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Course on Laws of Thermodynamics

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Lecture 10: First Law of Thermodynamics for Open Systems

Good morning I welcome you all to this lecture section of the course law of thermodynamics now today we will discuss the application of first law of thermodynamics to an open system or c control volume the application of 1st law to a close system as already been discussed and you have already come to know that 1st law is nothing but the law of conservation or energy and we have come to know this thing that the energy in transit or we transfer between a system and the surrounding or between two interacting systems are in the form of heat and work.

While energy in another form is stored in the system which bears the characteristics of a property this we have learnt from 1st law now today we discuss the application of same conservation of energy principle or 1st law to a close to an open system or a control volume before that we will recapitulate a theorem know as Reynolds transport theorem many of you may have read this thing earlier in fluid mechanics.

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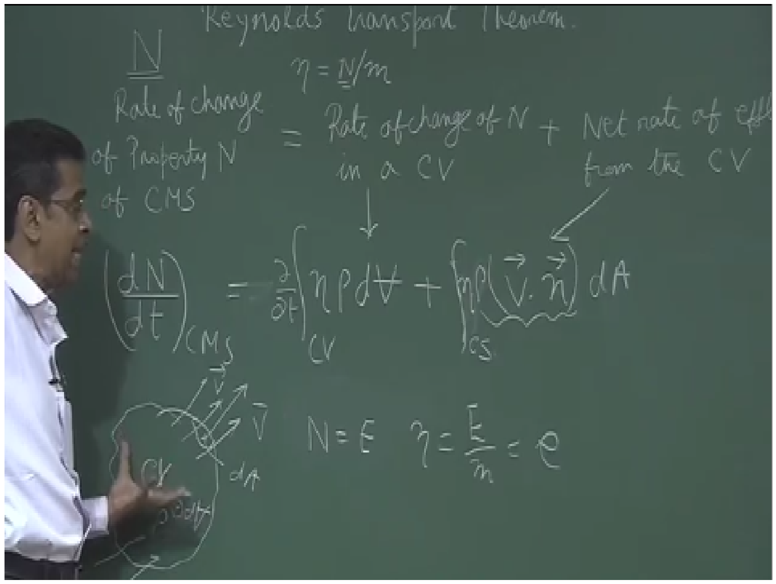

Now we will discuss this Reynolds transport theorem, what is Reynolds transport theorem no we know that this statement of the law related to classical mechanics and thermodynamics have usually been made on a control mass system approach or a Lagrangian particle approach all laws area started in terms of control mass system or two system but in engineering applications we have seen that since the control mass system is continuously deformable the it is easier to analyses the process or a system with respect to control volume on an open system approach.

So therefore some kind of mathematical transformation is require to relate this laws to the control mass system to that prior control volume or roping system and the this mathematical transformation or theorem that does this is known as Reynolds transport theorem which relates the change of a property with respect to a control mass system to that with respect to a control volume system.

For an expel I tell you when we define this second law of motion by Newton second law of motion that the rate of change of mass of a system that is a control mass system rate of change of mass of a substance or body is equal to the force acting on the body so therefore you see that this way the for example the conservation of mass we know the mass of a system control mass system or a body remains constant, so therefore the physical laws are postulated always on the approach of control mass system or close system.

Now the relationship between these applied prior control mass system to that of a control volume system is given by Reynolds transport theorem so I will state the Reynolds transport theorem without proving it what does it tell in this class, so Reynolds transport theorem tell that if we have an extensive property then rate of change of property let N is the extensive property rate of change of property N is a control mass system rate of change of property of control mass system I am writing CMS = Rate of change of N in a control volume system or simply we use control volume.

That is the open system + net rate of effects of N from the control volume that means across the control surface the rate of effects of N this can be this can be written methodically if we defined η as the corresponding intensive property for N that is this specific value of N that is N any extensive property whose corresponding intensive property as I have told you in earlier class is this specific value of the N that means N / unit mass then we can write the right hand side as dNdt for the control mass system.

Now this can be written as consider a control volume system like this control volume system if you consider at any point an elemental volume dv and the local density there is ρ we can write is η ρ dv over the control volume the integration is done over the control volume that is rate of change sorry ∂ ∂ t of this that ∂ ∂ t of the energy within the condole volume that N that means this is the N within the control volume/ unit mass ∂Dv.

