Applied Thermodynamics for Engineers
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Lecture – 02
Review of Thermodynamic Principles

Hello friends, so again we meet in this particular week, where we have started our course on applied thermodynamics for engineers and this week we are reviewing the basic principles of thermodynamics, or whatever you must have learned in your basic thermodynamics course. We are reviewing those topics and preparing ourselves to go into the deeper discussions on the topic of applied thermodynamics.

In the previous lecture, which is the first lecture of this course, we have just reintroduced or tried to revise the concept of thermodynamic system, state and properties. Different types of thermodynamics systems basically, the closed and open systems were discussed. Then about different ways of defining properties, whereby we can classify a property as intensive or extensive.

Then we discussed, the concept of thermodynamics state, equilibrium state and finally, the zeroth law of thermodynamics which give away the concept of the property called temperature. So, today we are going to take the discussion forward and looking to discuss about the first and second laws of thermodynamics.

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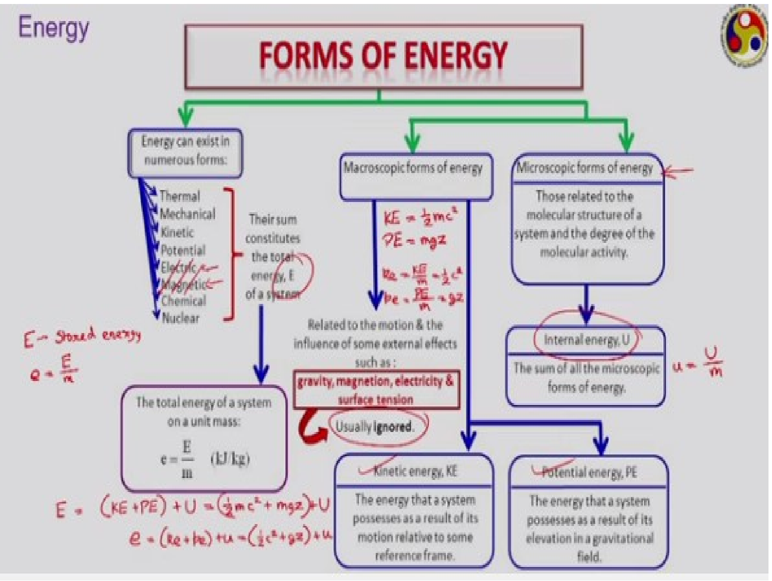

Energy

FORMS OF ENERGY

Energy can exist in numerous forms:

- Thermal
- Mechanical
- Kinetic
- Potential
- ~~Electric~~
- ~~Magnetic~~
- Chemical
- Nuclear

Their sum constitutes the total energy, E of a system

The total energy of a system on a unit mass:

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

$E \rightarrow$ Stored energy

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

$E = (KE + PE) + U = (\frac{1}{2}mc^2 + mgz) + U$

$e = (ke + pe) + u = (\frac{1}{2}c^2 + gz) + u$

Macroscopic forms of energy

$KE = \frac{1}{2}mc^2$

$PE = mgz$

$ke = \frac{KE}{m} = \frac{1}{2}c^2$

$pe = \frac{PE}{m} = gz$

Related to the motion & the influence of some external effects such as :

gravity, magnetion, electricity & surface tension

Usually **ignored**.

Kinetic energy, KE

The energy that a system possesses as a result of its motion relative to some reference frame.

Potential energy, PE

The energy that a system possesses as a result of its elevation in a gravitational field.

Microscopic forms of energy

Those related to the molecular structure of a system and the degree of the molecular activity.

Internal energy, U

The sum of all the microscopic forms of energy.

$u = \frac{U}{m}$

And the first term that we have here for discussion is the energy. Energy is a very important in any discussion of thermodynamics. Thermodynamics is often defined as a science of energy.

From a layman's point of view or any general discussion point of view, the energy content in a system can be classified into different categories as shown here. We can assume that energy can exist in a system in numerous forms like thermal energy, mechanical energy, kinetic, potential, electrical energy, magnetic energy, chemical or nuclear energy under certain situations. So, it is possible that a system can have all these kinds of energies and the sum of all these types of energies is called the total energy content of the system. We are going to use 'E' to denote the total energy content of the system. We also called it as stored energy so, this symbol 'E' is used to denote the stored energy. It is an extensive property that is why we are using the symbol 'E' and its specific version that is 'e' defined as

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

or stored energy per unit mass is an internal or intensive property.

But from thermodynamic point of view, there is no reason that you should go for so many different types of energies rather we can classify energy into two common categories or two broad categories.

- Macroscopic form of energy
- Microscopic form of energy

The macroscopic form of energy is related to the physical variables associated with the geometric orientation or position of the system. The most common classification being the kinetic energy and potential energy. A system possesses kinetic energy because of its velocity with respect to a certain reference frame, whereas it possesses potential energy because of its elevation with respect to a certain reference frame.

So, the role of the reference frame is very important. Both kinetic and potential energies are defined with respect to a certain reference frame and that is true for any macroscopic form of energy. Any macroscopic form of energy is always defined with respect to a certain reference frame.

For example, you can think of a train moving with a certain velocity and you are inside the train, now you throw a ball in some direction. What should be the velocity of that ball? The velocity of the ball should be its actual velocity plus the velocity of the train. But what kind of velocity to choose depends on your choice of the reference frame or choice of the observer. If the observer is standing inside the train, he will observe the velocity of the ball to be its actual velocity with which it is moving inside the train.

If the observer is standing outside the train on the stable ground, he will be seeing the ball to move with the velocity of the train plus its own velocity with which it is moving. If someone is standing outside the earth, you have to add the velocity of the earth also to the same. Therefore, value of the kinetic energy of the ball will keep on changing depending upon the choice of observer or your choice of the reference frame.

The choice of the reference frame is very important in the case of any macroscopic form of energy. In certain situations, we can also define macroscopic form of energy in terms of the motion and the influence of some external factors like magnetism, electricity, surface tension. But they appear only in certain very special cases and hence they are usually ignored in most of the common thermodynamic analysis.

So, the macroscopic form of energy can be considered to be only of two types; one is the kinetic energy, other is the potential energy.

Kinetic energy you know can be expressed as

$$KE = \frac{1}{2}mc^2$$

where c is the velocity of the system with respect to the reference frame.

Whereas, potential energy is expressed as

$$PE = mgz$$

where z is the elevation with respect to the reference frame.

Both these kinetic energy and potential energy are extensive properties because their magnitude depends on mass.

We can easily define an intensive version for both of them like 'ke' is kinetic energy per unit mass i.e.,

$$ke = \frac{KE}{m} = \frac{1}{2}c^2$$

So, if you know the value of the velocity, you can also specify the specific kinetic energy. Similarly, you can also specify a specific potential energy which is potential energy per unit mass i.e.,

$$pe = \frac{PE}{m} = gz$$

g being a constant, *pe* is only a function of the elevation. This was about the macroscopic form of energy.

Let us now consider microscopic form of energy. Microscopic form of energy relates to the energy which is associated with the molecular structure of the system and the degree of molecular activity that may be present under a particular situation or at a particular state. The molecules which are present inside the system can have different types of motion like translational motion, rotational motion and vibrational motion.

All these energies, especially translational, rotational and vibrational energies combined together leads to the microscopic form of energy. It is extremely difficult to quantify each of the subcomponents and not very necessary as well, therefore, all these types of microscopic form of energies associated with the molecular activity is combined into a group called internal energy. This internal energy denoted by 'U' which is an extensive property.

We can easily define the specific internal energy u as

$$u = \frac{U}{m}$$

which is an intensive property.

If we see the initial classifications of energy that was discussed before, all the energies, chemical energy or nuclear energy are also microscopic type as both chemical and nuclear energies are associated with the molecular activities. In case of a chemical reaction, atoms are exchanged between different molecules leading to a different molecular representation. Hence there is a change in the molecular activity level. Correspondingly, a change in the internal energy occurs.

Similarly, in nuclear energy, a nuclear reaction actually is associated with the breaking or explosion of the nucleus present inside an atom due to which there is a change in the orientation of protons and neutrons inside the nucleus. So nuclear energy is also related to molecular activity.

