Concepts of Thermodynamics

Prof. Suman Chakraborty
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

Lecture – 28

First Law of Thermodynamics for Unsteady Processes in a Control Volume

So, far we have discussed about the application of first law for a control mass system and for a control volume undergoing a steady state steady flow process. But all processes are not steady and it is important that we also understand how to address the problems where the state within the control volume at least changes as a function of time.

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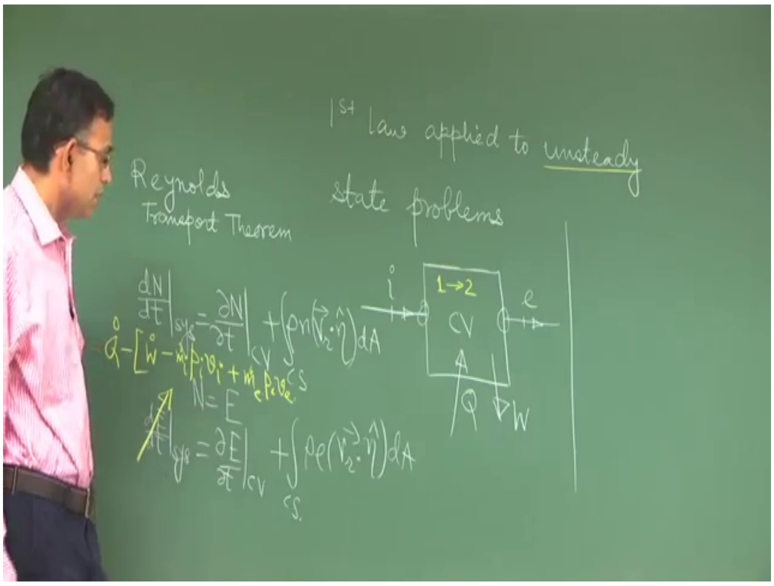

So, we will start today’s discussion on first law applied to unsteady state problems. So, what kind of situation we are considering? Let us just draw a box which is the control volume and the properties within the box. So, by properties within the box these box has numerous physical locations and at each physical location you can have a separate set of properties and physics does not disallow that, what is disallowed is from the concept of thermodynamic equilibrium consideration.

What is that? If we assume that this entire control volume is in thermodynamic equilibrium then we cannot you know distinguish the property set here from property set here, from property set here and so on. So, everywhere the property set why property set we means a pressure volume temperature or other relevant properties like internal energy and enthalpy, we will learn a few more properties as we advance in this course. So, all these properties, these properties if they are uniform over this control volume then only this control volume can remain in equilibrium, thermodynamic equilibrium.

So, whenever we say that we are talking about equilibrium thermodynamics we are implicitly considering that all these points are at uniform state, but there can always be a deviation from equilibrium and any natural process actually is deviated from equilibrium. So, that is how you have a little bit of conflict in conceptual pa paradigm between equilibrium thermodynamics and a more practical consideration of heat transfer within the system.

So, if you have heat transfer within the system you are likely to have temperature gradients; if you do not have temperature gradients how can you have heat transfer within the system? But equilibrium thermodynamics assumes that you are having a local equilibrium, but that local equilibrium can state can change with time because of may be a global heat transfer to or from the system or any work done by the system or work done on the system. But whenever the change takes place the change takes place in such a manner that the entire system quickly comes to equilibrium in response to that, whether quickly or slowly it is a matter of the properties of the system, but eventually it comes to equilibrium ok.

So, but so that is not actually impractical, the system can eventually come to equilibrium. What this equilibrium thermodynamics is not able to capture is how by function of time this system came from one equilibrium state to another equilibrium state. It simply can identify the equilibrium states, equilibrium state 1 changed to equilibrium state 2, but that does not occur instantaneously. However, a period of time through different transients these has occurred, that detailing is not within the per view of this macroscopic or classical thermodynamics.