And it is integrated over the entire control volume plus the main rate of mass a flux which can be written as ∂ η, η∂ this η is the mass the n per unit mass and this is the mass flash across the control surface, this control surface so V.n, n is an this to understand if you take for example this is the flash that means this is the velocity vector for example this is the velocity vector if you consider and elementally area on the surface control surface dA.

This is represented by a vector or like this we can consider that you need vector l is an unit vector which is directed normal outward, outward direction is positive direction and normal is the direction normal to the area, so V.d and this dot product V.n represent the component of the velocity, velocity vector is this the components of the velocity along the normal direction that means this is the velocity component normal to the surface area dA V.n, n is an unit vector normal to the elemental surface dA.

So therefore this as you know earlier from your fluid mechanism knowledge that this replace that ∂V.n, dA is the mass flow rate and this is be integrated over the control surface so therefore this is the rate of change of CB and this is the rate net rate of effects of n from the see this one so this is this and this one is this, now this can be written as this dt of this is the energy within the control volume dt of these E_{cv} dt of E_{cv} that is the change rate of change of energy within the control work.

dt or you can write δt does not matter now this can be written if you consider this η here we are writing η actually we are considered this is the sorry I am extremely sorry this is the control this is the general theory for any extensive property, now if we take this extensive property N as the energy and η as energy by m1 sorry E e is the specific energy that is energy per unit mass now before that I tell you one thing that this Reynolds transport theory with respective general property N can be written that any general extensive property N.

And here this N cam be replace by any property if we replace then as m that is mass then this will give you the conservation of mass with respective of control volume, if you written N as the momentum then it will give the momentum theory, has we have already rate for the control volume, and if we use the N as the energy it will give energy equation and apply to the control volume or open system here it should be very much remember that this theorem that the net rate of for the rate of change of property N, within the control volume plus net rate of reflects of N from the control volume equal to the rate of change of property N of its control mass system which coincides the control volume at that each time.

Okay now after this I come to the conservation of energy equation you please remember the equation so that it will be easier for you to follow these things this board is small enough space and you cannot accommodate everything now if you write this for.

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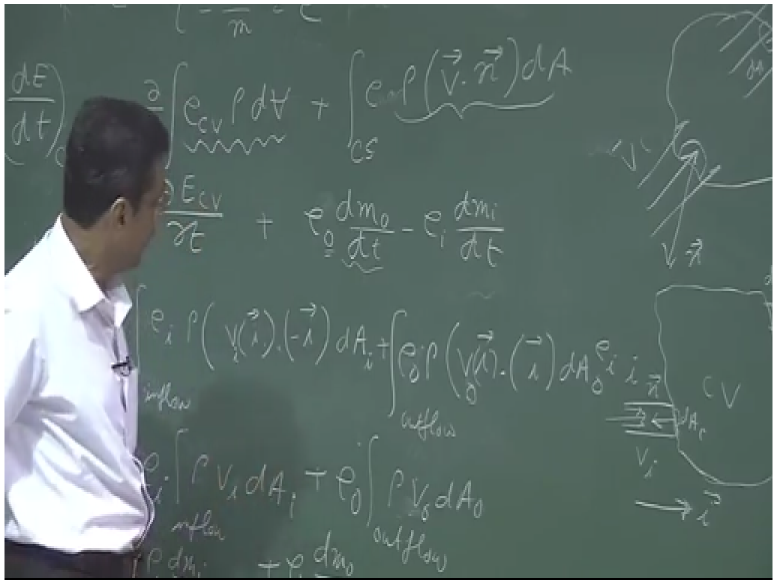

N = energy and obviously η will be energy per unit mass that is specific energy then this can be retained as these dE this Reynolds transpose theorem control mass system = δt of what will be their η is small e that is specific energy within the control volume into ∂dV + ∫e ∂ that is the velocity component perpendicular to the area dA over the control surface where n is unit vector like this here I write, where n is the unit again I am drawing this think this is the velocity weight that this is the out flow.

Velocity vector and we have an area dA here and let x normal is in this direction outward normal so this is the velocity of vector component along the normal direction, so this is the size of the mass flow rate across the control surface now this can be written as this dt for a control mass system is this can be again written as this is the total energy of the control volume the δt of δE δt of E_{cv} δE_{cv} δt that means this is the rate of change of the energy within the control world time rate of change, now if we consider.