And therefore, if at all present in the system, this chemical and nuclear energies are also considered as a part of the internal energy. However, the electrical or magnetic energies may appear only under certain special situations. There is no need to talk about it at this point. If we now combine both these macroscopic and microscopic form of energies, we can say that the stored energy of a system is considered to comprise of the macroscopic part (which is the kinetic energy and potential energy) and the microscopic part (which is the internal energy) i.e.,

$$E = (KE + PE) + U$$

Expanding the above equation, it can be written as

$$E = \left(\frac{1}{2}mc^2 + mgz\right) + U$$

$$\downarrow \qquad\qquad \downarrow$$

(macroscopic part) (microscopic part)

To define the specific stored energy i.e., ‘e’ that will be comprising of the corresponding macroscopic part and the microscopic part but all written in specific sense or intensive sense.

$$e = (ke + pe) + u$$

Expanding the above equation, it can be written as

$$e = \left(\frac{1}{2}c^2 + gz\right) + u$$

So, specific energy, total energy and total stored energy are different names used in an energy analysis. From that context you have to identify what actually we should use i.e., ‘E’ or ‘e’? These are the forms of energy is a system possesses. At the same time, the system can also receive energy from the surrounding or lose some energy to the surrounding due to the energy interactions with the surroundings.

Whenever system undergoes a process, there is some kind of interaction between system and a surrounding. As we have seen during the previous lecture, the interactions can be classified under two broad categories:

Mass

Energy

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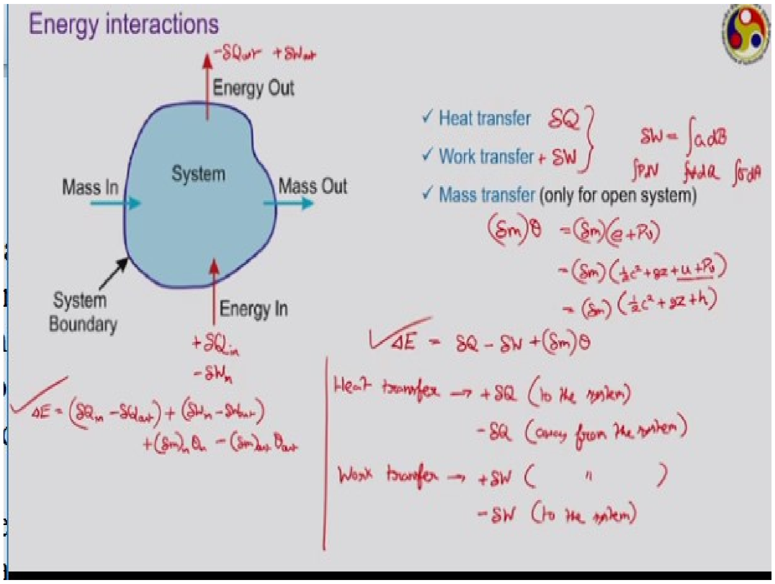

Energy interactions

✓ Heat transfer δQ

✓ Work transfer $+ \delta W$

$\delta W = \int a\,dB$ $\quad \int p\,dV \quad \int F\,dl \quad \int \sigma\,dA$

✓ Mass transfer (only for open system)

$$(\delta m)\theta = (\delta m)(e + Pv)$$
$$= (\delta m)\left(\tfrac{1}{2}c^2 + gz + \underline{u + Pv}\right)$$
$$= (\delta m)\left(\tfrac{1}{2}c^2 + gz + h\right)$$

$$\Delta E = \delta Q - \delta W + (\delta m)\theta$$

$$\Delta E = (\delta Q_{in} - \delta Q_{out}) + (\delta W_{in} - \delta W_{out}) + (\delta m)_{in}\theta_{in} - (\delta m)_{out}\theta_{out}$$

Heat transfer → $+\delta Q$ (to the system)
$-\delta Q$ (away from the system)

Work transfer → $+\delta W$ (")
$-\delta W$ (to the system)

Due to the mass interaction, the total mass content in the system may or may not change. Say, if the mass coming in is equal to mass going out, mass content of the system will not change but still there is mass interaction.

Similarly, energy can come also come inside the system and can leave the system if the amount of energy coming to the system is more than the amount of energy going out, then the magnitude of the stored energy of the system is going to increase. Now, this increase can be in kinetic energy or in potential energy or in internal energy or can be in all of them. But there will be an increase in the total stored energy. Similarly, if the energy going out is more, then there will be reduction in the total stored energy.

There are three ways by which a system can receive energy.

1. Heat transfer: Heat transfer is the energy transfer, which takes place because of a temperature difference between system and surrounding only and not due to any other reason. Commonly, we use a symbol 'Q' to denote heat transfer. The symbol 'δQ' is used to denote an infinitesimally small heat transfer during a small process.
2. Work transfer: Work transfer is another form of energy transfer which takes place when there is some kind of energy transfer between system and surrounding not because of temperature difference but because of something else. When the energy interaction between system and surrounding takes place because of a temperature difference we call that a heat transfer and when the driving potential is not temperature difference but something else, we call that work transfer. So, the driving potential for work transfer can be anything, apart from temperature difference, there are numerous possibilities to have a work transfer. Work transfer we generally denoted by 'W' and δW to denote an infinitesimally small work transfer during a process.

So, when system receives some heat or some energy in the form of heat transfer or work transfer, its energy content increases or the magnitude of stored energy increases. If the system loses energy in the form of heat transfer or work transfer, its total energy content reduces. But these are only two and I have told that the energy content of a system can changes because of three different kinds of interaction. Now, what can be the third one? We have already mentioned heat transfer which takes place because of temperature difference; we have also mention work transfer which is energy transfer because of not temperature difference but something else. Then, what can be the third one? The third one is mass transfer.

3. Mass transfer: Mass transfer is applicable only for open systems because for a closed system, there is no mass transfer. So, for a closed system, we can have only two kinds of energy interaction; heat transfer and work transfer. However, for an open system has some amount of mass moves inside a system, it also carries some energy with it. Similarly, when mass leaves an open system, it also carries some energy with it outside the system. Accordingly, the total energy content of the system should reduce, so mass transfer also leads to energy interactions. Suppose, 'δm' is the amount of mass transfer taking place during a particular process then, total energy transfer associated with this can be represented as $(\delta m)\theta$, where θ is the energy content of this moving mass and θ is the sum of stored energy of this mass (e) and the flow work (Pv), i.e.,

$$(\delta m)\theta=(\delta m)(e+Pv)$$

The flow work is the amount of energy which this mass receives as it moves over a pressure difference into the system or out of the system. So if we expand e, the equation can be written as follows:

$$(\delta m)\theta = (\delta m)(\frac{1}{2}c^2 + gz + u + Pv)$$

And you know, $(u + Pv)$ is combined to form another property, i.e., enthalpy or in this case specific enthalpy (h). Hence the equation can be written as follows:

$$(\delta m)\theta = (\delta m)(\frac{1}{2}c^2 + gz + h)$$

So, the total energy a system can receive can come either in form of heat transfer or in the form of work transfer or in the form of mass transfer or may be a combination of all these three.

If a system is subjected to all these kinds of energy interaction then, we can write the total amount of energy increase in the system as:

$$\Delta E = \delta Q + \delta W + (\delta m)\theta$$

where

ΔE is the change in the energy content of the system
δQ is the total amount of energy received in form of heat transfer
δW is the total amount of energy received in the form of work transfer
$(\delta m)\theta$ is the total amount of energy received in the form of mass transfer.

Here, I would mention about a convention generally, the work done by a system is considered as positive whereas, work done on the system is considered as negative. On the contrary, heat transfer to the system is taken as positive and heat transfer from the system is taken as negative. Therefore, whenever you are writing $+\delta Q$, you are referring to amount of heat transfer to the system.

Whereas, if you are mentioning about $+\delta W$, you are talking about work done by the system i.e., energy moving away from the system. So, quite often we may write this one in a form like this

$$\Delta E = \delta Q - \delta W + (\delta m)\theta$$

where δQ is positive i.e., amount work or heat transfer to the system and for δW, we are putting a negative sign to indicate that here δW is positive but energy is gone away from the system.

So, for heat transfer,

$+\delta Q$ when it is ‘to the system’
$-\delta Q$ is when it is ‘moving away from the system’

Whereas, in case of work transfer,

$+\delta W$ when it is ‘moving away from the system’
$-\delta W$ is when it is ‘to the system’

This convention came in just to be consistent with the definition of a work producing device, because most often, from the engines or work producing devices, we want work output, so when you are getting work back from the system, we call it a positive work.

