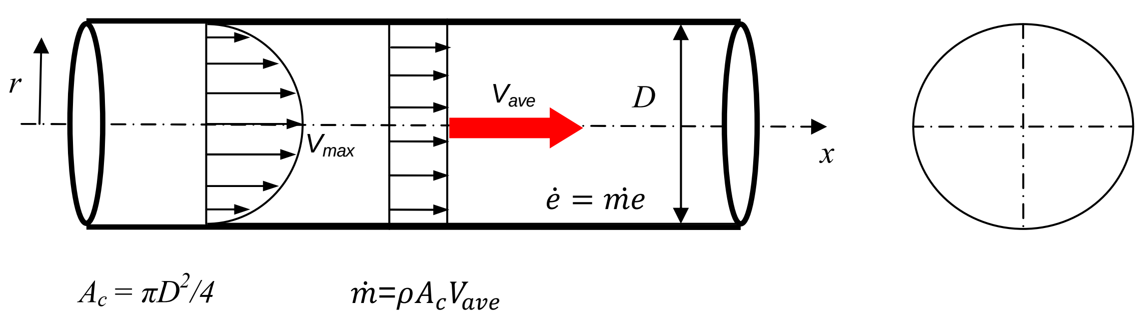

Fig.1: Mass and energy flow of a fluid with average velocity V_{ave} in a tube of diameter *D*.

Mass flow rate $\dot{m}$: the amount of mass flowing through a cross section per unit time. $dm = \rho A_c dx$

$$lim_{dt\to 0}\frac{dm}{dt} = \rho A_c lim_{dt\to 0}\frac{dx}{dt}$$

$$lim_{dt\to 0}\frac{dm}{dt} = \rho A_c V_{ave}$$

It is related to the volume flow rate $\dot{V}$ which is the volume of a fluid flowing through a cross-section per unit time:

$$\dot{m} = \rho\dot{V} = \rho A_c V_{ave} \quad (kg/s)$$

Energy flow rate $\dot{E}$: is the energy flow rate associated with a fluid flowing at a rate of $\dot{m}$

$$\dot{E} = \dot{m}e$$

Internal Energy

Internal energy is the sum of all microscopic forms of energy; it is related to the molecular structure activity and can be viewed as the sum of KE and PE of the molecules that can be categorized into the following components:

Sensible: the portion of the internal energy of a system associated with the kinetic energies of the molecules. It is directly proportional to the temperature of a gas.

Latent: the internal energy associated with the phase of a system. The phase change process can occur without a change in the chemical composition of a system.

Chemical: the internal energy associated with the atomic bonds in a molecule.

Nuclear: the tremendous amount associated with the strong bonds within the nucleus of the atom.

Mechanical Energy

Mechanical energy is defined as the form of energy that can be converted to mechanical work completely and directly by an ideal mechanical device, e.g. ideal turbine. Examples are kinetic and potential energies.

Notes: Thermal energy is not a form of mechanical energy.

Pressure by itself is not a form of energy. However, a pressure force acting on a fluid through a distance produces work, called *flow work*.

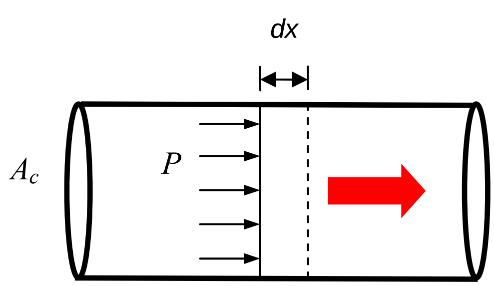

Fig. 2: Flow work.

$$\delta W_{flow\ work} = F.dx$$

$$\delta W_{flow\ work} = P.A_C.dx$$

We know that volume of the element shown in Fig. 2 is: $d\forall = A_C dx$; also the mass of the fluid in the element can be found from $dm = \rho d\forall$; thus the flow work is:

$$\delta W_{flow\ work} = \frac{P}{\rho}$$

The mechanical energy of a flowing fluid can be expressed on a unit mass basis:

$$e_{mechanical} = \frac{P}{\rho} + \frac{V^2}{2} + gz \qquad (J/kg)$$

Energy Transfer by Heat

The direction of energy transfer is always from the higher temperature body to the lower temperature one. Heat transfer can be defined as the form of energy that is transferred between two systems by virtue of a temperature difference.