This specific energy associated with from mass flask or the flow is constant across the control surface over the entire control surface both in case of influx and afflux this can be written as e_0 – where this is the o suffix o represent the outflow this is the rate of mass outflow from the control surface f(x).

Into this specific energy across the control surface outflow surface which is constant across the surface where the afflux is there, similarly e_i represent this specific energy associated with the flow across the inflow surface and this is the mass flow rate of the inflow surface if this is constant and we can write this as dm_0/dt – dm_0 minus sign comes because of the fact that this V· end or n- bar (V. n) is positive for outflow direction.

You see that the velocity vector and the outward normal vector to the area is in the same direction means this is positive whereas in case of an inflow area the normal is in this direction which is in the opposite direction, so this will be negative for inflow area and this will be positive for the outflow area, you can take an example like this in a simple example you can understand this afflux thing that.

If we consider a control volume like this where we already as a as recognized and inflow area like this which is this inflow area okay and we have an outflow area like this where this is the velocity flow out, now if we define this inflow area by suffix I and outflow area by suffix o and if we consider E_i the energy specific energy associated with the inflow that is the mass inflow is constant over this surface.

And similarly e_o is constant and across this surface e_o is constant across this surface and here also we consider VI is the velocity that is the inflow velocity and Vo is the outflow velocity and this two are the only recognized area through which the mass coming in and going out that is the influx and afflux in the control volume we will get that you can get this things from here then if you write this term the second term this term on the right hand side.

You get CS over the inflow area e_i if the inflow area e_i row now here we define a unit vector I in this direction unit vector I, so here V is V – Vi because V is in the opposite direction to that of I you understand this, this is I this is for the direction so therefore sorry then N is vi rather V x I, I am sorry dot the normal to this surface is in the opposite direction, the normal vector N in this case –I, the normal to this area inflow area this is inflow area the inflow area is –I.

So this ρV.N dD inflow similarly if we write the outflow area outflow area what happens ρ x e of first e_0 ρ x (V. I' I bar) and this into here the normal to this area that is normal outward it is, is equal to I so therefore this is I dA_o it is dA_i, it is dA_o that means any elemental area in the inflow any elemental area at the outflow section so therefore you see if E_i is constant across this inflow area E incomes out then Ei comes out and this I. –I -1.

So therefore –ρ V. dA so let us consider this V as Vi so I will give this as Vi this is the inflow area Vi inflow area so Vi dA, similarly here if you do that it will be if e0 is constant across the area it will come out and it will be simply ρ it will be 0 sorry it will be 0, dρ V0 dA_o over the it is this inflow this is the outflow, now this becomes mes the mass flow rate ρvidA over an area integrated over an area if vi is constant vi and ρ these values are constant in all cases we assume that they will come simply into be integration of dAi that means it will total Ai that means ρAv that is the mass flow rate or simply these integration is the mass flow rate that is dmi/dt+ this one will be e0dmo/dt.

So therefore we see that this integral which represents the net rate of energy +1 the control volume can be retain that e0.dmo/dt –eidmi/dt where dmo/dt and dmi/dt are mass flux out of the control volume mass flux into the control volume and eo and ei are the energy specific energy associated with the mass flow. So this is the mathematically expression by which I tell you that we can write this thing, so therefore the equation finally becomes like this, dm/dt control I can rub this thing and then I can write again so you just recall it.

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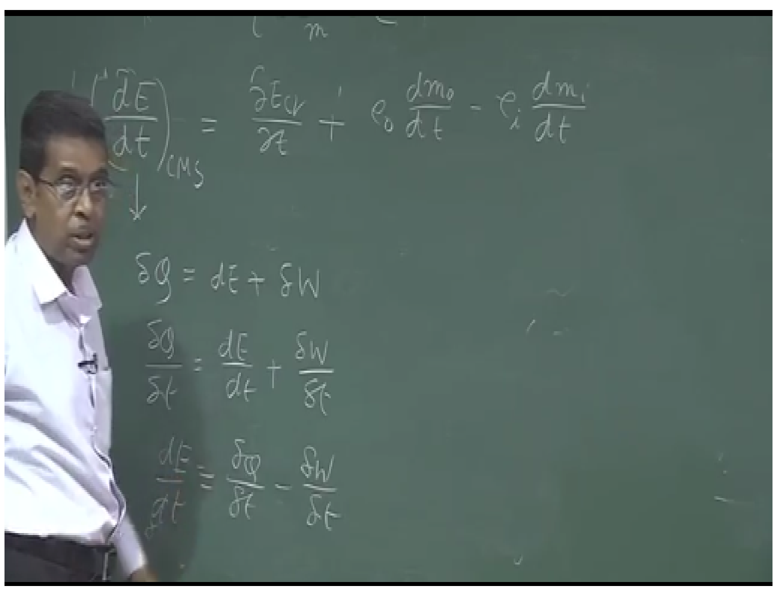