So, this is a you know brief discussion which I thought is required, because you know you may have a conflict of understating that if you have heat transfer then how can you have equilibrium. So, this we have to keep in mind that when you have heat transfer instantaneously the equilibrium state is disturbed, the system take some time to come to a new equilibrium state. In between what happens the dynamics that is not within the per view of macroscopic thermodynamics. Macroscopic thermodynamics will bother about only you know the change of state from one equilibrium state to another equilibrium state, not you know the how I mean the system dynamics changed in between.

So, this is the control volume. So, let me just draw a little bit more clearly, there is a generic inlet i, there can be large number of inlets. So, each will be symbolically denoted by I, there will be generic exit e again there could be multiple exits, there is a heat transfer q again this is generic if it is from the surrounding to the system then q is positive, if it is from system to surrounding then q is negative ok. So, then next is work done again very generically represented in this diagram, if work is done by the control volume or energy transfer due to work is from control volume to the surrounding then it is positive, if it is the other way then it is negative.

In the mean time the state within the control volume because it is unsteady it changes from 1 equilibrium state 1 to another equilibrium state 2, this is the new thing that is beyond the previous consideration, the previous the steady state steady flow problems this 1 and 2 states were identical equal. So, there was no change in state within the control volume. Now, the state within the control volume changes from state 1 to state 2 state one uniform over the control volume state two uniform over the control volume, this is the basic picture that we are keeping in mind. Now we will apply the Reynolds transport theorem to fit this picture. So, let us write the Reynolds transport theorem just for recapitulation.

So, just to recapitulate capital n is an extensive property, small n is capital n per unit mass V r is the velocity of the fluid relative to the control volume, theta is a unit vector outward normal to the surface across which the inflow or outflow is taking place. And you know this cs is the control surface, the surface of the control volume over which these flow boundaries are there. So, this is 1, this is 1 like that ok.

So, we will write N as the total energy of the system, remember total energy is internal energy plus kinetic energy plus potential energy ok. So, dN dt is dE dt, this is small e is capital e per unit mass, remember that e includes internal energy kinetic energy and potential energy. Now as per the description of first law of thermodynamics of the of a system this is the difference between heat transfer and rate of heat transfer and rate of work done.

So, when we say rate of work done normally it is the work associated with the control volume that is whatever work you can derive from the control volume plus an additional work that you require to maintain the flow in presence of pressure right. So, that is flow energy or flow work which we have discussed in great details in one of our previous lecture.

So, instead of you know re repeating that again I am just writing the expression for the flow work. So, this is the flow work associated with the inlet and this is the flow work associated with the outlet right. Remember it is we derived it as p by rho because in thermodynamics for easy interpolation we use specific volume instead of density. So, 1 by rho is v, flow work associated with the inflow is negative and flow work associated with the outflow is positive, there could be multiple inlets and exits.

So, there I mean you can generalize these with a summation symbol, but for you know simplicity I am not writing it and then the most important thing is that we are assuming that the pressure and specific volume are uniform over the respective inlet and exit sections.

So, pressure pe when we say, c is not a point e is you know the distributed collection of points across this. So, we are assuming that pressure is uniform over this which is very true for pipe flow, see typically this inlet and exit will be pipes. So, typically over the cross section of the pipe the pressure does not vary that much as compared to how it changes longitudinally. So, pressure will be uniform and this is not such a large cross section that density will also change substantially. So, for all practical purposes pressure and specific volume uniform across respectively i and e are not very bad assumptions ok.