There cannot be any heat transfer between two systems that are at the same temperature.

Heat is energy transition. It is recognized only as it crosses the boundary of a system.

Adiabatic process: is a process in which no heat transfer is involved. There are two ways a process can be adiabatic: 1) well insulated system, and 2) both the system and the surroundings are at the same temperature.

Heat has the unit of energy (kJ), the amount of heat transferred during a process between state 1 and 2 is denoted:

$$q_{12} = \frac{Q_{12}}{m} \quad (kJ/kg)$$

Rate of heat transfer: is the amount of heat transferred per unit time, $\dot{Q}_{12}$ in (*kJ/s*) or (*kW*).

Heat can be transferred by three mechanisms. All modes of heat transfer require the existence of a temperature difference.

Conduction: is the transfer of energy from more energetic particles to the adjacent less energetic ones as a result of interaction between particles.

Convection: is the transfer of energy between a solid surface and the adjacent fluid that is in motion; it involves the combination effects of conduction and the fluid motion.

Radiation: is the transfer of energy due to the emission of electromagnetic waves (or photons).

Heat and work are both directional quantities, and thus the complete description of a heat and work interaction (energy in general) requires the specification of both the magnitude and direction.

Heat sign convention: Heat Transfer to a system is positive, and heat transfer from a system is negative. It means any heat transfer that increases the energy of a system is positive, and heat transfer that decreases the energy of a system is negative.

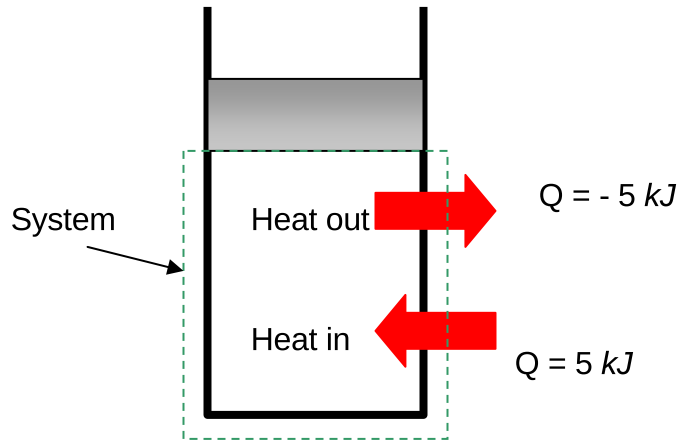

Fig. 3: Heat transfer sign convention: positive if to the system, negative if from the system.

Energy Transfer by Work

An energy interaction that is not caused by a temperature difference between a system and its surroundings is work.

Work can be defined as the energy transfer associated with a force acting through a distance.

$$W = F.d \quad (kJ)$$

$$w = \frac{W}{m} \quad (kJ/kg)$$

A rising piston, a rotating shaft, and an electric wire crossing the system boundaries are all associated with work interaction.

Power: the work done per unit time, denoted by $\dot{W}$ (*kJ/s*) or (*kW*).

Heat and work are energy transfer mechanisms between a system and its surroundings, and there are many similarities between them:

1. Both are recognized at the boundaries of a system. Boundary phenomena.
2. Systems possess energy, but no heat or work. They are not system properties.
3. Both are associated with a process, not a state. They have no meaning at a state.
4. Both are path functions; their magnitudes depend on the path following during a process as well as the end states.