That dm/dt sorry dE/dt for the control mass system is equal to ∂ECv/∂t+ okay, e0dmo/dt-ei dmi/dt that means in terms of outflow and inflow area e0dmo/dt if there are number of outflows areas then this will be added all together this will be added all together okay, so this for a single inflow area single outflow area of course here in this equation it does not matter it takes the entire mass flow rate from the outflow area where 0 is constant over the entire control surface at ei constant over the entire inflow control surface and dmi/dt is the total mass inflow rate of mass inflow.

Now comes to this, what is dE/dt for control mass system that is you know that for a control mass system already by the application of first law the ∂Q is dE+∂what is this, that means in a control mass system or a close system if you add ∂Q among of heat small heat, small amount of heat it required to the changing internal energy of the control mass system that means the energy stored in the control mass system plus the work done and our conventional sign is that ∂Q is positive when it is added to the control mass system and W the work is positive when it is comes out of the control mass system.

And dE is the change of internal energy that means the energy stored in the system it is the internal energy. Now what has done in internal energy can we stored in the system it will be either inter molecular it will be inter molecular energy, kinetic energy and potential energy which have been already discussed, so if we consider this thing that this is given for a time interval of δt then this d I write this as d because E is a property and it is a prefect differential so that we write this as dE whereas Q and W are the path functions.

So therefore it is written like this on the rate basis if I write this will be this, dE/dt is nothing but small amount of energy ∂E added over a time δt limit, δt tends to 0 becomes dE/dt you can think this way also that means it is the exact differential so it is the derivate with respect to time, but this is not so this is path function that is δQ/δt represents the rate of heat transfer to the system in this fashion and rate of work transfer from this system.

So therefore the rate of δQ/δt is dE/dt+δW/δt so therefore dE/dt for a control mass system equals to δQ/dt- δW/δt this is clear. So for a control mass system we recall the first law applied to a control mass system like this that is for a close system and we can derive from there that is the rate of change of internal energy within the system recalls to the rate of heat transfer to the system minus the rate at which the work comes out from the system.

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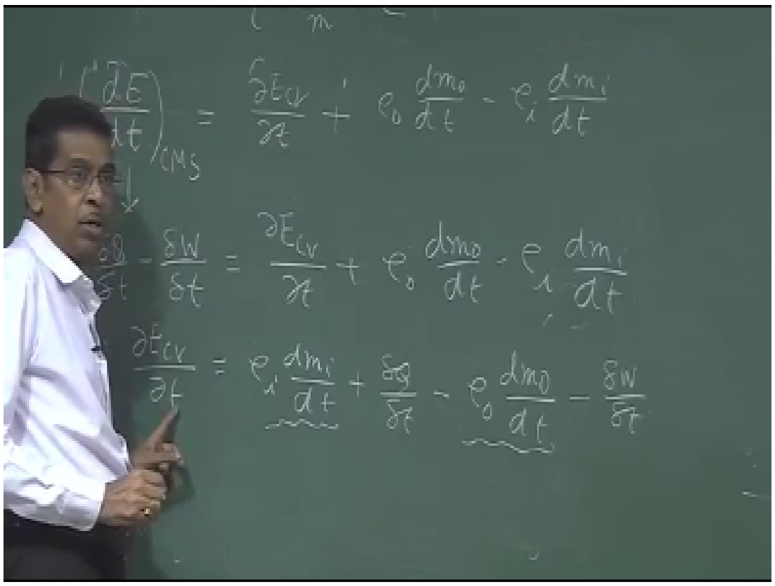

So if now we substitute these here, that dE/dt control mass system is $\delta Q/\delta dt$ now I told you when I apply this law the control mass system and the control volume system coincides that distance that means this is also with respect to the control volume system that means this is the rate at which control heat is added to the control volume system and the rate at which the work done by the control mass system this way we deal it try to understand this we substitute for the control mass system law, but since the control mass system and control volume coincides that distance.