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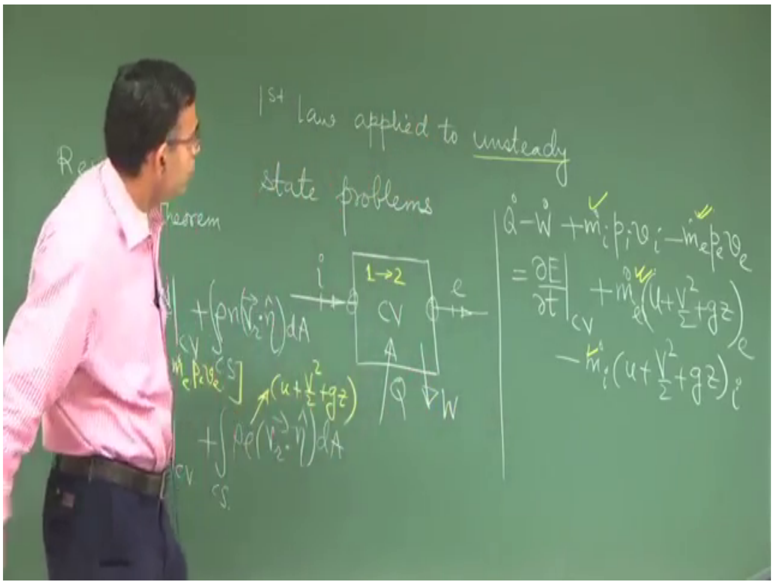

So, then we will write Q dot. So, this W dot is actually W dot that you can get across the control volume W dot CV, but I am just short form in short form I am writing W dot just to avoid any know confusion; then plus ok. Now, can you tell one thing, see how do you know you know from your common sense access that this work is negative and this work is positive.

So, I give you a physical feel about it. So, by what transfer what is happening? Some energy is either entering the control volume or energy is leaving the control volume, look into this symbol of work if energy is leaving the control volume then work corresponding to that is positive. So, here when the fluid is flowing out of the control volume it is carrying with it the energy. So, energy is leaving the control volume and that is why that is positive.

Here fluid is entering the control volume. So, some energy is pumped into the fluid in the form of work. So, that is why it is negative ok. So, the you know why I am telling all these because the sign of heat and work these are very important, the algebraic signs so far as problem solving writing algebraic expressions. So, if you get a confusion in this instead of you know getting into the basic derivations from the scratch you can use your common sense to figure out, whether you will put a plus to that or minus to that.

So, that is what I am emphasizing it. So, this then let us write the right hand side ok. Now this e is what? Internal energy plus kinetic energy all per unit mass. So, all the velocities are measured relative to the inertial reference frame so that V r and V will be you know the same. So, then you have to recognize that these property, internal energy kinetic energy potential energy these may vary across the cross section.

But we are again assuming that these cross section or control surface rather which is which may be small cross section of a pipe, this control surface is such that over which these properties are uniform. That means, height does not change appreciably, velocity also does not vary appreciably which is again you know not a very good assumption; why? Because, if you have studied fluid mechanics you know that the velocity across the section of the pipe varies.

So, instead of using the local velocity you can use average velocity here with something called as multiplied by something called as kinetic energy correction factor, this is taught in fluid mechanics. I can understand that there are students studying this thermodynamics course who may not have studied fluid mechanics here. So, I am not getting into all those details.

So, we are we are desperately trying to represent these v average square by two the kinetic energy of the system and that fortunately is possible if the velocity is very uniform across the section and that occurs when the flow is so called turbulent. In most of the practical engineering applications you will find typically in the industry, you will find that there are flow rates sufficiently large to have turbulent flow and then the velocity is uniform over this section. So, this truly represents the kinetic energy without much you know error ok.

So, given that we can argue that you can bring this property which is uniform over the section outside the integral and rho into V r dot eta dA integrated is the mass flow rate, positive for outflow negative for inflow; so, we can write ok. So, the assumption is very clear these properties are uniform over i and e ok. So, this is often called as uniform flow assumption, that you know the flow at the sections respective sections i and e are associated with uniform property ok, this is often called as uniform flow assumption. Then we can club this term with this and this term with this double tick term with this double term. So, u becomes u plus p v if you club this with this. So, internal energy is replaced by enthalpy if you bring it in this side ok.