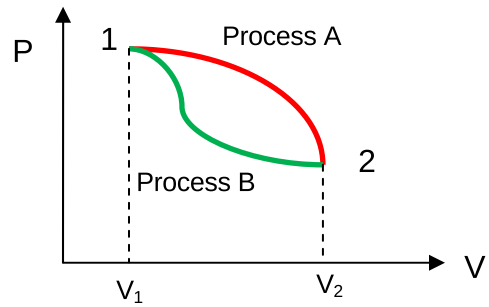

Fig. 4: Properties are point functions. But heat and work are path functions.

Path functions have inexact differentials designated by symbol δ, e.g. δQ.

$$\int_1^2 \delta Q = Q_{12} \quad (\text{not } \Delta Q)$$

Properties, however; are <u>point functions</u>; they depend on the state only, and not on how a system reaches the state. Thus they have exact differentials designated by symbol *d*, e.g. dV.

$$\int_1^2 dV = V_2 - V_1 = \Delta V$$

<u>Work sign convention</u>: work done by a system is positive, and the work done on a system is negative.

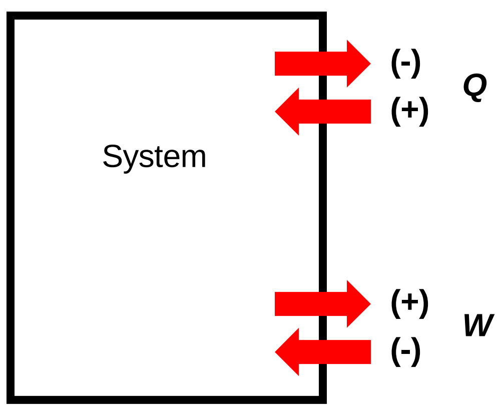

Fig. 5: Sign convention for heat and work.

Example 1: Electrical work

A well-insulated electrical oven is being heated through its heating element. Determine whether it is work or heat interaction. Consider two systems: a) the entire oven (including the heater), and b) only the air in the oven (without the heater) see Fig. 6.

Solution:

The energy content of the oven is increased during this process.

a) The energy transfer to the oven is not caused by a temperature difference between the oven and air. Instead, it is caused by electrical energy crossing the system boundary and thus: **this is a work transfer process**.

b) This time, the system boundary includes the outer surface of the heater and will not cut through it. Therefore, no electrons will be crossing the system boundary. Instead, the energy transfer is a result of a temperature difference between the electrical heater and air, thus: **this is a heat transfer process**.

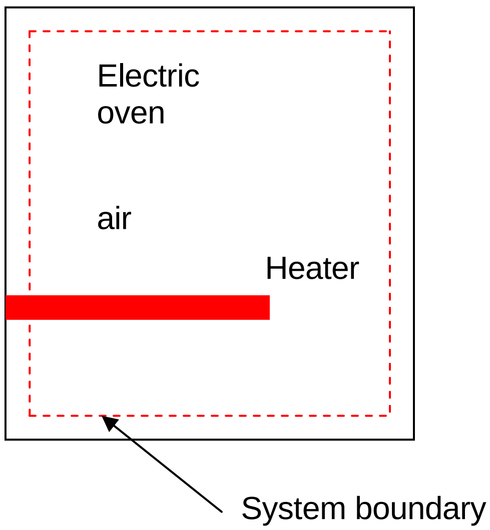

Fig. 6: Schematic for example 1.

Electrical Work

The work that is done on a system by electrons. When *N* coulombs of electrons move through a potential difference *V*, the electrical work done is:

$$W_{electrical} = V.N \quad (J)$$

The electrical power can be calculated from:

$$\dot{W}_{electrical} = V.I \quad (W)$$

where *I* is the electrical current in ampere.

Mechanical work

There are several ways of doing work, each in some way related to a force acting through a distance.

$$W = F.s \qquad (kJ)$$

The sign is easily determined from the physical consideration, i.e. the sign convention.