So then everything is now with respect to the control volume system that means these now states that this is for the control volume system heat and working direction this is for the control volume system that is the date of change up in a juie the control volume and this is the rate of reflex this is the rate influx this becomes the nitrate of flux. So now if we write this in a different fashion then you write $\partial Ecj / \partial t$ = just I write in a little different doing that is ei dmi dt little rearrangement + $\partial q \; \partial t$ – eg ρ dm0 / dt - $\partial w / \partial t$.

Now you can better understand this equation is much more convenient that is the rate of change your being internal energy within the control volume request to the amount of energy coming in to the control volume on the form of the flow energy that is coming associated with the slow that is influx rate must flowed in to this specific energy that means this is the total energy coming to the control volume with the flow plus the heat that control volume receives the rate at which the control volume receives energy Interviewer: he form a minus the total energy going out one is going out with this flow that is the flow energy that is the energy going with the flow out flow this is the mass flow rate out flow mass flow rate in to this specific energy at the out flow surface minus the work that is going out that the energy that is going out in terms of work.

And this comes from the simple physical intuition form the conservation of energy clear, now if there is no flow this two terms will be 0 and this two terms will be 0 this term and this term so this will simply convert to the law that is $\partial E_{cv} /\partial t = \partial q/ \partial t - \partial w/ \partial t$ that is same to the close system because in a close system there is no mass influx. Now mass influx or mass efflux now $\partial q/\partial t$ and $\partial w/ \partial t$ will be opposite heat may be taken from this system or may be done to the system in that case the sign will be change.

That means this clearly shows that the total energy of the control volume changes depending up on its net gain in the energy, so control volume transfers energy or interrex energy with the surrounding in two forms one associated with this mass flow another in terms of work in heat transfer. So therefore we will account what energy a control volume has taken or gain from the surroundings or another interacting system in the form of flow energy coming with flow and either heat and work transfer and similar way the energy heat leaves in the form of flow associated with the flow and also in terms of work and heart and if we make a balance this will give the change of internal energy within the control volume.

Now here after this we have to know one thing after this I have be told allow is that the specific energy associated with the mass flow at inlet or outlet in flow or out but what are those specific energy is that a flow or a stream of flow contains when a stream of flow comes in to a control volume for example in this room if stream of air comes in to it carry some mass similarly it carries some energy for example you have very much familiar with the kinetic energy it comes with some velocity v so it also brings a kinetic energy that is the rate of kinetic energy rate of mass flowing to $v^2/ 2$.

Similarly other forms of energy are there that is inter molecule energy u that is e is in terms of specific value I am telling the specific inter molecule of energy by what should apply temperature so any substance at any temperature has got some inter molecule energy which is the result of the kinetic energy of the molecule from the molecular theory. So this is the inter molecular energy plus the flow work already you are come across this term the flow work that means a stream coming has got some energy by what should does work on the neighboring layer one layer of this stream of flow does work on the neighboring layer and that work is known as flow work and that is in some form of energy is inherent to within the stream at a particular cross section by what should ands which it can do work on the neighboring cross section to make its flow through.

This has been already discussed and sometimes this we tell as pressure energy then it will lose term in fluid mechanic where p is the pressure of this stream of flow and v is he specific volume plus the kinetic energy v^2 / 2 and the potential energy all are per unit mass. So therefore this specific energy carried by a flow of stream is given by this specific internal energy specific flow work specific kinetic energy that is per unit mass plus specific potential energy. With this thing in mind we can replace this in terms of this and quick and write that.

