Heat and Mass Transfer
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Lecture No. 02

When we stopped last time, at the end of the previous lecture, you will recall that i was describing to you a liquid flat plate collector. I had shown you a photograph of a flat plate collector array used for heating water, shown you a pictorial view of a flat plate collector and then I was just drawing a cross-section of a flat plate collector when we stopped. Here is that cross section which I had drawn last time.

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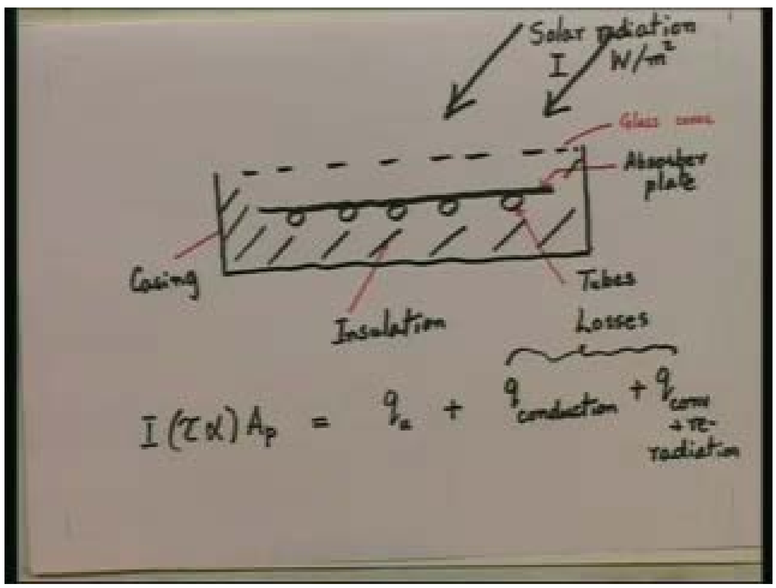

The components which I had described to you last time are clearly seen in this cross section across a flat plate collector. The components are: at the top, we have the at the top we have the glazing or the glass cover, then the absorber plate which absorbs the heat from the sun, the absorber plate, then the tubes which are fixed below the absorber plate- flow tubes which are fixed below the absorber plate - through which the water to be heated flows. Below that we have insulation, this is the insulation, to prevent or to fix or cut down loss of heat by conduction from the bottom and finally all these components are held together in the casing which is this: the casing made of metallic sheet which holds together this hole - all the components of this device. These are the main component of this, of a flat plate collector.

Now, my purpose in describing flat plate collector was to show how different modes of heat transfer occur in this device. So, let us starts with the input first. What is the input? The input is solar radiation falling on this device. Solar radiation falls - these are the arrows showing the solar radiation falling on this device - and this solar radiation which is falling let us, say the flux is I, so many watts per square meter. Typically, solar radiation is short wavelength radiation ranging from about .3 to 1 micron. Now, this radiation falls and after falling on the glass cover, it will, most of it will be transmitted through the glass cover and then hit the absorber plate. At the absorber plate again, which usually has a black coating on it, most of this radiation will be absorbed on the absorber plate as heat and will heat up the absorber plate. So, if I were to write what is happening to it, to this flux which is falling: I will say I is the flux falling, the radiative flux falling. Tau into alpha is the amount, tau is the amount that is transmitted through the glass cover which is usually a number like .9, .95; alpha is the fraction that is absorbed in the plate which also is a number close to 1, around .95, between .95 and 1. So, tau alpha represents the heat flux which is absorbed in the absorber plate - is transmitted through the glass cover and absorbed in the absorber plate. And then if I multiply this by the projected area of the absorber plate Ap, I have this as the input energy. So many watts of energy is absorbed in the absorber plate.

Now, where does it go? The first place where this heat goes which is absorbed in the absorber plate is - it falls on the absorber plate, heats up the absorber plate and then flows by convection as useful heat gain into the water which is flowing through these tubes. So, the first part is the useful heat gain which I will call as q_u which is the heat gained by the water flowing through and this is what the flat plate collector is there for. But in addition, we lose some energy. We lose some energy by conduction from the bottom inspite having insulation so we will say plus heat loss from the bottom and the sides by conduction. And we also lose some heat back from the top because there is a glass cover so we lose some heat back from the top by convection and re-radiation. So plus losses due to convection and re-radiation from the top. This is heat balance on the absorber plate. So, the second and the third term represent the losses and the first term represents the useful heat gain.