If the force is not constant, we need to integrate:

$$W = \int_1^2 F.ds \quad (kJ)$$

There are two requirements for a work interaction:

1. There must be a force acting on the boundary
2. The boundary must move.

Therefore, the displacement of the boundary without any force to oppose or drive this motion (such as expansion of a gas into evacuated space) is not a work interaction, **W=0**.

Also, if there are no displacements of the boundary, even if an acting force exists, there will be no work transfer **W = 0** (such as increasing gas pressure in a rigid tank).

Shaft work

Energy transmission with a rotating shaft is very common. Consider a constant torque *T* that is applied to a shaft, for a specified constant torque, the work done during *n* revolutions is determined as:

$$T = F.r \rightarrow F = \frac{T}{r}$$

This force acts through a distance *s*, which is related to the radius *r* by:

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

The shaft work is determined from:

$$W_{shaft} = F.s = \left(\frac{T}{r}\right)(2\pi r)n = 2\pi n T \ \ (kJ)$$

The power transmitted through the shaft, work done per unit time:

$$\dot{W} = 2\pi \dot{n} T \quad (kW)$$

Where $\dot{n}$ is the number of revolution per unit time.

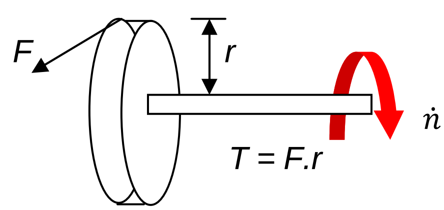

Fig.7: Shaft work is proportional to the torque and the number of revolutions of the shaft.

Spring work

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

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

where k is the spring constant and has the unit *kN/m*. The displacement x is measured from the undisturbed position of the spring. The spring work is:

$$W_{spring} = \int_{x_1}^{x_2} F(x)dx = k \int_{x_1}^{x_2} xdx$$

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

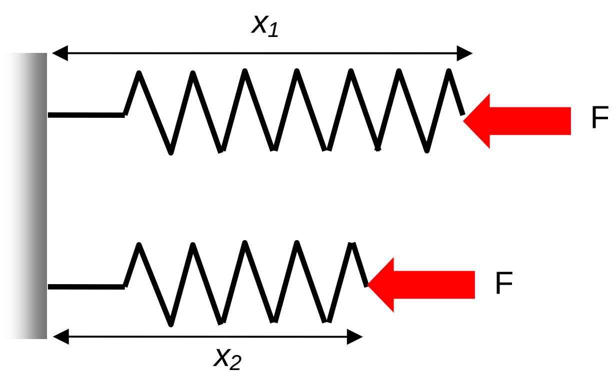

Fig.8: Compression of a spring under the influence of a force.

Note: the work done on a spring equals the energy stored in the spring.

For work done on elastic bars the equation given above for linear springs can be used. This equation holds as long as the applied force is in the elastic region; that is not large enough to cause plastic (permanent) deformations.

Non-mechanical forms of work

Non-mechanical forms of work can be treated in a similar manner to mechanical work. Specify a generalized force F acting in the direction of a generalized displacement x, the work transfer associated with the displacement dx is:

$$\delta W = F.dx$$

First Law of Thermodynamics

First law, or the conservation of energy principle, states that energy can be neither created nor destroyed; it can only change forms.

The first law cannot be proved mathematically, it is based on experimental observations, i.e., there are no process in the nature that violates the first law.

During careful measurements of a series of adiabatic processes, Joule concluded that: for all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process.

As a result of the first law, we can define the property *total energy* E.

Note: the first law makes no reference to the value of the total energy of a system. It simply deals with the *change* in the total energy.

Energy Balance

According to the first law, the net 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 total energy leaving the system.

