POWER PLANT SYSTEM ENGINEERING

Lec 1: Thermodynamics Concepts (Part I)

Dear learners, greetings from IIT Guwahati. We are in the MOOCs course Power Plant System Engineering. I welcome you all for this course. So, in the first module we have designed it based on the previous topics of thermodynamics. So, in this module we will try to review the basic concepts of thermodynamics, different terminologies that are used in this basic course on thermodynamics. Then we will touch upon another fundamental topics of interest which is the properties of pure substance.

So, there we will touch upon the major aspects about the different equations that are used for perfect gas; side by side, we will also emphasize on mainly water, saturated water, superheated water and superheated steam and their properties. So, in this first module we will try to touch upon how to use steam tables, property data tables that are very vital for subsequent lectures in this course. And in the subsequent lectures we have mainly dealing with steam power systems, gas power systems and renewable energy power systems. So, all these things are like power generating devices, but very basic concepts for this power generating devices comes from the theory or laws of thermodynamics; that is first law and second law.

So, these two things subsequently lead to the concept of heat engines in which it is possible for any device that works in a cyclic manner which can produce low grade energy of heat to the shaft work what is our work output. So, with this concept all subsequent modules are designed. So, at this point I need to emphasize that basic aspects of thermodynamics is very vital. However, we will restrict our attention to particularly some concepts, which we will be using frequently in the subsequent module. So, let us revisit the basic aspects of thermodynamics.

So, in this first lecture which is part 1 we will talk about thermodynamic concepts. So, mainly we will be discussing on terminologies, then first law of thermodynamics steady flow energy equations, then we have property relationship and mainly we will see what perfect gas is and what imperfect gas is. Then we will touch upon some of the steady flow devices which are basically governed by the first law or steady flow energy equations. So, to start with the terminology let us try to understand that in our basic introduction course I have emphasized this figure. So, basically there are 3 types of energy i.e. thermal energy, electrical energy and mechanical energy and these energies are very vital for the human necessity & mankind survival.

However the conversion of one form of energy to other form is possible. So, it is very easy that we can have a conversion between mechanical and electrical, then we can also have mechanical and thermal & again thermal and electrical. However, apart from this basic energy sources and for which the main basic resources is the fossil fuel, there are other types of energy which are available in the nature like solar, geothermal, chemical fuels, nuclear, hydro or wind . So, those are the kind of what we call them as a renewable form of energy or alternative resources, but they can be coupled to any one of the energy resources and ultimately we need to have electrical energy in the end for our survival of the mankind.

And in order to have this particular conversion we require the concept of thermodynamics. So, ideally speaking that the word thermodynamics is derived from a Greek word that is thermi and dynamics. Thermi means heat, dynamics means power. So, conversion of heat to power is the basic necessity to deal with various application area. And in this various application areas we have power plants which is either steam or gas based or we can have IC engines, we can have gas turbine engines or aircraft engines, then we will also have refrigeration and air conditioning.

However, in this power plant system engineering, we will be talking mainly about those devices that can produce power. So, refrigeration and air conditioning is a separate topics because it consumes power for cooling purposes. So, that is a different topic of interest, however our main attention will be the production of power through various means which

I have mentioned in this figure. Then moving further to deal with different terminologies we all know that in thermodynamics we define a system in which our attention is focused and any systems is associated with its boundary that means, any change in the systems is felt within this boundary and beyond this boundary we call this as a surroundings. So, system and surroundings constitutes universe.

So, this is the very basic philosophy of thermodynamics and of course, one can think of this boundary as a fixed boundary or a moving boundary. Then while talking about the systems, the system with thermodynamic viewpoint system is treated as a closed system or open system. So, in a closed system we can say that there is some fixed amount of mass which is concentrated in the system and this mass can be compressed or expanded within its own systems that means, change of state of the system of the mass is allowed within that vicinity, but however the system is not allowed to have interaction of mass from the outside. So, that is what we say for a closed systems there is no mass interactions, but the closed system has a flexibility it can interact with surroundings by virtue of energy interactions.