Look at the diagram, if energy going in i.e., if it is heat going in, we call it δQ_{in} which is positive, and heat coming out is δQ_{out}. Similarly, if work is going inside, we call it δW_{in} and work is given by the system, we call it δW_{out}.

In order to avoid confusion, it is better to avoid any convention, but just mention whether energy is going into the system or out of the system. Whenever energy is going into the system, in energy balance, you should treat as positive. So, this can be written in the form of equation as follows:

$$\delta E = (\delta Q_{in} - \delta Q_{out}) + (\delta W_{in} - \delta W_{out}) + ((\delta m)_{in}\theta - (\delta m)_{out}\theta)$$

where

$(\delta Q_{in} - \delta Q_{out})$ is the net heat that has gone into the system

$(\delta W_{in} - \delta W_{out})$ which is the net amount of work that has gone into the system

$((\delta m)_{in}\theta - (\delta m)_{out}\theta)$ which is the net mass transfer

So, we can also write in this form where we take the convention that heat transfer to the system as positive and heat going away from the system as negative. Whereas, work done by the system is positive and work done on the system is negative. We can also write in this form where we are explicitly mentioning in and out, so any energy going into the system is taken as positive, coming out of a system is taken as negative. Both are one and the same.

Out of all these three kinds of energy interaction that are possible, heat transfer and mass transfer are quite straightforward that is a heat or energy in the form of mass going into the system is taken as positive and there can be no other kind of variation. Mass transfer can take place because of its own reason and heat transfer can take place because of temperature difference. But work transfer can take place because of various possible reasons. Therefore, work transfer can always also be calculated in different ways depending upon what kind of work transfer we are considering.

We can have a moving boundary work in which the boundary of the system physically moves, we can have electrical work whereas transfer some kind of electrical energy, we can have also work in the form of spring action, work in the form of a stretching of liquid flame etc. For each case, we can calculate the work transfer in different ways.

You must have calculated different formulas of work transfer in your basic thermodynamics course where you would have observed that any kind of work transfer relation has a form somewhat like this:

$$\delta W = \int a dB$$

where a refers to an intensive property and dB refers to the change in the value of some extensive property. Say, in the case of a moving boundary work there, the work output is given as:

$$\delta W = \int P dv$$

where *P* is pressure and intensive property and *dv* refers to the change in volume which is an extensive property.

If you consider electrical work, it is generally given as:

$$\delta W = \int \cancel{V} dQ$$

where ~~*V*~~ is the potential difference and *dQ* is the amount of charge that flows in the direction of the potential difference. So, potential difference or voltage difference is an intensive property and the amount of charge as it depends on the system, i.e., size of the system, it is an extensive property.

Suppose, we need to find the amount of work required to raise a film or form a soap bubble. Then, corresponding work can be generally given as:

$$\delta W = \int \sigma dA$$

where σ is the surface tension and *dA* is the change in area.

Again here, surface tension is the intensive property and area depends on the size of the system, so it is an extensive property. So, always the work transfer can be expressed as the product of an intensive property which is generally the reason for this work transfer multiplied by the change in some extensive property which is the effect of that work transfer.

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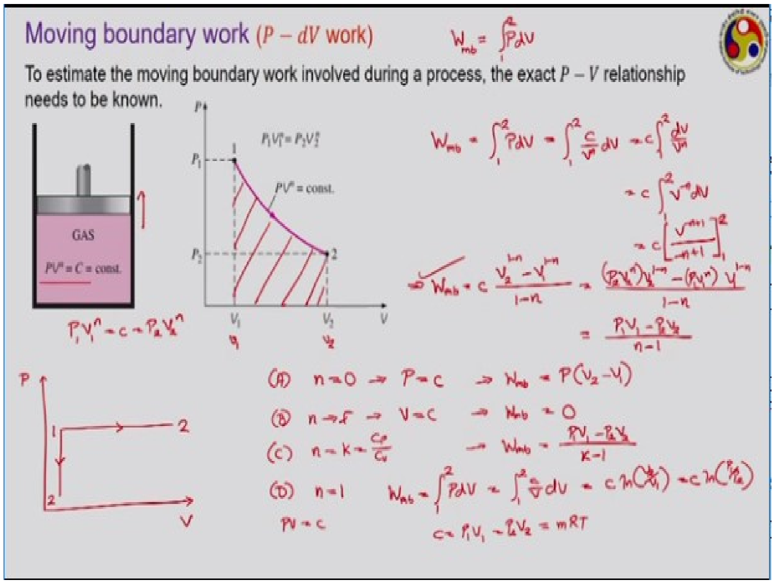

Moving boundary work ($P-dV$ work) $W_{mb} = \int_1^2 PdV$

To estimate the moving boundary work involved during a process, the exact $P-V$ relationship needs to be known.

$P_1V_1^n = c = P_2V_2^n$

$$W_{mb} = \int_1^2 PdV = \int_1^2 \frac{c}{V^n}dV = c\int_1^2 \frac{dV}{V^n}$$

$$= c\int_1^2 V^{-n}dV$$

$$= c\left[\frac{V^{-n+1}}{-n+1}\right]_1^2$$

$$\Rightarrow W_{mb} = c\,\frac{V_2^{1-n} - V_1^{1-n}}{1-n} = \frac{(P_2V_2^n)V_2^{1-n} - (P_1V_1^n)V_1^{1-n}}{1-n}$$

$$= \frac{P_1V_1 - P_2V_2}{n-1}$$

(A) $n = 0 \rightarrow P = c \rightarrow W_{mb} = P(V_2 - V_1)$

(B) $n \rightarrow \infty \rightarrow V = c \rightarrow W_{mb} = 0$

(C) $n = k = \frac{C_p}{C_v} \rightarrow W_{mb} = \frac{P_1V_1 - P_2V_2}{k-1}$

(D) $n = 1$ $\quad W_{mb} = \int_1^2 PdV = \int_1^2 \frac{c}{V}dV = c\ln\left(\frac{V_2}{V_1}\right) = c\ln\left(\frac{P_1}{P_2}\right)$

$PV = c$ $\quad c = P_1V_1 = P_2V_2 = mRT$

Now, in this course of applied thermodynamics, we are mostly concerned with the moving boundary work. We are hardly going to talk about any other kind of work and therefore, there is no reason to discuss any of them further. But moving boundary work being the one that where you are going to focus on, I would like to spend a little more time on that. Moving boundary are also often called the *PdV* work because as we have seen the amount of moving boundary work W_{mb} can be given as:

$$W_{mb} = \int_1^2 PdV$$

where 1 is the initial state of the process, 2 is the final state of the process and this integration PdV gives the magnitude of the work. We generally use the subscript 'mb' to denote it is a moving boundary work.

To estimate the moving boundary work involved during a process 1 to 2, we need to know this exact *PdV* relationship. Let us consider an example. Here our situation is a gas is enclosed into a piston cylinder arrangement. As the piston is moves, some process is been taking place. Our process is initially we are at the state point 1 where the pressure is high and volume is low. Then we are moving in this direction that is the system is expanding, so that the pressure reduces, the volume increases and finally reaches point 2.

So, P_1 and V_1 is the initial pressure and volume which identifies the initial state point. As per the phase postulate, we can specify two independent intensive properties to identify in the state of a system. So instead of 'V', if we write 'v' because if 'V' and 'v' are independent then the state 1 is completely defined. Now, what kind of system is this one, open or closed? As there is no mass transfer involved, it is a closed system. So, mass remains constant and therefore 'v' and 'V' are and using any one of them, we can easily calculate the other.

Similarly, if we know the final pressure P_2 and corresponding to specific volume, V_2, then we can completely define the state point 2. But to know the W_{out} only the knowledge about final 2 state and initial state 1 are not sufficient. We have to know the exact PdV relationship followed during the process.

Now, here it is assumed that the system follows an equation,

$$PV^n = constant$$

Then, how can you calculate the work output from this? So, the moving boundary work in this case is:

$$W_{mb} = \int_1^2 PdV$$

as $PV^n = constant$, we can write this one as:

$$W_{mb} = \int_1^2 PdV = \int_1^2 \frac{C}{V^n} dV$$

As the constant coming out of the integration, we can write it as:

$$W_{mb} = \int_1^2 PdV = \int_1^2 \frac{C}{V^n} dV = C \int_1^2 \frac{dV}{V^n}$$

$$W_{mb} = \int_1^2 PdV = \int_1^2 \frac{C}{V^n} dV = C \int_1^2 \frac{dV}{V^n} = C \left[\frac{V^{-n+1}}{-n+1}\right]_1^2$$

So, accordingly the moving boundary work in this case can be calculated as

$$W_{mb} = C\,\frac{V_2^{1-n} - V_1^{1-n}}{1-n}$$

So, what should be the value of the constant C in the above equation?