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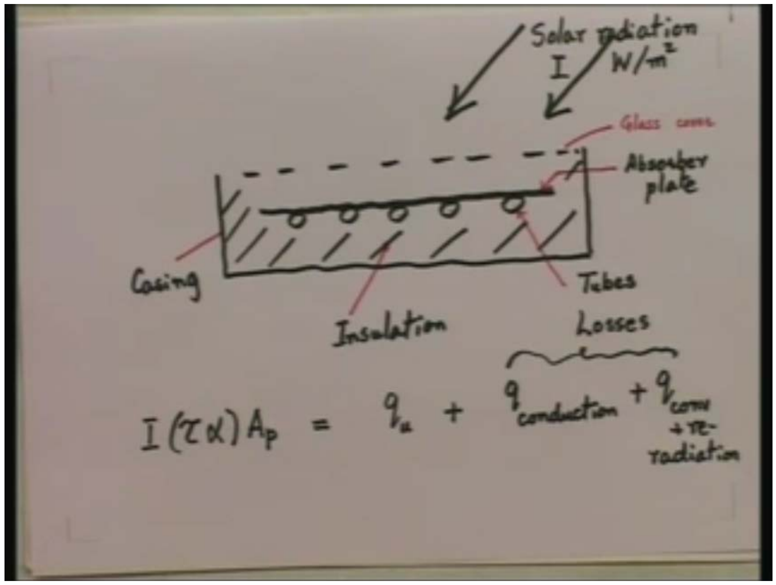

So, now you see all the modes operating here input radiation, input energy is radiation. The useful heat gain is heat gained by convection; the losses are by conduction through the insulation and also by convention and re-radiation from the top that is going out to the surroundings from the top. So here is a device in which all the modes occurs and if you want to analyze such a collector you will have to have equations to calculate each of these quantities. Then only will you be able to obtain the useful heat gain and the efficiency of such a collector. And that's why we are studying heat transfer. As you go along, you will be in a position to do such calculations. Now, I think it is time to move on to another topic and that is to put down the laws of heat transfer. So now we start speaking about the laws of heat transfer.

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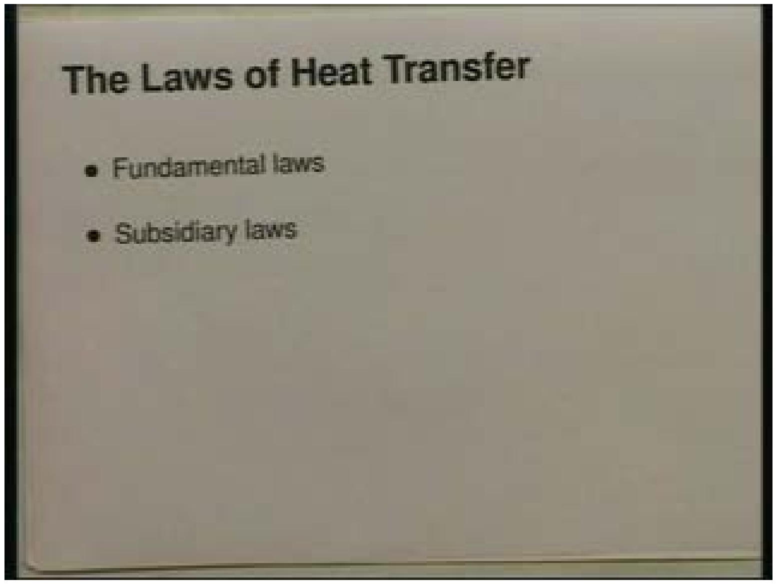

As you can see, we have two types of laws - fundamental laws and subsidiary laws. Fundamental laws are laws which from the basis of the subject and which must always be satisfied whenever we are solving for any situation in heat transfer. Every subject that you study in engineering science like heat transfer or thermodynamics or fluid mechanics or solid mechanics rests on certain fundamental laws. You have got to always satisfy the fundamental laws. And subsidiary laws on the other hand are laws which might be empirical in nature that is based on experimental evidence. They may be partly derivable from fundamental laws and partly based on experimental evidence and so on. So, subsidiary laws are upto us. We use those subsidiary laws which are useful to us for the development of a particular situation but fundamental laws have always got to be satisfied.