Now, when you move on to one open system and many times we refer it as a control volume, in which the volume of the system is going to change because this open system allows for the mass to come in and to come out and of course, it also allows energy to enter into this system and it can go out. So, through this process the open systems allows both mass and energy interactions and on a special case when we have this there is no mass and energy interactions is possible, we call it an isolated system.

Then moving further, in thermodynamics; State means when a particular a system is specified by its location or identity and this identity is normally referred in terms of pressure volume coordinates and we call this a thermodynamic state. So, when the all properties of a system has a definite value then it is called as a state and properties are nothing, but the coordinates of the state. Now when the coordinates change so that means, there is a change of state. So, when there is a change of state then it has to go in a certain path that means, there is a succession of change of states happens for the system and that we call it as a path. Now if you identically or completely define this path then we call this as a process. So, thermodynamically we have many processes like isothermal, isobaric, isochoric and so many processes are there.

So, that means, mathematically we can specify how the change of state happens when the system goes from one point to other point. Now when we have many number of processes /multiple number of processes and that happens in such a way that for a given system, when it starts with a particular location and it undergoes different states and its path is specified that means, there is a change of state. So, it is defined by some certain processes, but when you say it is a cycle the initial state and the final state must be identical. So, we can say define the cycle, as a series of change of states in which the final state is identical with the initial state. So, in this particular figure, we can say that we start with defining a state of a system at point 1 and it goes to point 2 in in a path which is B, but however, again that point 2 comes back to original state in another process or path. So, we can say that, 1-B-2-A-1 forms a cycle.

Then another kind of study is that, we also deal with or come across, quasi static processes. So, obviously, when the coordinates of a system change, we say that there is some change of state happened. So, it happens in a particular process, but what happens if this change of state happens in a very slow manner, then we view the systems as a series of changes that happens within the systems and this change happens in a very slow manner. So, as a results although there is a change internally, but external effect due to this change is very much negligible because system is always said to be in equilibrium with its surroundings at all points. So, such a process is defined as a quasi-static process. So, a quasi-static process occurs through series of equilibrium states and although there is a change of state, but the surroundings is not affected by this change because system and surroundings are always in the equilibrium state.

So, through a simple figure, we can explain about a quasi-static process. If you look at this figure, we have a piston cylinder device and in this piston we have a gas, which is at initial state p_1, V_1, T_1 and this initial state has happened due to a weight which is kept on this piston. So, we have the systems, its boundary. So, what happens is there are two instances, if you remove this particular weight completely, then obviously the system which is at initial state will move on to this final state p_2, V_2, T_2.

So, initial coordinates of the system was $p_1, V_1, T_1$and final coordinates of the system become p_2, V_2, T_2. But, through this process what happens that there is a change, but that change was instantaneous because we have taken out this weight instantly from this piston. But that means the point 1 goes to point 2 and the change that happens in the intermediate locations is very instantaneous. So, such process cannot be called as a quasi-static process rather what we can think of that, this particular weight can be imagined to be divided into a small weights that constitutes this W, that means they will have n number of weights and these n number weights combinedly gives the total weight W. So, what we do is that you take 1 by 1 weights. So, when you start with initial state 1, you take one of the weights then it goes to another point then you take another weight it goes to another point and likewise there is a change that happens and through this process, the final state becomes 2 that means when you take the last weight then it becomes 2.

So, through this process what happens that, there are changes happening through this intermediate state points, but they are occurring in a very slow manner. So, we call them as equilibrium states and the complete process as a quasi-static process. So, this is very vital, because most of the processes are defined thermodynamically to happen in a quasi-static manner. Then we have a concept of work and heat because when you deal with energy there are 2 variants of energy that thermodynamics tells us; one is in the form of work other is in the form of heat. So, when we view this as work, we can say work is a kind of energy which is viewed in rising mass or that means through that energy we can imagine that a mass can be taken from one height to other and sometimes we call this as a pdV work and that pdV work we normally refer it in a closed system.