The value of C can be calculated using the knowledge of either the initial state or final state. Because at the initial state, we are going to have $P_1V_1^n$ = a constant; that should be also equal to $P_2V_2^n$, i.e.,

$$P_1V_1^n = C = P_2V_2^n$$

So, we can replace either $P_1V_1^n$ in the place of C or $P_2V_2^n$ in the place of C.

$$W_{mb} = C\,\frac{V_2^{1-n} - V_1^{1-n}}{1-n}$$

For the sake of completeness, what we generally do in the first case we take $P_2V_2^n$ multiplied by $V_2^{\,1-n} - P_1V_1^n$ multiplied by V_1^{1-n} divided by $1 - n$, i.e.,

$$= \frac{(P_2V_2^n)V_2^{1-n} - (P_1V_1^n)V_1^{1-n}}{1-n}$$

so, it is finally going to be in the form as

$$= \frac{P_1V_1 - P_2V_2}{n-1}$$

So, the moving boundary work for this particular generalised process can be represented as the above-mentioned equation. So, from the knowledge of the initial and final states and also knowing the exponent, we can easily calculate the moving boundary work for this process. The $PV^n = constant$ is a very general relation. We often call it a polytrophic relation because just by changing the value of n, we can represent different kinds of processes. For example, let us take case (A):

if we take $n = 0 \rightarrow P = C$

i.e., we are going to talk about a constant pressure process or an isobaric process. In that case your moving boundary work expression will be very simple as follows:

$$W_{mb} = P(V_2 - V_1)$$

i.e., the work output that you are going to get from your system.

Whereas, if we have value of n to be extremely high almost tends to infinity case (B):

if we take $n = \infty \rightarrow V = C$

i.e., we are going to talk about a constant volume process or an isochoric process. And in this case, your work output will be = 0, i,e.,

$$W_{mb} = 0$$

Now let's have a look at the PV diagrams for these two situations. You have P in the vertical axis and V in the horizontal axis. So, when n = 0, P is a constant process line like this, starting from point 1 and going to point 2, and this is our process for n = 0. Whereas when we are talking about n tends to infinity, we are talking about a constant volume process. So, this is a corresponding representation going from 1 to 2 following a constant volume line.

Now, we know that the PdV work on moving boundary work can also be viewed as the area enclosed by this curve. Like in this case, this shaded portion on the PV plane is the work output. So, when we are considering a constant pressure process, you get a rectangle. Hence, we can easily calculate the moving boundary work. Whereas, in case of a constant volume process, there is no area enclosed, it is just a vertical line and therefore, the output is 0.

Similarly, in case (C):
if we take $n = k$, which is the ratio of specific heats i.e.,

$$k = \frac{C_p}{C_v}$$

then, we are referring to a constant entropy process. As we are not introduced to the concept of entropy today, I am just leaving it as it is. And in this case work done by the moving boundary is expressed as:

$$W_{mb} = \frac{P_1 V_1 - P_2 V_2}{k - 1}$$

where k generally is > 1, so this form a sufficient.

One exception that we have to consider if we have n = 1 i.e., case (D):
now putting n = 1 does not give you anything or it actually leads to a 0/0 situation. Because n = 1 means you have $PV = constant$ which basically is an isothermal process. Now, for this case we

cannot use this expression of moving boundary work rather we have to calculate separately. So, what will be the moving boundary work in; for an isothermal process, it is:

$$W_{mb} = \int_1^2 P dV = \int_1^2 \frac{C}{V}\, dV = C \ln\left(\frac{V_2}{V_1}\right) = C \ln\left(\frac{P_1}{P_2}\right)$$

where *C* can be of different forms like we can take

$$C = P_1V_1, \text{ or } C = P_2V_2$$

and if the gas considered here is following the ideal gas equation of state, then, we can also take

$$C = mRT$$

So, this way we can calculate the moving boundary work for different idealised processes. Once we know the relationship between P and V, we can easily calculate the moving boundary work. So, now we know how to calculate the moving boundary work for a system whether work input to the system or work output from the system and along with that once we have the information about corresponding heat transfer and mass transfer, then we can relate all of them to identify the change in the total stored energy of the system.

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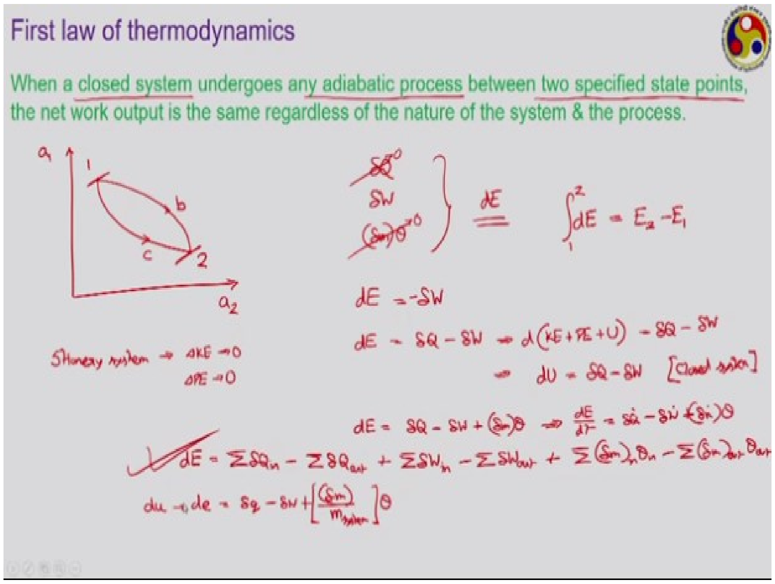

First law of thermodynamics

When a closed system undergoes any adiabatic process between two specified state points, the net work output is the same regardless of the nature of the system & the process.

$$\left.\begin{matrix} \cancel{\delta Q}^{0} \\ \delta W \\ \cancel{(\delta m)\theta}^{0} \end{matrix}\right\} \underline{\underline{dE}} \qquad \int_1^2 dE = E_2 - E_1$$

$$dE = -\delta W$$

$$dE = \delta Q - \delta W \Rightarrow d(KE + PE + U) = \delta Q - \delta W$$

$$\Rightarrow dU = \delta Q - \delta W \quad \text{[Closed system]}$$

Stationary system → ΔKE → 0

ΔPE → 0

$$dE = \delta Q - \delta W + (\delta m)\theta \Rightarrow \frac{dE}{dt} = \delta\dot{Q} - \delta\dot{W} + (\delta\dot{m})\theta$$

$$\checkmark\ dE = \sum \delta Q_{in} - \sum \delta Q_{out} + \sum \delta W_{in} - \sum \delta W_{out} + \sum (\delta m)_{in}\theta_{in} - \sum (\delta m)_{out}\theta_{out}$$

$$du \to de = \delta q - \delta w + \left[\frac{(\delta m)}{m_{system}}\right]\theta$$

We have already written the equation in the previous slide and now, we can formally relate them in terms of the first law of thermodynamics. First law of the thermodynamics is the statement which relates this energy interaction and the corresponding change in the stored energy. There are several statements or several versions of the first law of thermodynamics available in different textbooks. One most common mistake that all the students do is that they consider the first law of thermodynamics as just a statement of the energy conservation.

First law of thermodynamics definitely leads to the principle of energy conservation but it is not a principle, it is not a statement of energy conservation rather it is a law by its own right. It is a very, very strong fundamental statement and there are three to four different statements that we can choose from, but here I have decided to go for this statement which probably is the strongest one. Just reading it out here, the first law of thermodynamics is that: when a closed system undergoes any adiabatic process between two specified state points, the network output is the same regardless of the nature of the system and the process.

Reading it once more, here we are talking about a closed system, it is undergoing any adiabatic process that means, there is no heat transfer taking place during the process and the process has been taking place between two specified state points. So, if you try to plot the process on any property diagram, let us say this is our property 1; a_1 and another property a_2 and these are the two state points: point 1 and point 2. Point 1 is the initial state point and point 2 is final state point. So, we are talking about a closed system undergoing any kind of adiabatic process, and when that happens between these two state points 1 to 2 then, the network output associated with a constant process will always be the same independent of the nature of the process and the system. That means, if we think about drawing one adiabatic process like this, let us say a process b and another adiabatic process like this, let us say process c. Both of them will give you the same work output because both of them are taking place between the same two state points, both of them concerns a closed system undergoing adiabatic process. Now, as I have mentioned earlier a system can undergo three kinds of energy interaction; heat transfer, work transfer and mass transfer.