Now, what is a fundamental law? A fundamental law is one whose validity rests on the fact that it has never been disproved. It is a negative way of stating it but that is really the heart of the matter. A fundamental law is valid because it has never been disproved by any experimental evidence that we have before us and for the subject of heat transfer, the fundamental laws which we will have to satisfy are the following as seen here.

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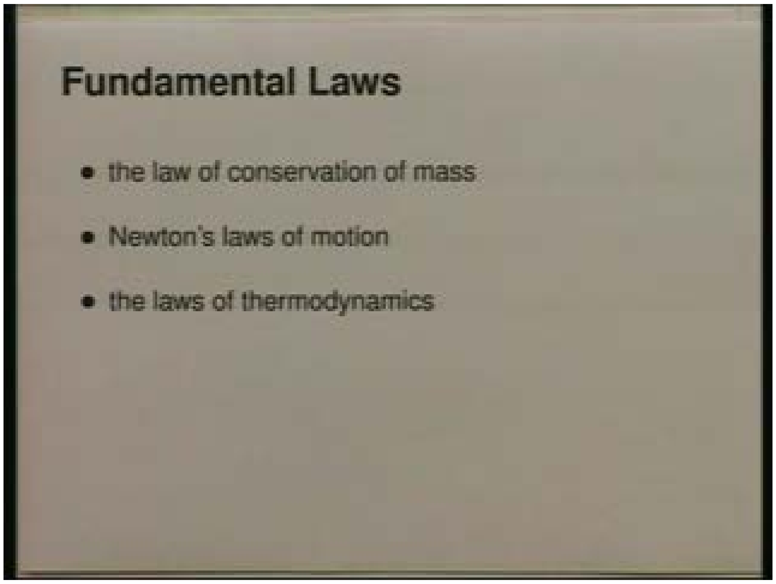

The fundamental laws that we will have to satisfy are - the law of conservation of mass, Newton's laws of motion and the laws of thermodynamics - these are our fundamental laws. We always got to satisfy these regardless whatever situation we are solving for during the course of this teaching, this subject or doing any problem in this subject. The subsidiary laws with which we will be dealing are the following; with which we will be mainly dealing are the following.

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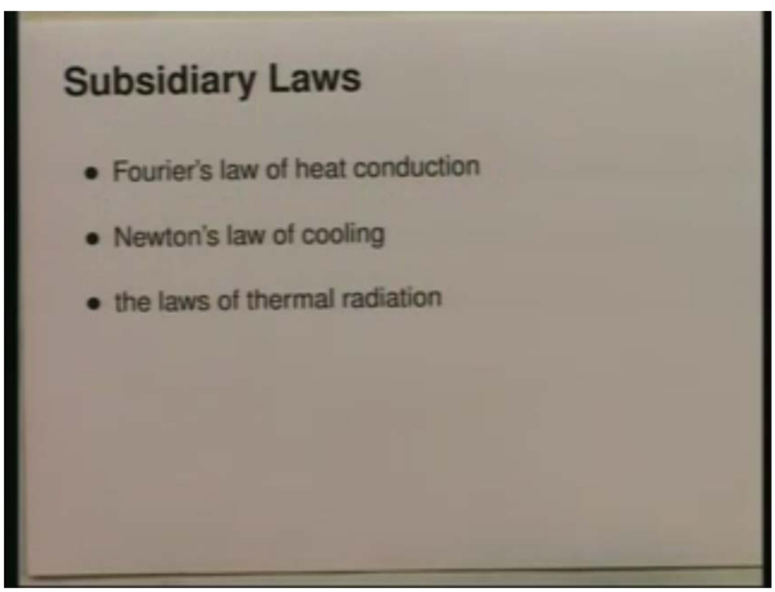

We will be having Fourier laws of heat conduction - using it wherever necessary. We will be using Newton's law of cooling and we will be using the laws of thermal radiation. We may use some other subsidiary laws also from time to time. Like for instance, we may need an equation of state for describing a gas in which case we may use the perfect gas law or we may need some other equation or state to describe a gas or a liquid in which we may use that equation and so on. So, subsidiary laws - the use of subsidiary laws- depends upon our convenience but fundamental laws have always got to be satisfied. We will take these up now one by one.