Now anything that happens by virtue of temperature difference, so those form of energy interactions, we call it as heat and this energy interaction is possible when they cross the system boundary. That means as long as they are within the system we do not see it as an interaction rather we say there is a change, but that change remains within the boundaries.

That means whether you say work or heat, it is a boundary phenomena and we view them only when they cross the boundary.

Then another important point is that the work and heat during a quasi-static process depends on the path they follow. For example, in this process if you say that the change of state that happens from 1 to 2 in a quasi-static or equilibrium states manner, we can say that, there is a path followed by this and this path can be completely specified and through this process there is an interaction either heat or work and hence both heat and work are called as path functions. And of course, they are treated as inexact or imperfect differential and they are not associated with a particular state, rather they are associated with a process.

That means their identity is with respect to a process not to a particular state. Another point I need to emphasize here that terminologies that we use for work and heat interactions. So, there are possibilities that heat can be added to the systems or heat can be rejected from the systems. So, when we add this heat then Q is treated as positive when you take out this heat, we call this as negative. And in same terminology when work is done by the systems, we say it is positive and work is done on the systems, it is negative.

So, all these notations has to done side by side. So, heat addition means positive & work done by the system means it is positive. So, these notations all other consequences can be framed. Then we will move on to properties and thermodynamically we view the properties either intensive or extensive. That means every system is defined by its own identity or states.

That state is defined by its thermodynamic properties i.e. pressure, volume, temperature, but they are broadly categorized either they are intensive or extensive. So, intensive properties are independent of mass and size. For example, temperature, pressure, density; they are treated as intensive properties. Then we have extensive properties that depends on the size of the systems that is mass dependent. So, for example, mass, volume and energy; they are treated as mass dependents.

For example, you can say that which properties are intensive and extensive. Let us take a container or rigid system which has a volume ‘V’, temperature ‘T’, pressure ‘p’, mass ‘m’ and it contains a gas which has a density ‘ρ’. Now what we do, we can make a partition that means this is your initial state and we make this partition state. When you make a partition what may happen mass may be half. So, that means if you could just drop a partition among them mass we can make it half, volume also we can make it half, but the gas or fluid which is in the both the partitions will have same pressure, same temperature and same density. That means pressure, temperature and density do not change whether mass changes. That means pressure, temperature, density they are mass independent that is what you call the name as intensive properties and others are extensive properties.

Now coming back to energy, energy is nothing but the potential of flow that exist in various form chemical, mechanical and in mechanical also you can have kinetic and potential. Then you can also have thermal, nuclear. And apart from that we will also deal with another kind of energy that is called internal energy which happens within the systems and it is a microscopic form of energy and why did you define this because it talks about the molecular motions which either can be translation, vibration or rotations and combinedly we call this as internal energy. And when we say that internal energy is associated with the kinetic energy of the molecules we say it is a sensible energy & that happens due to change in the temperatures. So, when this internal energy is used for binding the molecules in its phase and we want to go for a change of phase, then such energy we call as latent energy. However this internal energy is a strong function of temperatures and that is for pure substance and in our entire course we will talk about internal energy as the function of temperature only.

Then let us review the first law of thermodynamics. We call this as conservation of energy principles. So, it says that energy of the system undergoing a change or processes can be increased or decreased by exchange with the surrounding and they can be converted from one form to other within that system. So, through this process, it says that energy is conserved. There is a possibility of change of energy from one form to other form, but the accountability is that how total energy which enters into the system must go out of the system. So, energy auditing will tell you that total accounting of energy that enters and goes, they must balance each other. However the conversion is allowed, but it does not indicate whether the conversion of energy takes place from one form to other completely or performed perfectly or not. And to define this energy or to define the first law the most ideal system that we can choose is open system because an open system allows both mass and energy interactions and this energy interaction is possible either by heat or work.