Now, here we are talking about a closed system where there is no mass transfer, and also about an adiabatic process where there is no heat transfer. The only kind of energy interaction the system is experiencing is work transfer and the magnitude of that work transfer is always the same regardless of the nature of the process.

What does that mean? That means that change in the stored energy, these three together will cause some change in the stored energy of the system. Now, as the amount of work output remains the same so, the change in this stored energy will also be the same regardless of the process. That means, the change in the stored energy does not depend on the process path rather that depends only on the choice of this initial and final state that means the change in the stored energy actually is a point function and hence it is a property. So, stored energy is a property of the system and that is why instead of using the 'δ' notation, we can use the 'd' notation. Also during a particular process, the change in the stored energy of the system can be directly calculated as:

$$\int_1^2 \mathrm{d}E = E_1 - E_2$$

without bothering about how this process want to be taking place. So, in this particular situation, for a closed system with undergoing an adiabatic process, the change in this energy:

$$dE = \delta W$$

Now, depending upon the direction of the W, the value of E will be decided generally, work done by the system we take as a positive. So, if the system is doing some work actually, energy is going away from the system and total stored energy will be reducing or decreasing and is represented as follows:

$$dE = -\delta W$$

If there is heat transfer involved with this, then with the same statement, we can associate heat transfer and we can get a much more common form of the first law of thermodynamics which is:

$$dE = \delta Q - \delta W$$

Or if we expand this dE, d(Kinetic Energy + Potential Energy + Internal Energy) i.e.,

$$dE = d(KE + PE + U) = \delta Q - \delta W$$

So, the difference of heat transfer and work transfer gives the net change in the stored energy of the system. On a specific case if we consider a stationary system, i.e., in a stationary system change in the kinetic energy tends to 0 ($\Delta KE \rightarrow 0$), the change in the potential energy tends to 0 ($\Delta PE \rightarrow 0$), or you can say these were the change in kinetic and potential energy are negligibly small compared to the change in the internal energy.

In that specific case,

$$dU = \delta Q - \delta W$$

i.e., a net energy interaction can directly be related to the change in the internal energy of the system. Now, these statements are for closed systems. If it is about an open system then you have to consider mass transfer also with this, in that case change in stored energy will be:

$$dE = \delta Q - \delta W + (\delta m)\theta$$

where $(\delta m)\theta$ is the energy associated with mass transfer.

If the system is undergoing different kinds of or experiencing multiple types of heat, work t and mass transfer, then, we can write a much more generalised statement as

$$dE = \Sigma\delta Q_{in} - \Sigma\delta Q_{out} + \Sigma\delta W_{in} - \Sigma\delta W_{out} + \Sigma(\delta m)_{in}\,\theta_{in} - \Sigma(\delta m)_{out}\,\theta_{out}$$

where

$\Sigma\delta Q_{in}$ is summation of all kind of heat transfer that is going into the system;

$\Sigma\delta Q_{out}$ is summation of all kind of heat that is going out of the system;

$\Sigma\delta W_{in}$ is summation of all kind of work that is going into the system;

$\Sigma\delta W_{out}$ is summation of all kinds of work transfer done by the system;

$\Sigma(\delta m)_{in}$ is summation of all kinds of mass that is going into the system;

$\Sigma(\delta m)_{out}$ is summation of all form of mass coming out of the system.

So, this can be taken as a much fundamental statement of the first law of thermodynamics which is equally applicable to both closed and open systems. Sometimes, we may be looking to use in a per unit mass form or even in a rate form, like for open systems, often we use in a rate form in that case, you can write as:

$$\frac{dE}{dT} = \delta\dot{Q} - \delta\dot{W} + \dot{m}\delta\theta$$

where

$\dot{Q}$ is the rate of heat transfer

$\dot{W}$ is the rate of work transfer

$\dot{m}$ is the rate of mass transfer.

And if you want to write in per unit mass, it will be as follows:

$$de = \delta q - \delta w + \left[\frac{\delta m}{m_{system}}\right]\theta$$

So, the first law of thermodynamics basically relates the different kinds of energy interaction that the system can experience with the change in the stored energy of the system. And by suitably combining these terms and also sticking to our sign conventions, you can easily calculate each of those components. Even if you are confused about the sign conventions just forget about it keep on using this particular form i.e., energy coming in minus energy going out is equal to the change in the stored energy of the system. And only in the special case of stationary system, you can replace this E symbol with internal energy directly because the change in kinetic and potential energies can be neglected in this case.

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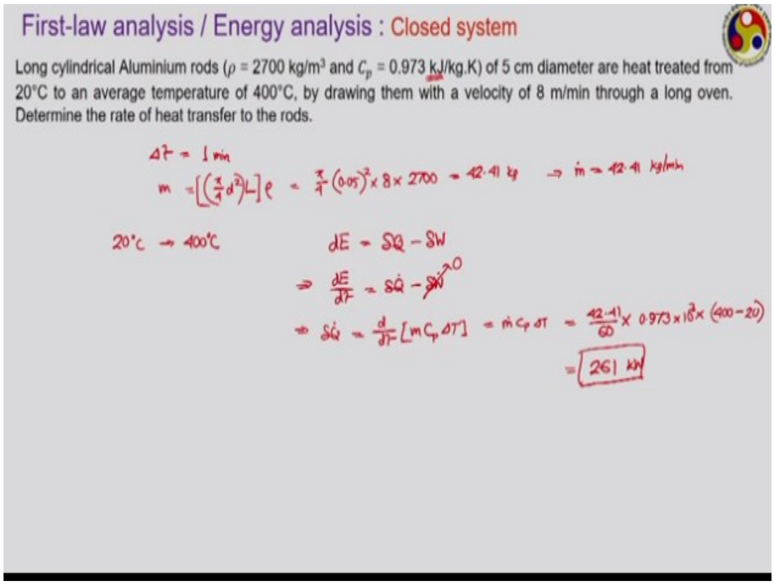

First-law analysis / Energy analysis : Closed system

Long cylindrical Aluminium rods (ρ = 2700 kg/m^3 and C_p = 0.973 kJ/kg.K) of 5 cm diameter are heat treated from 20°C to an average temperature of 400°C, by drawing them with a velocity of 8 m/min through a long oven. Determine the rate of heat transfer to the rods.

$\Delta t = 1$ min

$m = \left[\left(\frac{\pi}{4}d^2\right)L\right]\rho = \frac{\pi}{4}(0.05)^2 \times 8 \times 2700 = 42.41$ kg $\rightarrow \dot{m} = 42.41$ kg/min

20°C → 400°C

$dE = \delta Q - \delta W$

$\Rightarrow \frac{dE}{dt} = \delta\dot{Q} - \cancel{\delta\dot{W}}^{\,0}$

$\Rightarrow \delta\dot{Q} = \frac{d}{dt}[mC_p\Delta T] = \dot{m}C_p\Delta T = \frac{42.41}{60} \times 0.973 \times 10^3 \times (400-20)$

$= \boxed{261 \text{ kW}}$

Let us do a couple of examples. First law-based analysis is often called energy analysis because here, you try to calculate the change in the stored energy and relate that to a corresponding energy interaction. So, first law analysis and energy analysis are the same thing.

I have couple of very simple problems, one for closed system and one for open system. Just read the first one which is for a closed system. Here, I have several long aluminium rods, properties of aluminium are given and each rod is of 5 cm diameter. They are being heat treated in an oven, during the heat treatment they are entering the oven at 20 ^{0}C, coming out with an average temperature of 400 ^{0}C and they are moving to the oven with a rate of 8 m/min.

So, you have to determine the rate of heat transfer to the rod. To start with, let us consider a time span of 1 minute. Then, over the time span how much mass of this aluminium rod has gone through the oven? So, the mass that has passed through the oven can be calculated as the size of this aluminium rod.

$$\Delta t = 1 \text{ min}$$

$$m = \left[\left(\frac{\pi}{4}\, d^2\right) L\right] \rho = \frac{\pi}{4}\, (0.05)^2 \times 8\ \times 2700 = 42.41\, kg$$

Accordingly, we are getting, as I have precalculated the numbers and it is coming as 42.41 kg. You can also write this one as in terms of mass flow rate as:

$$\dot{m} = 42.41\, kg/min$$

So, this is the rate of mass of aluminium that is flowing to the oven and during this fluid temperature changes from 20 ^{0}C to 400 ^{0}C.