Now, before that however, before i start describing the laws one by one - fundamental and subsidiary - let me introduce the concept of what we mean by a closed system and what we mean by an open system. This is an important concept and you have probably done it already while studying fluid mechanics and thermodynamics but it is good to repeat it.

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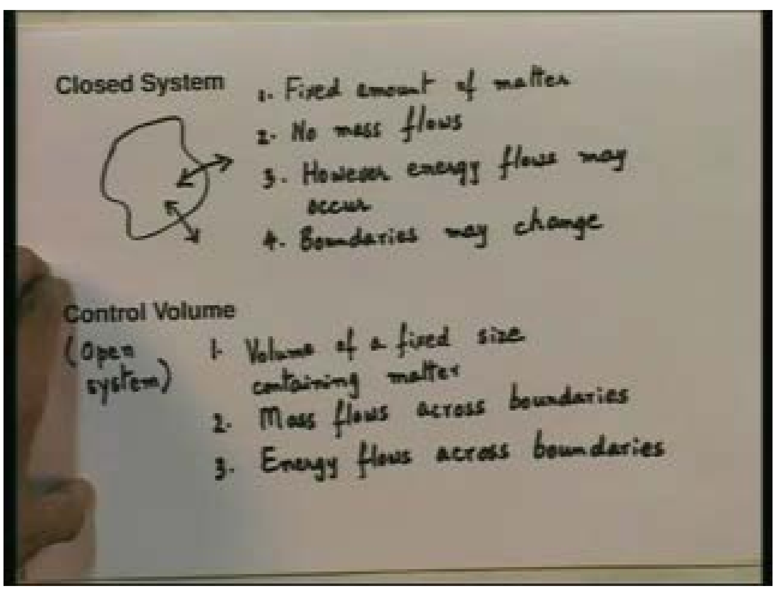

A closed system is one which has a fixed amount of matter. Number 1 - a closed system is one which has a fixed amount of matter - that matter may be a solid liquid or a gas. It doesn't matter what we are referring to but a fixed amount, a fixed mass of matter.

Across the boundaries of the close system, let us say this is my closed system and - at some instant - these are the boundaries. This is the matter within it. Across the boundaries of this closed system - in or out - there is no mass flow. No mass flows across the boundaries of the system. However, across the boundaries of the system, there may be energy flows. However energy flows may occur. These energy flows - energy interactions with the surroundings - may be in the form of heat interactions or work interaction. It doesn’t matter. But energy flow can occur across the boundaries of the close system and finally the fourth thing to remember about a closed system is the boundaries may change with time as interactions take place. However the amount of mass, remember, does not change. That means that at some instance, this is the boundary that I am drawing; at some other instance the boundary may have changed, the shape, the size may have changed but the amount of mass inside it will not have changed. These are the characteristics of close system.

On the other hand, a control volume is one in which the characteristics are number 1 - the volume which we are talking about, the volume is of a fixed size, containing matter – that is a control volume. Number 2 - mass flows may occur across the boundaries, mass flows across boundaries of the control volume. And number 3 energy flows also occur across the boundaries. That is what we mean by control volume.