So, hence we will view this open system as a benchmark to define this first law. Now apart from this we also introduce one other form of energy which is called as flow energy and the flow energy that comes because there is a mass that enters into it. So, we say that mass has certain energy which pushes the fluid into the systems and that fluid also gets pushed out from the systems. And this change happens by virtue of this pressure difference and we combinedly call them as flow energy. So, the total energy that enters, either it can enter as a potential energy form, kinetic energy form, internal energy form or flow energy form. And also this energy that can leave out from the system is also in the same form. Apart from that the open system also interacts with heat or work.

Now the most ideal way of looking at this change of state to happen is that, it is a completely transient state where mass inflow & outflow can also vary with time. But ideally to frame our first law in a very precise manner, we will assume it to be a steady state, steady flow systems SSSF system and for that we are going to see, how we need to make this energy auditing, which takes care about the all form of energy. So, a steady flow system allows the heat interactions, work interactions apart from this mechanical energy. That mechanical energy comes by virtue of potential and kinetic energies.

Now let us see that do this energy auditing for this open systems. So, in this figure, if you apply the first law, what we can see, what is entering into the system that is state 1 and ΔQ that is through heat interaction. So, this ΔQ is nothing, but the net heat which gets added into the system. So, that is why it is taken as positive. So, the entire thing that enters is taken as positive and the net work interactions that is work done by the systems we will interpret as ΔW or we sometimes we call as a steady flow work and it is in the right hand side of this equation. Apart from that what is entering through this state 1 is combination of PE_1, KE_1, IE_1 and FE_1.

Similarly what goes out is PE_2, KE_2, IE_2 and FE_2. So, these are the things that goes out. Now individually we can interpret what is potential energy $= mgz$, kinetic energy $= \frac{1}{2} mV^2$ and internal energy $= mu$ and flow work $= p(mv)$ where v is specific volume or volume.

So, likewise we can interpret. So, heat transfer that crosses the boundary it is net heat added ΔQ, steady flow work is ΔW. Now here we can say this is a path function. So, we have to define and we view them when they cross the system and as I mentioned that when you say it is ΔQ, it occurs by virtue of temperature difference and when you say steady flow work transfer for an open system it is interpreted as $\int Vdp$. Now to define these things we have two things here, one is we have to define the path because both heat and work are path functions.

"First law equation for an open system",

$$PE_1 + KE_1 + IE_1 + FE_1 + \Delta Q$$

$$= PE_2 + KE_2 + IE_2 + FE_2 + \Delta W (mgz)_1 + \left(\frac{1}{2} m V_s^2\right)_1 + (mu)_1 + \{p(mv)\}_1 + \Delta Q$$

$$= (mgz)_2 + \left(\frac{1}{2} m V_s^2\right)_2 + (mu)_2 + \{p(mv)\}_2 + \Delta W$$

Heat transfer across system boundary,

$$\Delta Q = (Q_A - Q_R) = mc_n(T_2 - T_1)$$

Steady flow work transfer , $\Delta W = \left(W_{by} - W_{on}\right) = -\int_1^2 Vdp$

So, for that reasons, a general relationship for pressure volume we can write, $pV^n =$ Constant.

This n is going to vary, whether it is constant pressure, constant volume, isothermal, isentropic or polytrophic processes. And here also we will define another term that is c_n, and that c_n stands for specific heat and it also depends on what type of process it is. So, for constant pressure it is c_p, for constant volume it is c_v, for isothermal process it is ∞, for isentropic process it is 0 and for polytrophic process, $c_n = c_v\,(\frac{k-n}{1-n})$. So, through this process, through this exponential term n we can define the various terms in this equations. And many a times you also interpret the steady flow energy equations per unit mass basis.

So, we can define

The specific volume, $v = \frac{V}{m}$

The Specific internal energy, $u = \frac{U}{m}$

So, accordingly per unit mass basis if a fixed mass entering and leaving the open system we can simplify this equations. And in fact, this particular figure also shows for a different value of n what is the pdV work , that can be defined.

Another term for the open systems that the first law talks about apart from the internal energy, is the term enthalpy. So, enthalpy is nothing, but the sum of internal energy & flow energy.