So, let us apply the first law of thermodynamics. what kind of system is this? It is a closed system of course, the topic is of closed system, but also on the statement if we consider this aluminium rod as your system, then there is no mass flow as such. So, accordingly we can write for the aluminium rods,

$$dE = \delta Q - \delta W$$

or if you write in rate form, then

$$\frac{dE}{dT} = \delta\dot{Q} - \delta\dot{W}$$

So, the time rate of change of stored energy of the aluminium rod can be calculated if we know the rate of heat transfer and rate of work transfer. Now, what is the rate of work transfer here? Rate of heat transfer is the one that we have to calculate finally. But, what is rate of work transfer? Here, we can assume that there is no work transfer at all and so, the rate of heat transfer is actually equal to the time rate of change of the internal energy.

And now, how can you calculate this change in internal energy? The time rate of change of internal energy can be calculated as:

$$\delta\dot{Q} = \frac{d}{dt}\left[mC_p\Delta T\right] = \dot{m}C_p\Delta T = \frac{42.41}{60} \times 0.973 \times 10^3 \times (400 - 20) = 261\ kW$$

We need to be very careful about this units or this suffix. So, it is kilojoule, I would always suggest do every calculation in terms of basic SI unit that is why I am multiplying with this 10^3. So, this gives you the final rate of heat transfer, it is going to come around 261 kW or kJ/s and this is the rate of heat transfer to the rod.

It is a very simple example of the application first law of thermodynamics and closed system. We shall be solving several similar problems once we get into the third module.

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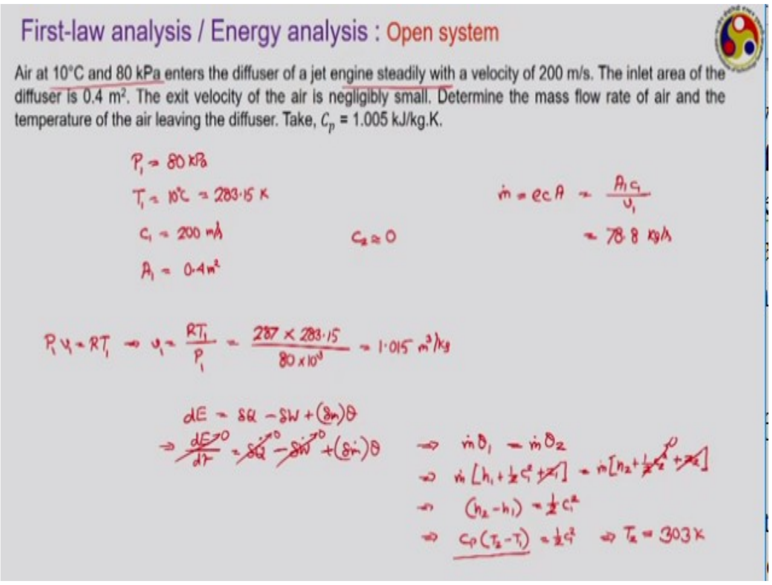

First-law analysis / Energy analysis : Open system

Air at 10°C and 80 kPa enters the diffuser of a jet engine steadily with a velocity of 200 m/s. The inlet area of the diffuser is 0.4 m². The exit velocity of the air is negligibly small. Determine the mass flow rate of air and the temperature of the air leaving the diffuser. Take, C_p = 1.005 kJ/kg.K.

$P_1 = 80\ kPa$

$T_1 = 10^\circ C = 283.15\ K$

$C_1 = 200\ m/s$

$A_1 = 0.4\ m^2$

$C_2 \approx 0$

$\dot{m} = \rho c A = \frac{A_1 C_1}{v_1} = 78.8\ kg/s$

$P_1 v_1 = RT_1 \Rightarrow v_1 = \frac{RT_1}{P_1} = \frac{287 \times 283.15}{80 \times 10^3} = 1.015\ m^3/kg$

$dE = \delta Q - \delta W + (\delta m)\theta$

$\Rightarrow \cancel{\frac{dE}{dt}}^{\to 0} = \cancel{\delta Q}^{\to 0} - \cancel{\delta W}^{\to 0} + (\delta \dot{m})\theta$

$\Rightarrow \dot{m}\theta_1 = \dot{m}\theta_2$

$\Rightarrow \dot{m}\left[h_1 + \frac{1}{2}c_1^2 + \cancel{z_1}\right] = \dot{m}\left[h_2 + \cancel{\frac{1}{2}c_2^2}^{0} + \cancel{z_2}\right]$

$\Rightarrow (h_2 - h_1) = \frac{1}{2}c_1^2$

$\Rightarrow \underline{c_p(T_2 - T_1)} = \frac{1}{2}c_1^2 \Rightarrow T_2 = 303\ K$

I have another example for an open system. Read the problem carefully, here we are having an air entering a diffuser at 10 ^{0}C and 80 kPa, so inlet pressure and temperature for air is given. Let us identify the inlet status 1, so you have

$P_1 = 80$ kPa

$T_1 = 10\ ^0$C.

The symbol 'T' symbol generally refers for absolute temperature. So, it is better to write this one as 283.15 K.

It flow steadily with a velocity, i.e., the entry velocity is given as 200 m/s. So,

$C_1 = 200$ m/s

$A_1 = 0.4$ m^2

where A_1 refers to the inlet area that is 0.4 m^2

The exit velocity of air is negligibly small that means C_2 can be taken to be equal to as negligibly small. So

$C_2 = 0$

We have to derive the mass flow rate of air and the temperature of the air leaving the diffuser. So, how can you do the calculation? The property C_p of air is given.

First, you have to calculate the mass flow rate, how can you calculate the mass flow rate of air? What is mass flow rate of a gas flowing through a constant area? We can easily write mass flow rate as:

$$\dot{m} = \frac{\rho C A}{v}$$

Now, how to get the specific volume? Here, we are talking about air, if we consider air to be an ideal gas, then specific volume of air can easily be calculated using the ideal gas equation of state which is as follows:

$$PV = RT$$

or

$$v = \frac{RT}{P}$$

or

$$v_1 = \frac{RT_1}{P_1}$$

if you are applying at the inlet plane.

Now, what is R here? R is not universal gas constant but R is the gas constant for air in this case and the value of the gas constant for air is 287 J/kgK.

$$v_1 = \frac{RT_1}{P_1} = \frac{287 \times 283.15}{80 \times 10^3} = 1.015\, m^3/kg$$

Again that kPa, that suffix you have to remember or that prefix to this so, 'v' is known, you know the specific volume at the inlet plane which will coming as $1.015 m^3/kg$. So, once you put it back 'A' and 'C' at the inlet plane, you can put all the conditions for inlet plane.

So, accordingly we can write m as:

$$\dot{m} = \frac{\rho CA}{v} = \frac{A_1 C_1}{v_1} = 78.8\ kg/s$$

So now you have the mass flow rate. Now, you have to apply the first law to calculate the temperature of air leaving the diffuser. So, applying the system, in this case it is an open system, we have to apply the equation accordingly.

For an open system, we know that:

$$dE = \delta Q - \delta W + (\delta m)\theta$$

or if we write in rate form:

$$\frac{dE}{dT} = \delta\dot{Q} - \delta\dot{W} + (\delta\dot{m})\theta$$

Now, in this case we are talking about steadily following engine i.e., there is no net change of energy or change in the energy content of the system, and this value of dE/dT will be 0. And it is a diffuser, so no net work output, δW also equal is to zero. And accordingly, we can consider a balance between the remaining terms. Now, how much is the net heat transfer that is taking place? There is no mention about any source of heat or any heat leakage to the surrounding, so this one also goes to 0. And ultimately, what you are left with is a balance between mass flow rate.

$$\dot{m}\delta\theta_1 = \dot{m}\delta\theta_2$$

that is also represented as:

$$\dot{m}\left[h_1 + \frac{1}{2}c_1^2 + z_1\right] = \dot{m}\left[h_2 + \frac{1}{2}c_2^2 + z_2\right]$$

In this problem, C_2 = to 0, z_1 and z_2 can cancel out because there is no information given about the elevation. And accordingly, we can calculate :

$$(h_2 - h_1) = \frac{1}{2}c_1^2$$

And from your knowledge of basic thermodynamics, you must be knowing that enthalpy can be related as:

$$C_p(T_2 - T_1) = \frac{1}{2}c_1^2$$

From this you can calculate the T_2 to be equal to final value will becoming 303 K.