So, the physical difference is that between a control mass process and the process which is taking place in a control volume with flow is that here you have this additional thermal energy that the fluid must poses to maintain the flow in presence of pressure. So, the thermal energy for a flowing fluid is represented by enthalpy and not by internal energy, this is the physical understanding of a flow process as compared to a you know stationary you know non flow process. So, then let me utilize this part of the board to you know complete the derivation which will require one or two more steps.

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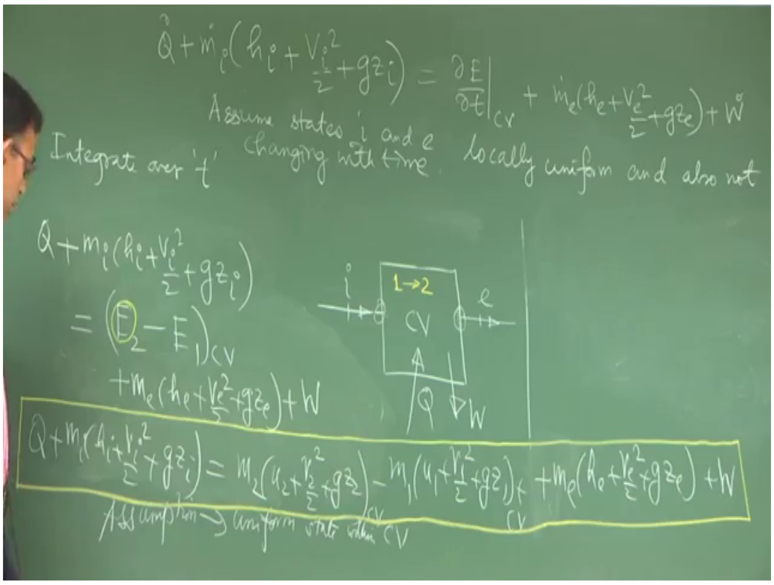

$$\dot{Q}+\dot{m}_i\left(h_i+\frac{V_i^2}{2}+gz_i\right)=\left.\frac{\partial E}{\partial t}\right|_{CV}+\dot{m}_e\left(h_e+\frac{V_e^2}{2}+gz_e\right)+\dot{W}$$

Assume states i and e locally uniform and also not changing with time.

Integrate over 't'

$$Q+m_i\left(h_i+\frac{V_i^2}{2}+gz_i\right)=\left(E_2-E_1\right)_{CV}+m_e\left(h_e+\frac{V_e^2}{2}+gz_e\right)+W$$

$$\boxed{Q+m_i\left(h_i+\frac{V_i^2}{2}+gz_i\right)=m_2\left(u_2+\frac{V_2^2}{2}+gz_2\right)_{CV}-m_1\left(u_1+\frac{V_1^2}{2}+gz_1\right)_{CV}+m_e\left(h_e+\frac{V_e^2}{2}+gz_e\right)+W}$$

Assumption → uniform state within CV

So, Q dot plus m dot i I am just writing i on the left. So, far so good, now as I told that in equilibrium thermodynamics we are not really bothered about how the change of state takes place in between. We are only bothered about the change from equilibrium state 1 to equilibrium state 2.

So, we will integrate these over time from time state 1 to time state 2. So, if we do that and assume so, we make an assumption that this inlet state has not changed over time right; see inlet state has a chance of changing over time. So, we are assuming that inlet state has not changed over time. So, assume states i and e locally uniformed and also not changing with time right, these are the two things that we are already assuming.

So, in that case if you integrate this equation over time; so, this is like a constant over time i e sorry h i v i square by 2 g zi m dot i is d m i d t these when integrated will become m i right. So, what we will get q dot integrated will become q so integrate over time. So, you have q plus m i, this when integrated over time will be the difference in E from time state 2 to time state one within the control volume. So, this will be E at state 2 minus E at state one right within the control volume, plus me he plus v square by 2 plus g ze plus W ok. W dot integrated over time will become W. Then in the next step so, what is this E this E is E within the control volume. So, that is not suppose to contain the term enthalpy as a thermal energy, that will contain internal energy as a part of thermal energy.