So, Enthalpy, $H = U + pV$

And there is also a definition for specific heat, which is change in the internal energy with respect to change in temperature. So, for gases, we can have two specific heats because we can view this specific heat in two different ways, either at constant volume or at constant pressure. So, accordingly, specific heat can be defined at constant pressure as c_p or at constant volume c_v and the difference between them is the characteristics gas constant, R (c_p -c_v =R), for a given fluid. Then we also have specific heat ratio, $k = \frac{c_p}{c_v}$

And many a times we also interpret that if c_v is a function of temperature, so accordingly, it cannot be taken as a constant. So, it has to be in the integral form. Similarly, for enthalpy as well, in which c_p can be treated as a function of temperature. So, this is the summary of open systems.

Now, let's move to the closed systems. So, in the closed system we mentioned that there is only energy interaction & no mass interactions. So, in that way, if you start our basic equation that is first law for an open system and try to apply it for closed system, many terms will get cancelled. That means, we do not have these terms because these changes; the first law does not allow them and also the flow energy term will vanish.

So, the first law for closed system

$$\cancel{mgz_1} + \cancel{\frac{1}{2}mV_{s1}^{2}} + (U_1 + \cancel{p_1V_1}) + \Delta Q = \cancel{mgz_2} + \cancel{\frac{1}{2}mV_{s2}^{2}} + (U_2 + \cancel{p_2V_2}) + \Delta W$$

$\Rightarrow U_1 + \Delta Q = U_2 + \Delta W$

$\Rightarrow \Delta Q = \Delta U + \Delta W$

And in differential form we say; $\partial Q = du + \partial w$

So, here ∂Q & ∂w are path functions, so inexact differentials, and since u is a property, it is an exact differential.

So, this is nothing, but the first law for the closed system. Now, already I defined cycle. So, cycle means in our subsequent lecture we will talk about that if you want to extract energy or convert energy from one form to other, particularly heat to work you need a working fluid, that has to operate in a cyclic manner and that working fluid has to undergo some change of states and this change of states is accounted such that it forms a cycle. For example, this is a particular cycle and it is nothing, but a diesel cycle the process goes from 1-2-3-4 in a particular fashion and similarly same process can be done in T-S diagram. So, through this concept, we can say that if you want to extract heat from fuel then, we must use a working fluid that works in a continuous manner such that, this working fluid changes its state from 1-2-3-4-1 and so that it forms a cycle.

And for this particular diesel cycle it is seen that since initial states and final states are identical there is no change in the internal energy.

But for this ideal diesel cycle $\Delta U = 0$, and $\Delta Q = Q_A - Q_R = \Delta W$ and this can be viewed as a closed system. So, the energy auditing will tell that the total change in the heat interactions also balances to work, so $\Delta Q = \Delta W$. So, this is the first law for a cycle.

In the previous courses of thermodynamics we might have known different processes, we are not going deep into all those things rather I will try to emphasize, what are the different thermodynamic processes and this particular table talks about the summary sheet for different processes; isothermal, constant pressure, constant volume, reversible, adiabatic, polytrophic, throttling, all of which are commonly used in all kinds of thermodynamic devices and correspondingly their state relationship that means how this pressure volume relations are taken into account and other properties like we look at the change of state in terms of internal energy, enthalpy, entropy, non-flow work, flow work, heat transfer.

So, this is the summary sheet and the derivations are already there in the basic level of thermodynamics course which we are not going deep into. Now, another point that I need to emphasize here, many a times we will be talking about perfect gas and non-perfect gas. Basically, we all know on the equation for an ideal gas, i.e. $pV = mRT$

Where, p stands for pressure, V stands for total volume, m stands for mass, R stands for characteristics gas constant for that gas and T stands for the absolute temperature. So, this equation holds good for an ideal gas.

Now, if it is a non-ideal gas, then this equation changes to another form where you introduce a term what is called as Z, which is called as compressibility factor.