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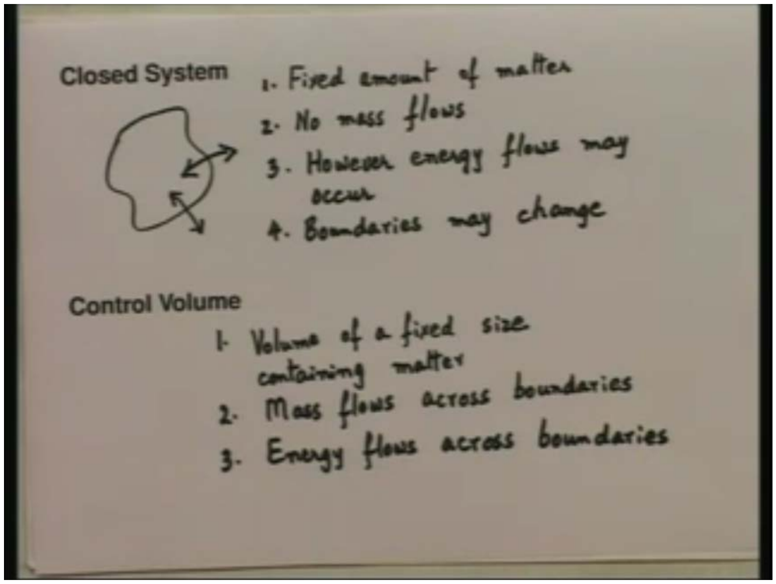

A control volume - some volume of fixed size in space containing matter, that matter may be a solid liquid or a gas. Across the boundaries of the control volume, mass may flow I or out, energy may flow in or out. That energy may be in the form of work or heat. Control volume is also referred to many times as an open system. Both the terminologies are used. A control volume is also often referred to as an open system. So, these are two concepts and when we talk about our laws now - the fundamental laws - we will put down statements of these laws both for a closed system as well as a control volume.

You will see straight away that, generally, when we are talking about solids doing problems of heat conduction in solids, we will look for the closed system approach. That means a system having a fixed amount of matter whereas when we do problems associated with fluids, liquids or gases that is liquids or gases we will prefer to adopt a control volume approach. So, I will now go to the fundamental laws and we will state the fundamental laws using both approaches - the close system approach as well as the control volume approach. Now let us take up the first law - the first law as I said, first fundamental law was the law of conservation of mass.

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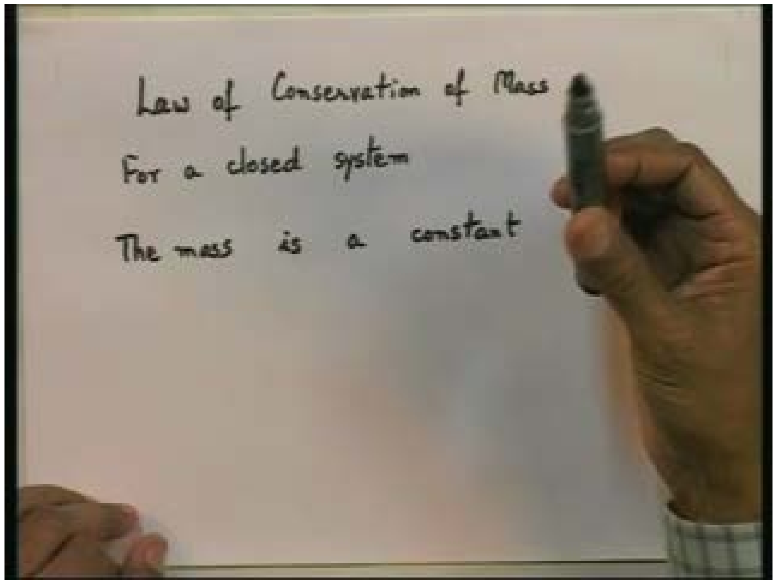

Now what is the statement of the law of conservation of mass for a closed system? Law of conservation of mass for a closed system: for a closed system, the law of conservation of mass simply says the mass of a closed system of fixed identity having matter of fixed identity is the same, is a constant. It is almost like making a trivial statement, a trivial and an obvious statement. All that we say is the mass of a closed system, the mass is a constant.