So, this is the key you have to keep in mind for inflow and outflow the thermal energy includes enthalpy for the state within the control volume you know the energy thermal energy part is contributed only by internal energy. So, Q plus m i h i plus V i square by 2 plus g zi equal to, now the most important assumption that act state 2 we are a or at state 1 we are assuming that the properties are uniform. So, uniform state within the control volume so; that means.

So, m 2 this we can write m 2 into. So, the assumption is uniform state within control volume ok. So, you can see the control volume is undergoing an unsteady state unsteady process, but at each time state it is uniform over space. So, this is called as unsteady but uniform state ok.

So, this equation which you know let me make a; so, there is a h e term which I have I have to write. So, the or me term plus me h e plus v square by 2 plus g ze plus W. So, this equation let me make it a box. So, that you know you can. So, q plus energy transfer at the inlet is equal to the change in state of energy between state 1 to state 2 plus the energy coming out in terms of flow and work.

So, it is basically energy in equal to energy out plus energy change within the control volume. So, this is energy in, through heat through flow this is energy, this is energy out and this is the change in energy within the control volume. So, whatever energy is getting into the control volume may be a part of that is leaving, the remaining can increase the energy from state 1 energy to state 2 energy right. So, this is the bro, this is the broad energy balance.

Essentially after a whole lot of mathematical toil we have written an equation which we can write simply from common sense with energy balance if we can understand it properly. Now only one point small point that remains to be noted here is that we have included energy balance, but we should also include mass balance consistent with the energy balance.

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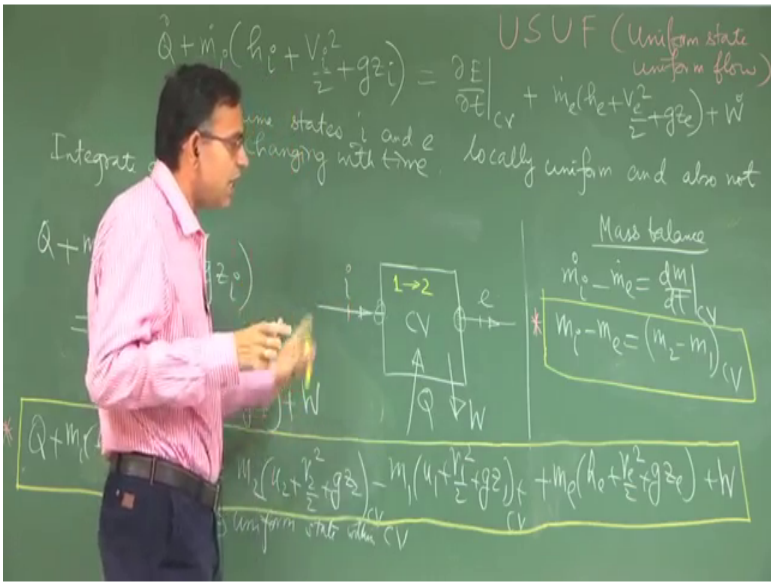

So, what is mass balance here?. So, m dot i minus m dot e right, the rate at which mass enters the control volume minus the rate at which mass leaves the control volume the difference is changing the mass of the control volume. So, this is mass conservation.

So, if we integrate this over time m i minus m e this is m 2 minus m 1 very simple. So, these two equations together constitute the energy balance and mass balance frame work of a process called as USUF Uniform State Uniform Flow, the under lying assumption is that it is uniform, but unsteady, but at a given instant of time the properties within the control volume are uniform. That is why the state thermodynamic state is uniform and the flow sections are also having uniform properties. So, uniform state, uniform flow is the terminology that is correctly associated with the description of this energy balance and this mass balance.

Let us stop here today in the next class we will start working out a few problems illustrating these basic equations.

Thank you very much.