Modified equation of state $, pV = mZRT; Z =$ Compressibility factor

That means, identically, if it is a non-perfect gas, we also say it is not an ideal gas because the molecules are close enough to exert forces on each other, whereas the perfect glass is highly compressed and highly cooled and in critical conditions. It means that there is an intermolecular force that binds the molecules that is one part. Second thing is that ideal gas law is not violated because each molecule tries to occupy some space.

So, the total volume we accounted as V is less than that. So, for that reasons, we have different equation of states, that is called as Van der Waals equation state & there are many such thermodynamic states for non-ideal gases can be specified. However, we will not deal with this, but what I am trying to say here is that if there is a non-ideal / non-perfect gas, how you deal with it. So, we introduce a factor that same equation we introduce a term what is called as a compressibility factor. And this compressibility factor is plotted in a chart and this chart has Y-axis as Z and X-axis is reduced pressure and there are plots like different values of reduced temperatures. So, we say Reduced pressure, $p_r = \frac{p}{p_c}$ and Reduced temperature, $T_r = \frac{T}{T_c}$ and p_r and T_r are any arbitrary pressure and temperature that the gas is specified. Whereas, p_c and T_c are called as critical values of pressure & temperature respectively, that means pressure and temperature at critical conditions. So, these varies from gas to gas. So, for these values we can refer to gas table, like nitrogen will have a different values of p_c and T_c oxygen will have different values of p_c andT_c. So, those numbers we can find out from the tables which are available in any common textbook. That means, when you know p_c and T_c then we can define these p_r, T_r.

So, what is the significance of these two? That means, if you know this p_r and T_r for a given gas then we can easily use this chart to find out the deviation or compressibility factor and when you find this the compressibility factor, you can see that whether the assumption of ideal gas equations is violated or not. So, that is the advantage of introducing this compressibility chart, but until we require very accurate information, in most of the cases the validity of ideal gas is unanimously accepted.

And the last segment of this is to introduce some steady flow devices which is governed by this first law of thermodynamics and steady flow devices are nothing, but devices, those operate on steady processes; thermodynamic processes and in which the fluid flows through the control volume steadily what we view is that fluid properties can change from point to point and at a fixed point they remain same for the entire processes. In this steady flow device category we have like nozzles & diffuser, turbines & compressors, heat exchanger and throttle valves.
So, what does this nozzle do? Nozzle expands the fluid that means, velocity increases at the expense of pressure. The diffuser does exactly opposite to that of nozzle.

Then we have turbines and compressors. In the turbines, the gas expands and in the compressor gas is compressed. So, this is what we say turbines and this is what the compressors. So, for compressor we require work input & turbine produces the power.

Then we have heat exchanger, heat exchanger means it does not have a role in production of power it mainly deals with the interaction of heat. So, we can have two ways that means, when you say it is a control volume two fluids can mix with each other. So, we can have a mixing chamber. So, that means, the combined fluid can leave. So, that is one way. The other way is that, we can pass the two fluids in two different entities and they do not mix with each other rather they only exchange the heat. So, that way we call this as a heat exchanger.

Then another kind of device which is a throttle valve. So, throttle valve is a kind of a plug or capillary tube, what it does is that there is a drop in pressures. So, through this throttling valve devices what remains constant is the enthalpy.

So, if you look at enthalpy, $h = u + pV$. In a throttle valve, enthalpy remains constant. However, your initial state your temperature T_1may be equal to$T_{2,}$, enthalpy may be same, but then the change in the volume & increase in the pressure will match such that enthalpy remains constant. And looking at those simple relations, the steady flow energy equations can be framed for steam generator or heat exchanger, steam turbines, compressors, the nozzles and diffuser. So, all these derivations are available in these books. So, this is nothing new, but this can be derived based on this figure in these equations.