The first law for a closed system or a fixed mass may be expressed as:

net energy transfer to (or from) the system as heat and work	=	net increase (or decrease) in the total energy of the system

$$Q - W = \Delta E \quad (kJ)$$

where

Q = net heat transfer ($=\Sigma Q_{in} - \Sigma Q_{out}$)

W= net work done in all forms ($=\Sigma W_{in} - \Sigma W_{out}$)

ΔE = net change in total energy ($= E_2 - E_1$)

The change in total energy of a system during a process can be expressed as the sum of the changes in its internal, kinetic, and potential energies:

$$\Delta E = \Delta U + \Delta KE + \Delta PE \quad (kJ)$$

$$\Delta U = m\left(u_2 - u_1\right)$$

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

$$\Delta PE = mg\left(z_2 - z_1\right)$$

Note: for stationary systems $\Delta PE = \Delta KE = 0$, the first law reduces to

$$Q - W = \Delta U$$

The first law can be written on a unit-mass basis:

$$q - w = \Delta e \left(\frac{kJ}{kg}\right)$$

or in differential form:

$$\delta Q - \delta W = dU \quad (kJ)$$

$$\delta q - \delta w = du \left(\frac{kJ}{kg}\right)$$

or in the rate form:

$$\dot{Q} - \dot{W} = \frac{dE}{dt} \quad (kW)$$

For a cyclic process, the initial and final states are identical, thus $\Delta E = 0$. The first law becomes:

$$Q - W = 0 \; (kJ)$$

Note: from the first law point of view, there is no difference between heat transfer and work, they are both energy interactions. But from the second law point of view, heat and work are very different.

In a cycle, the net change for any properties (point functions or exact differentials) is zero. However, the net work and heat transfer depend on the cycle path.

$$\Delta E = \Delta U = \Delta P = \Delta T = \Delta(\text{any property}) = 0$$

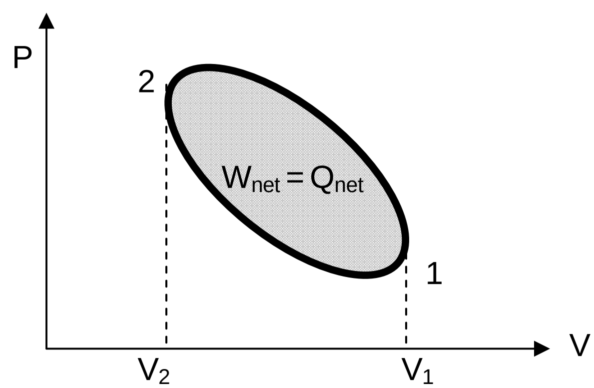

Fig. 9: network done during a cycle.

Efficiency

Efficiency indicates how well an energy conversion or transfer process is accomplished.

In general, efficiency can be defined as:

$$\eta = \frac{Benefit}{Cost}$$

$$Performance = \frac{Desired\ output}{Required\ input}$$

Mechanical efficiency:

$$\eta_{mech} = \frac{Mechanical\ energy\ output}{Mechanical\ energy\ input} = \frac{E_{mech,out}}{E_{mech,in}}$$

Mechanical efficiency of electrical motors ranges from 35% to 97%.

A pump/fan/compressor is usually packaged together with its motor and a turbine with its generator. Therefore, their efficiency is typically stated as the *combined* or *overall efficiency*, defined as:

$$\eta_{pump-motor} = \eta_{pump}\eta_{motor} = \frac{\dot{W}_{pump,out}}{\dot{W}_{elec}} == \frac{\Delta\dot{\mathrm{E}}_{\mathrm{mech,fluid}}}{\Delta\dot{\mathrm{E}}_{\mathrm{elec,in}}}$$

$$\eta_{turbine-motor} = \eta_{turbine}\eta_{motor} = \frac{\dot{W}_{elect,out}}{\dot{W}_{turbine,in}} = \frac{\Delta\dot{\mathrm{E}}_{\mathrm{elect,out}}}{\Delta\dot{\mathrm{E}}_{\mathrm{mech,fluid}}}$$

<u>Thermal efficiency</u>: is the fraction of the heat input that is converted to the net work output.

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

The thermal efficiencies of work-producing devices are low. Ordinary spark-ignition automobile engines have a thermal efficiency of about 20%, diesel engines about 30%, and power plants in the order of 40%.