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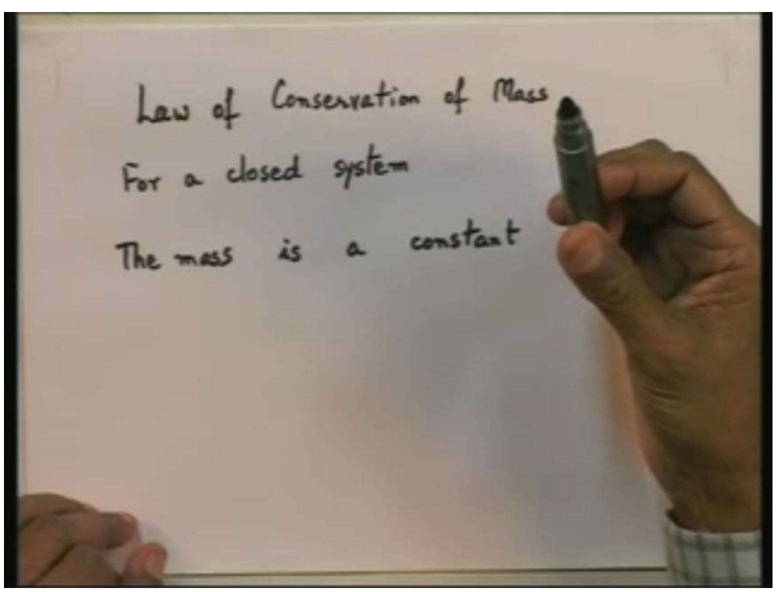

Let us say as an example, this pen that I have in my hand, let us say this is the closed system containing whatever mass it does. All I am saying is its mass is a constant. So, making a trivial statement. A statement that is always trivially satisfied but the moment I go to a control volume approach, I shall have to derive an equation corresponding to the law of conservation of mass. I will have to put down such an equation. No more will it be a just a trivial statement like what we obtain with the closed system approach. Now, what would be the statement for the control volume approach? First of all, before doing that let us look at a fluid flowing through a control volume

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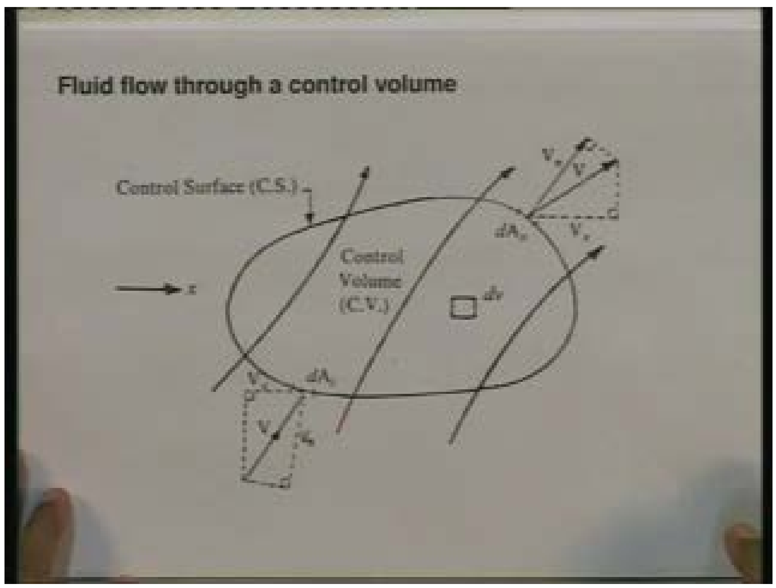

and put down some nomenclature, get familiar with it and then I will go to the statement of the law of conservation for mass. I am showing you here a control volume through which a fluid is flowing. These are the stream lines of the flow. So, this is the control volume, the surface of this is called control surface. Mind you, this could be a three dimensional figure. On the paper it may look to two dimensional. Arbitrarily, I have called some direction the X direction. Now, wherever the flow enters, the area through which it enters, the elementary areas through it enters we will call as dA_i and wherever flow leaves we will use the nomenclature dA_o. The V is the velocity vector entering here, V is the velocity vector leaving here and V_n is the normal component of the velocity vector, normal to the area dA_i or dA_o.

Now the convention we will adapt is: Vn is positive for flow inwards, Vn for dAo is positive for flow outwards. That is a convention. We could have a different convention- just a matter of a negative or positive sign. V_x and V_x shown here are the components of V in the x direction. Again I emphasize this could be a three dimensional situation. That means V_x and V_n need not be in the same, in this plane of the paper at all. dV is an elementary volume inside the control volume. So, if I add up all the dVs over the whole control volume, I get the volume of the control volume.