First law equation for a steady state steady flow system, $H = U + pV$

$$m\,g\,z_1 + \frac{1}{2} m V_{s1}^2 + \left(U_1 + p_1 V_1\right) + \Delta Q = m\,g\,z_2 + \frac{1}{2} m V_{s2}^2 + \left(U_2 + p_2 V_2\right) + \Delta W$$

Steam generator/Heat exchanger: $PE_2 - PE_1 \approx 0;\ KE_2 - KE_1 \approx 0;\ \Delta W = 0$

$\Rightarrow \Delta Q = H_2 - H_1\ \ \&\ \Delta q = h_2 - h_1$

Steam /Gas turbine: $PE_2 - PE_1 \approx 0;\ KE_2 - KE_1 \approx 0;\ \Delta Q \approx 0$

$\Rightarrow \Delta W = H_1 - H_2\ \ \&\ \Delta q = h_1 - h_2$

Pump/Compressor (Incompressible fluid): $PE_2 - PE_1 \approx 0;\ KE_2 - KE_1 \approx 0;\ \Delta Q \approx 0$

Additionaly, $U_2 = U_1$ & $V_2 = V_1 = V$ so that $\Delta W = V\left(p_1 - p_2\right)$ & $\Delta w = v\left(p_1 - p_2\right)$

Nozzle/Diffuser: $PE_2 - PE_1 \approx 0;\ \Delta Q \approx 0;\ \Delta W \approx 0$

Exit velocity, $V_{s2} = \sqrt{2\left(h_1 - h_2\right)} = \sqrt{2v\left(p_1 - p_2\right)}$ (incompressible fluid)

$V_{s2} = \sqrt{2\left(h_1 - h_2\right)} = \sqrt{2c_p\left(T_1 - T_2\right)}$ (ideal gas)

Throttling: $PE_2 - PE_1 \approx 0;\ KE_2 - KE_1 \approx 0;\ \Delta Q \approx 0;\ \Delta W \approx 0$

$\Rightarrow H_1 = H_2\ \ \&\ h_2 = h_1$

So, we start with these equations that is the first law equation for a steady flow energy system. Based on the nature of the device, many terms can be neglected for a particular steady flow device and accordingly we can frame these steady flow energy equations for different components like generator, steam generator, heat exchanger and gas and steam turbines, compressors, nozzles and diffuser. Because these devices has a specific role to perform.

So, this is all about for the discussion. So, with our discussion, let me try to solve some numerical problems which we have covered in this lecture.

Q1. Nitrogen is stored in a 0.3 m^3 rigid tank at 70 bar and 23℃. Find the mass of nitrogen in the tank and the error if perfect gas law is used.

So, in this first problem I have just given a demonstration that whether we have the ideal gas equation which you all know.

At the same times if the gas is treated as a non-ideal or non-perfect gas or you do not use this non-perfect gas then what is the solution.
So, for that this particular problem demonstrates that we have a tank rigid tank that stores nitrogen,
It has a volume V= 0.3 m^3
& it has a pressure $p =$ 70 bar & T = 23℃ or 296 K.

So, this is the gas which is stored in the tank and we need to find out mass by two means, Case-1) By assuming a non-perfect gas and Case-2) if the perfect gas equation is assumed. So, in other words let us say nitrogen is a non-perfect gas, then how do you calculate the mass?

So, for that what you have to refer? You have to refer the data table which is available in any thermodynamics books and i.e., the data table for gases or for pure gases.
So, for nitrogen and this will implies two important values, those are called as critical values.
One is critical pressure for N_2, p_c = 34 bar
Other is the critical temperature for N_2, T_c = 126.2 K

And more details about this critical conditions will come in the next class, in which we will deal with the pure substance. So, for the time being let us see these as the critical pressure and critical temperature.

Then we can find the reduced pressure and temperature.
So, they are
Reduced pressure, $p_r = \frac{p}{p_c} = \frac{70}{34}$ = 2.05

& reduced temperature, $T_r = \frac{T}{T_c} = \frac{296}{126.2} = 2.34$

So, we have two numbers p_r and T_r. Now refer the generalized compressibility chart. In fact, this chart is available in any of the thermodynamics book, this particular chart was taken from the book that is Moran and Shapiro. The snapshot of this graph shows this way.