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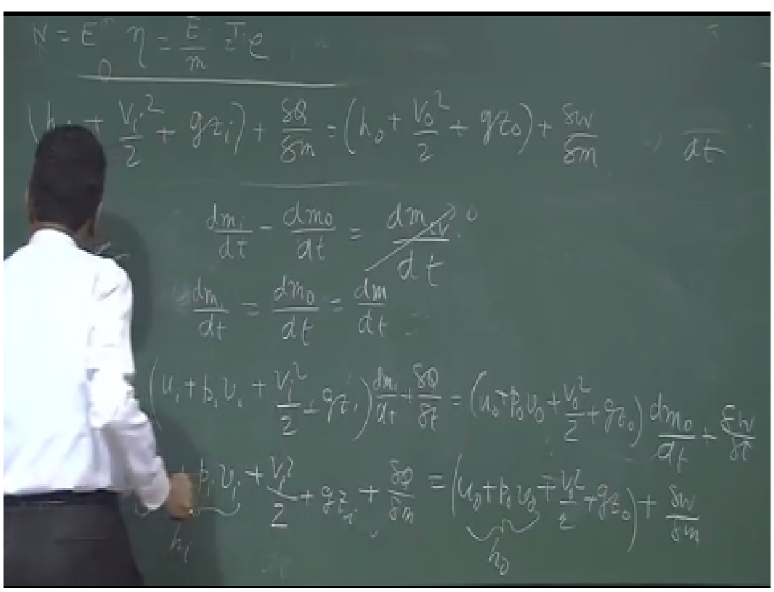

∂Ecv /∂t = e_i is u_i + corresponding quantity at the inlet plus Vi_2 / 2 + gzi okay + δ q /∂_t –u0 + e0 +p_0v0+ v_0^2/2 + gz0 okay into d_{m0} d_t this is this -+∂Q/∂t so this is the general form of the conservation of energy equation and apply to the volume or a open system so this is the general equation applied to a control volume the general energy equation that law upon the energy apply to a control volume or open systems.

Now this is the $dm/dt+\partial Q/\partial t$ so this part is the inflow energy rte of inflow energy rate of heat coming into the control volume rate of outflow energy okay and the work out from the control volume that means this is the control volume that means this is the control volume if you got this is the inflow energy coming in so this is the outflow energy going out and we consider that $+\partial Q/\partial t$ is the rate at which heat is given and rate at which one so it is general energy equation.

Now at some condition study state of the control volume now before that I write that dm/dt that inflow rate- the outflow rate this is the conservation of mass this also will be like this dm_{cv}/dt that means that the rate of mass inflow- rte of mass outflow will be the rate of change will be the mass control system so this is the typical continue equation the conservation of within the control systems.

Now in case when dmi/dt is equal to that means this is 0 that means there is no mass accumulation in the control volume in fact when the control volume operates in a steady state the all property remains same that means the net energy outflow will be 0 energy inflow and energy outflow not only inflow outflow the total energy taken by the control volume and the total energy giving by the control volume will be same the energy will be same.

And also if the mass trucks at inflow and outflow remains same there will be no mass struck increase in the control volume if in this case this equation can be written as in that case there will be no change of energy within the control volume if we consider that is the operation of the control volume when there will be no change of energy with the respective time of control volume.

And no change of mss with that respective time in the control volume then this equation can be written in simple way like this then we can write $U_i+P_i\ V_i+V1^2/2+gz_1*dmi/dt\ +\partial Q/\partial t=U+P_o\ V_o+0^2/2+gz_0*dmi/dt\ +-+\partial Q/\partial t$ which means that the total energy taken by the control volume consisting of the flow energy coming in plus the heat coming in, in the rate basis equal to the rate of energy living the control volume.

This is energy leaving as a suitable mass flow out and the work out so therefore this gives the clear concept that the study states the total energy gain by the control volume or rate of total energy gain by the control volume equals to that rate of total energy leaving the control volume so this si the special case when study state is the all property remains constant that energy and the mass.

And in this case it is usual to write everything in the form of unit mass in a sense that if we divided by dmi/dmo this re the equal dmi/dt and let this is dmi/dt then if we divide again the entire equation by dm/dt then you can get this expression $Ui+Pi\ Vi+Vi^2/2+gzi$ then this will be the heat transfer per unit mass is equal to U0+P0 V0+P02/2+gz0 okay+∂Q/∂m this is per unit it is use well to write per unit mass based in steady flow process. Then now you recall this U+Pv is the enthalpy age so this will be enthalpy at inflow condition and this is the enthalpy at out flow condition

So therefore we can write in short that we can write in short that now we can write in short this $hi + V_i^2/2 + gzi + \delta q/\delta m$ = here $ho + V_o^2$ / gz0 + δw/ δm, so this the version of the general energy equation for a control volume system or open system at steady state. From the general energy equation at steady state that means it is the energy equation or the conservation of energy applied to control volume system or open system at steady state.