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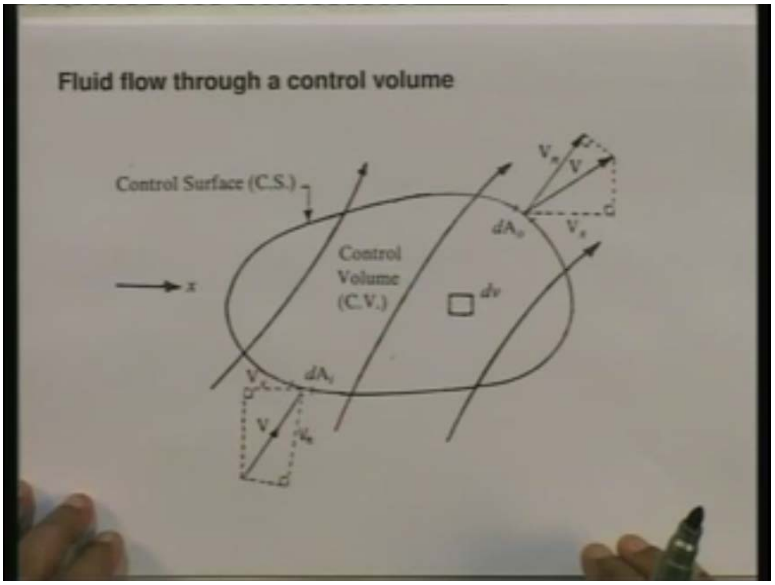

Now what would be the law, the statement of the law of conservation of mass? If I have flow through a control volume, intuitively I can see the statement is going to be the following. What will I get? I will get the following. I will say mass is flowing in; mass is flowing out. The rate at which mass flows in minus rate at which mass flows out must be equal to the rate of change of mass inside the control volume - that's an intuitive statement. You can prove it even rigorously if you want but that is the intuitive statement which seems to be acceptable. So that is the state, that is the equation I will need to satisfy if I am adapting a control volume approach. Let me repeat it - rate at which mass flows in into the control volume minus rate at which mass flows out of the control volume is equal to rate of change of mass inside the control volume. Now, let us put it down in symbols using the symbols of the figure which I just showed. What will I get in symbols? This is the equation that I will get.

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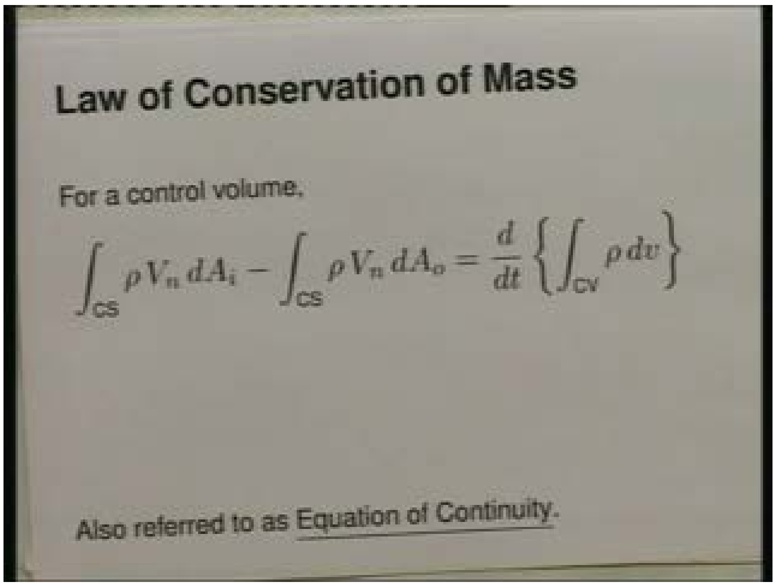

The statement that I will get in symbols is rate at which mass flows in; now consider an area dA_i, V_n into dA_i, rho into V_n into dA_i is the number of kilograms per second that flow in through the area dA_i. If I want all the mass flowing in, the sum of all flowing into all the dA_is, I integrate this expression over the control surface wherever dA_i exists. Similarly, I want the mass flowing out, the rate at which mass flows out. So, rho V_n dA_o so many kilograms per second flow out through dA_o. I want the rate at which mass flows out all over the control surface. Integrate again over the control surface wherever dA_o exists.