So, what we can say is that, for this p_r and T_r; we have $p_r \cong 2$. So, this X- axis talks about p_r that is 2 and these are the lines of constant T_r. So, constant T_r line starts somewhere in this line and it is very close to this particular one. So, if you go along this vertical the T_r line will stop somewhere here and this particular if you drop horizontal line onto this then we can drop down close to the value of $Z \cong 0.98$ or we can say it is close to 1.

Case-1:

So, putting this we can write this main equation for non-perfect gas we say,

$pV = mZRT$. ($Z \cong 0.98$)

$\Rightarrow m = \frac{pV}{ZRT}$ & for N_2, we can take this R = 0.297 $^{\text{kJ}}/_{\text{kg. K}}$

$\Rightarrow m = \frac{70 \times 10^5 \times 0.3}{0.98 \times 297 \times 296}$

$\Rightarrow$ $m = 24.375$ kg

Case-2:

Now, if you say it is a perfect gas, other equation will turned out to be, $pV = m_{id}RT$ and through this process we can also calculate mass for the ideal gas. So, we say, if nitrogen treated as an ideal gas

$pV = m_{id}RT$

$\Rightarrow m_{id} = \frac{pV}{RT} = 23.88$ kg

So, the questions was asked what is the percentage of error introduced.

% of error = $(\frac{m-m_{id}}{m_{id}}) \times 100 = (\frac{24.375-23.88}{23.88}) \times 100 \approx 2\%$

So, for this problem if you say that nitrogen is treated as a non-ideal gas then we will introduce only 2 percent error.

Q2. A certain water heater operates under steady flow conditions by receiving 4.2 kg/s water at 75°C and enthalpy 315 kJ/kg. The water is heated by mixing with steam which is supplied to the heater at temperature of 105°C and enthalpy 2680 kJ/kg. The mixture leaves the heater at 100°C and enthalpy 420 kJ/kg. Calculate the supply rate of the steam.

So, this problem is based on the steady flow devices. In this case it is a water heater and it operates in steady flow conditions. It takes water at certain enthalpies and temperatures and water is also heated with a steam and the steam is supplied at certain conditions 105℃ and enthalpy 2680 kJ/kg and of course, the mixture is leaving at 100 ℃ and 420 kJ/kg. We need to find the supply rate of the steam. So, to do that you can recall simply an open system that consists one fluid in and there is another fluid enters there, but only a single fluid leaves. So, there is two inlet and one outlet. So, one case we say it is a water other case we say steam. So, it is a water heater.

So, conditions of water mass of water=m_w, & enthalpy of water= h_w
Then, mass of steam=m_s &enthalpy of steam= h_s
And we have mixture, mass of mixture=m_m &enthalpy of mixture=h_m.

So, there are two equations that we can frame for this water heater problem

1. Mass balance, we say that, $m_w + m_s = m_m$
2. Energy balance, by neglecting all other terms and only retaining the heat terms we say, $\Delta W = 0,\ \Delta Q = 0,\ \Delta(\mathrm{PE}) = 0$ & $\Delta(KE) = 0$

So, we can write, steady state steady flow equation (SSSF equ$^{\mathrm{n}}$),

$m_w h_w + m_s h_s = m_m h_m$

$\Rightarrow m_w h_w + m_s h_s = (m_w + m_s) h_m$

Now, what we require is the supply rate of steam. So, we require m_s.

$$\Rightarrow m_s = \frac{m_w(h_m - h_w)}{h_s - h_m}$$

So, data that is given, $m_w = 4.2$ kg/s

$h_w = 315$ kJ/kg

$h_s = 2680$ 2680 kJ/kg

$h_m =420$ kJ/kg

Now, inserting these value we write,

$$m_s = \frac{4.2(420-315)}{2680-420} = 0.195 \text{ kg/s} = 0.195 \times 360 \ \approx 703 \text{ kg/h}$$

So, supply rate of steam is 703 kg per hour.

So, these are the two sample problems for this lecture today. With this I conclude this lecture. Thank you for your attention.