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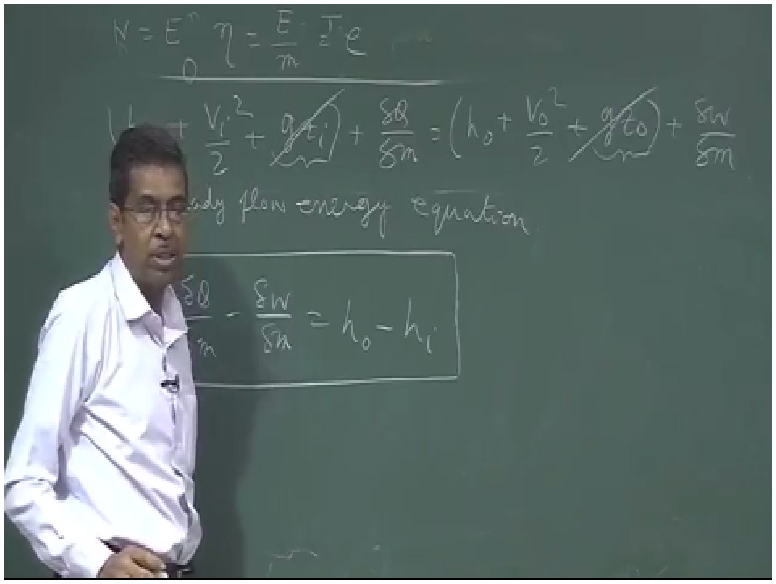

This is known as steady flow energy equation, okay this is steady flow energy equation, now usually in many cases this change in kinetic energy are neglected, this is not much with respect to the change in enthalpy and the heat and work transfer and change in the collusion energy is obvious is neglected because change in pollution is energy is very small because one cannot have an engineering apparatus which is huge height.

So there is the substantial change in the energy between the inflow and out flow, so this will never happen so that the change of kinetic energy and potential energy in many cases are negligible compared to the enthalpy changes and work and heat interaction. Of course there are certain cases where kinetic energy will not be neglected, that are the case of nusselt where the thermal energy which is the enthalpy rather you can tell being is converted to the thermal energy is converted to the kinetic energy.

So the outflow kinetic energy much more than the inflow but except those cases we can write for a special case therefore $\delta q/\delta m$ - $\delta w/\delta m$ is h0 – hi, so where the kinetic energy changes and potential energy changes and neglected this energy equations can be simplified to this. Then you see that this enthalpy whose difference from outlet surface, outflow surface and inflow surface give the work and heat interaction. The difference between the heat added and the work done.

In many devices there is only work interactions for example turbine and compressor which are insulated so that the heat transfer is negligible, so either it gives work in case of turbine or it takes work, so therefore it is the only the work interaction in that case which is equal to h0 – hi.

Similarly there are certain devices like heat exchanger δq/δm is there. Therefore we can get the heat expression for heat added as this h0 – hi, so understand.

So therefore we see that this give a physically interpretation and how much useful the significance of enthalpy that means in the open system it is the difference of the enthalpy which gives us the value the work and heat interaction for the control, with the surrounding it is simply the difference of the enthalpy, provided the kinetic energy changes and potential energy is neglected only the enthalpy differs.

Otherwise we have to take care where there is the substantial change of kinetic energy this and this but potential energy changes are always neglected, this does not come into the picture okay, so today upto this, that means we have considered the application of the principle of the conservation of energy to an open system or a control volume by evoking the Renaults transport theorem. And finally we arrived at this steady flow energy equation which is the application conservation of energy to the control volume steady.

This is the special case from the general energy equation which I have written earlier and in a very simple case where the kinetic energy and potential energy changes neglected, this gives us the heat and work interaction are given by the δq/δm - δw/δm simply by the enthalpy difference from the outflow surface and that in the inflow surface okay. So one thing to be remembered that potential energy changes are always neglected but kinetic energy are usually neglected except for a special cases of nusselt and diffusers, where kinetic energy is been converted in diffusers to thermal energy and nusselt thermal energy into kinetic energy okay, thank you for today, thank you.