Therefore, you will be getting temperature to be something like 303 K. So it is about 20 K rise in temperature, there will be small change in the fractional number, you can do the calculation on your own. But here, this Δh is represented as

$$\Delta h = C_p \Delta T$$

This relation we shall be develop in the next week again for your clarification. So, this is the way we perform the first law of analysis for any system.

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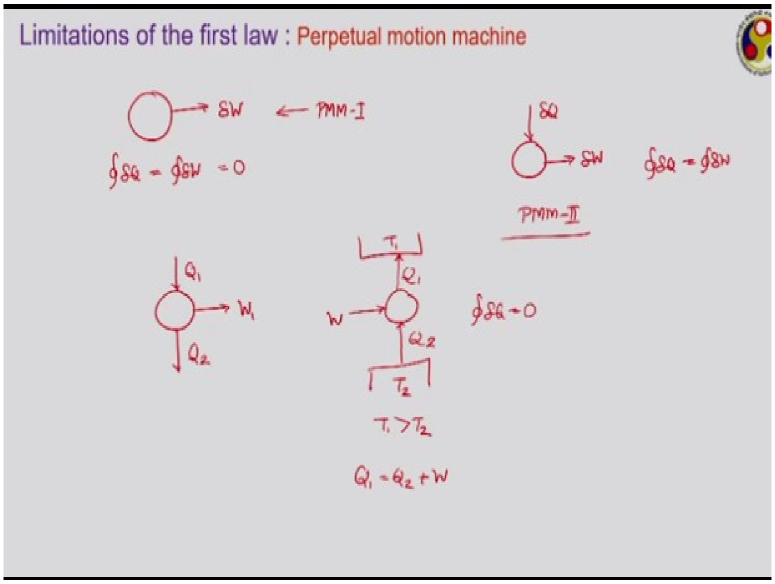

Limitations of the first law : Perpetual motion machine

Now, first law while being a very simple form or very simple tool for performing energy analysis has its own limitation. And that limitations are given in terms of the perpetual motion machines. Now, let us consider a system like this. Now, this is a system if we consider that the system is not doing anything but giving you δW amount of work output, is it possible? It is definitely not possible as per the first law of thermodynamics as long as the system is operating in a cycle, it cannot give.

Because following the first law, we can always write as:

$$\oint \delta Q = \oint \delta W = 0$$

As in this case, when it is operating in a cycle without any heat transfer, both of them has to be equal to 0. So, this is not possible, this situation is called perpetual motion machine of the first kind of PMM-I. Now, you consider another cycling device, it is a device which is receiving δQ amount of heat and giving δW amount of work.

Now, is it possible as per the first law of thermodynamics? It is definitely possible, because as per the first law again, cyclic integral of δQ has to be equal to cyclic integral of δW. Therefore, as long as this δQ and δW are equal, this definitely satisfying the first law of thermodynamics. But all the attempts to produce a device like this has led to practical failure and therefore, we call them or we call this kind of device that perpetual motion machine of the second kind or PMM-II.

PMM-II satisfies the first law of thermodynamics but still it is not possible to produce a manufacture, because there has to be some other laws of thermodynamics which it is violating and that law is a second law of thermodynamics. To the same system, suppose it is receiving Q_1 amount of heat converting a part of that W_1 and rejecting the remaining Q_2 to somewhere else, this is definitely possible. That means whatever amount of heat a system is receiving, it is not possible for it to convert 100% of that to work rather a portion of the heat has to be rejected and then only we can realize the system.

Look at another example now, here you have a system, you have 2 bodies; one kept at temperature T_1, other kept at temperature T_2 and $T_1 > T_2$. Now, this system over a cycle is taking some Q amount of heat from this low temperature of body and rejecting the entire heat to the high temperature of body. Now, is it satisfying the first law of thermodynamics? Definitely, it is satisfying because whatever amount of energy it is getting, same amount of energy is going out, so,

$$\oint \delta Q = 0$$

and hence no need of work transfer. But again, any effort to produce such a device is not possible you know by practice, we can never transfer heat from a low temperature body to a high temperature body.

We need some additional effort and that addition effort is possible only if you provide some work input to device, so that it takes Q_2 amount of heat from this low temperature body, receives W and then the combination of this 2;

$$Q_1 = Q_2 + W$$

that answer to the high temperature body, then only it is possible. Without the work transfer, this is again a PMM-II. So perpetual motion machines of the second kind are devices which highlights the first law of thermodynamics or I should say they satisfy the first law of thermodynamics but they must be violating some other laws because of which they are not provide possible to produce a practice and that law is a second law of thermodynamics.

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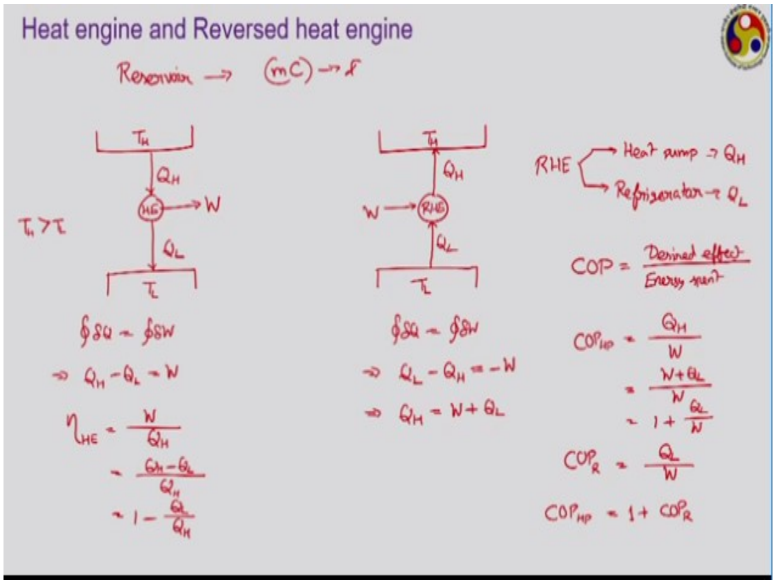

Heat engine and Reversed heat engine

Reservoir $\rightarrow (mC) \rightarrow \infty$

RHE → Heat pump → Q_H
RHE → Refrigerator → Q_L

$$\oint \delta Q = \oint \delta W$$

$$\Rightarrow Q_H - Q_L = W$$

$$\eta_{HE} = \frac{W}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

$$\oint \delta Q = \oint \delta W$$

$$\Rightarrow Q_L - Q_H = -W$$

$$\Rightarrow Q_H = W + Q_L$$

$$COP = \frac{\text{Desired effect}}{\text{Energy spent}}$$

$$COP_{HP} = \frac{Q_H}{W} = \frac{W + Q_L}{W} = 1 + \frac{Q_L}{W}$$

$$COP_R = \frac{Q_L}{W}$$

$$COP_{HP} = 1 + COP_R$$

But before mentioning about the second law, I have to mention the concept of heating engine and reversed heat engine. And even before that I have to introduce the term reservoir. Reservoir is a hypothetical concept. It refers to a source of energy from where you can take as much energy you can or you can deposit as much energy you can without causing any change in its temperature. That means, whatever may be the amount of energy you are taking from this reservoir or whatever may be the amount of energy you are adding to this, its temperature will remain unchanged. Then only we call it a reservoir. Reservoir can be viewed to be a body with infinite heat capacity, i.e., the product of mass and specific heat has to be infinite. Then, only we call it a reservoir because then only whatever amount of heat you add is temperature remains unchanged. Now, practical example of reservoirs may be ocean and environment. Whatever amount of energy you take from an ocean, its total energy content remains almost unchanged. Because the mass is such huge that it hardly matters, same is for the environment. And even when here much smaller sized body can also act as a reservoir, if the amount of energy that you are taking from it or giving to it is quite small. Like think about a big icebox, which can house several or 100's of bottles of some soft drinks. Now if you are adding a small can of cola into this, then its temperature is hardly expected to change because its heat capacity is so high. Now, heat engine is a device which operates between two reservoirs over a cycle. This is one reservoir kept at temperature T_H, this is another reservoir kept at temperature T_L, where T_H is high temperature, T_L is low temperature. The heat engine is a cyclic device which takes heat from this high temperature body, converts a part of that to work and rejects the remaining Q_L to the low temperature body. So, over a cycle, it is taking heat from the high temperature body amount in Q_H, rejecting heat to a low temperature body amount in Q_L and giving work output W. So, if you apply first law of thermodynamics onto this following:

$$\oint \delta Q = \oint \delta W$$

This we can write it as:

$$Q_H - Q_L = W$$

Generally, the performance of such heat engines are defined in terms of efficiency. Efficiency of a heat engine is defined as:

$$\eta_{HE} = \frac{W}{Q_H}$$

where

W is the the work output

QH the amount of energy given to get that work output

So, using the first law expression, W can be written as $Q_H - Q_L$ and therefore:

$$\eta_{HE} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

So, this is called a heat engine and if we now reverse the direction of all of them then what you get? That we get is called a reversed heat engine. Again, we are having high temperature reservoir T_H, low temperature reservoir T_L and you have a reversed heat engine. In this case, it is taking suppose Q_L amount of heat from this low temperature body receiving W amount of work and then depositing the combination as Q_H to the high temperature body. Again, following first law of thermodynamics, we have Q_H or in this case sticking to our sign convention, Q_L is given to the system is receiving Q_L, so

$$Q_L - Q_H = -W$$

$$Q_H = W + Q_L$$

Now, reverse heat engine generally is also classified into two categories. A reversed heat engine can be classified either as a heat pump or as a refrigerator. This classification depends upon what is your object. The schematic diagram remains exactly the same, but in case of a heat pump, your objective is to add heat to the high temperature body. i.e., your objective is Q_H, here you want to add heat to the high temperature body. You can visualise the heat pump as something where the T_L is environment and you are living in a very cold place, outside is extremely cold and that T_H refers to a room. So, despite outside being cold, you want to take heat from outside and add to the room, so that you can keep the room warm.

Refrigerator is another situation where you want to extract energy from this low temperature body, so Q_L is the objective function. As the term suggest it is similar to our refrigerator, where the outside is hot, so here this T_H refers to the ambient temperature and you want to extract energy from a freezer, so that we can maintain low temperature there.

To define the performance of a reversed heat engine, we use a term called COP; coefficient of performance. COP is defined as:

$$COP = \frac{Desired\, effect}{Energy\ spent}$$

where

Q_L represents desired effect

W represents energy spent

So, COP for a heat pump as per the definition will be:

$$COP_{HP} = \frac{Q_H}{W} = \frac{W + Q_L}{W} = 1 + \frac{Q_L}{W}$$

Similarly, COP for a refrigerator, what is your objective? Objective is:

$$COP_R = \frac{Q_L}{W}$$

and we can easily combine these expressions and it can be shown that:

$$COP_{HP} = 1 + COP_R$$

So, COP for a heat pump is always greater than 1.

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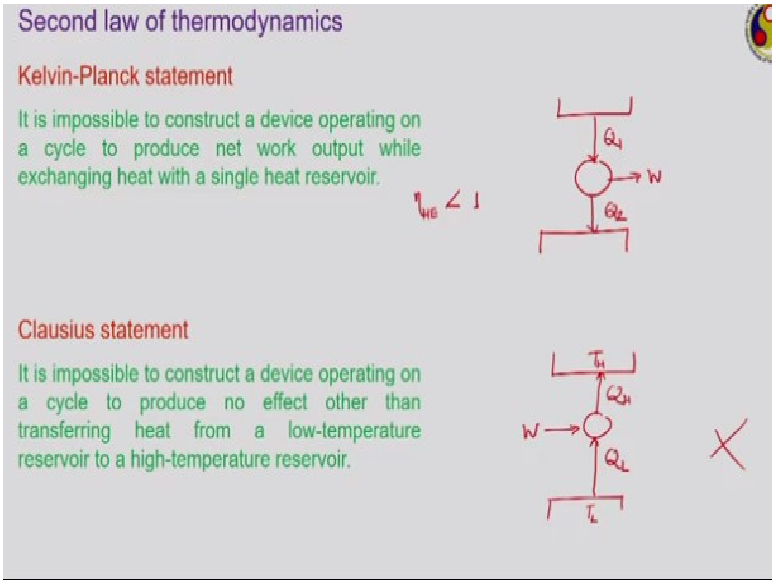

Second law of thermodynamics

Kelvin-Planck statement

It is impossible to construct a device operating on a cycle to produce net work output while exchanging heat with a single heat reservoir.

Clausius statement

It is impossible to construct a device operating on a cycle to produce no effect other than transferring heat from a low-temperature reservoir to a high-temperature reservoir.

With this, we finally move on to the second law of thermodynamics, there are several statements of second law of thermodynamics but two of them are very common. The first one is the Kelvin-Planck statement which is the ideal statement for the heat engines. It says that it is impossible to construct a device operating on a cycle to produce net work output while exchanging heat with the single heat reservoir, i.e., if you are having a single heat reservoir and heat engine or a device which continuously takes heat from this and convert everything to work, it is not possible. To make it possible we need to have another low-temperature reservoir, so that a part of the heat needs to be rejected to it. Then only we can have a proper heat engine and continuous work output from it. So, in a way it says that the efficiency for a heat engine can never be or 100%, it is always less than 1. Because we can never convert 100% of the supplied energy to work.

The other statement is Clausius statement which says that it is impossible to construct a device operating on a cycle to produce no effect other than transferring heat from a low temperature reservoir to a high temperature reservoir. It means suppose this is your high temperature reservoir, just how it drawn the PMM1 earlier. So, if you want your device just to take some Q amount of heat from this low temperature body and deposit everything to the high temperature body, it is not possible. Some amount of work input will be required, so that it takes Q_L amount of heat and gives Q_H amount of heat to this accordingly operating either as a heat pump or the refrigerator. So, Kelvin-Planck statement is a fundamental statement for the heat engine whereas, Clausius statement is a fundamental statement for the heat pumps and refrigerators.

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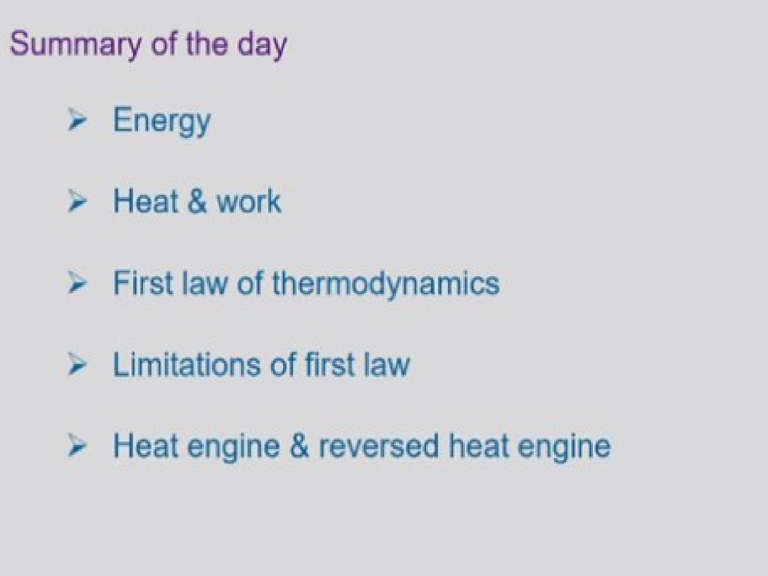

Summary of the day

- Energy
- Heat & work
- First law of thermodynamics
- Limitations of first law
- Heat engine & reversed heat engine

So that is where I would like to close today. Today we have reviewed the first and second law of thermodynamics, so we started out a discussion by defining different types of energy associated with the system particularly, the concept of stored energy and internal energy. then we talked about the energy and transition in the form of heat and work, then first law of thermodynamics we have discussed and its application to closed and open systems. Then we have discussed about the limitations of first law in the form of perpetual motion machines and accordingly, the concept of heat engines and reversed heat engines were introduced and their operating principles were defined in terms of the second law of thermodynamics.

So that is it for the day. In the next lecture I would like to go into the detail of the second law of thermodynamics by introducing the concept of reversible processes subsequently leading to the Clausius inequality and the definition of entropy. So, in the third lecture of this module, we are going to talk about the second law analysis of closed and open systems based upon the entropy, till then thank you very much.