So, the first term minus the second term - rate at which mass flows in minus rate at which mass flows out is equal to rate of change of mass inside the control volume. The expression within the brackets is the mass in the control volume. Take an elementary area dv, multiply by rho, I get the mass of fluid in the volume dv. I want the mass of fluid in the whole control volume. So, integrate this expression over the whole control volume - volume integral. I get the mass inside the whole control volume. Take d dt of that, I get the rate of change of that mass inside the control volume. So this in symbolic terms is the expression for the law of conservation of mass, the most general expression for the law of conservation of mass for which we will have to satisfy. This is also referred to often as the equation of continuity and it is an important equation which we need to satisfy at all time. Now, the flow itself which we have, the types of fluid flow that we have, can be classified in various ways as shown in the next transference.

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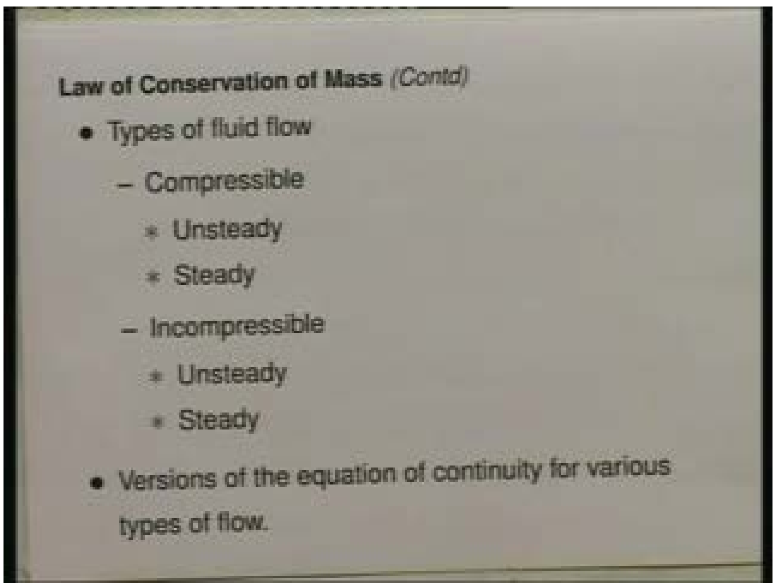

We can have a compressible flow; we can have an incompressible flow. A compressible flow is one in which the density may vary over the volume or the space in which we are interested and incompressible flow is one in which the density does not vary. The flow may be steady or unsteady. What do we mean by a steady flow? A steady flows means the parameters of interest to us do not change with respect to time. What are the parameters of interest to us? If it is a fluid-flow heat transfer problem, a fluid say water flowing in a pipe, typically the parameters of interest to us are the pressure of the water, the velocity of the water; if it's a three dimensional flow, all the components of velocity-

V_x V_y V_z - three velocity components and the temperature of the water. So, typically the parameters of interest would be pressure, velocity and temperature. If these do not change with respect to time, it would be what we call as a steady flow; if they change, if any one of them changes with respect to time it becomes an unsteady flow. So, we have four types really - compressible and incompressible and each of them can be steady or unsteady.

Now, we can write down simplified versions of the equation of continuity for these four types of flow that I mentioned. Let us go back to the equation that we had a moment ago. I am going back again to that equation. Now suppose this was our general equation. So, this equation which I have put down, shown you earlier, is for a compressible unsteady flow. That is the most general kind of flow. The expression that we put down is for a compressible unsteady flow. Suppose I say it is a compressible flow but it is a steady flow. Then what will happen in that event? The moment I say it is a compressible flow but a steady flow, the expression on the right hand side which stands for the rate of change of mass inside the control volume - this right hand side will be automatically zero. And so this will be zero and we will have rate at which mass enters is equal to rate at which mass leaves the control volume. This term is equal to this term.

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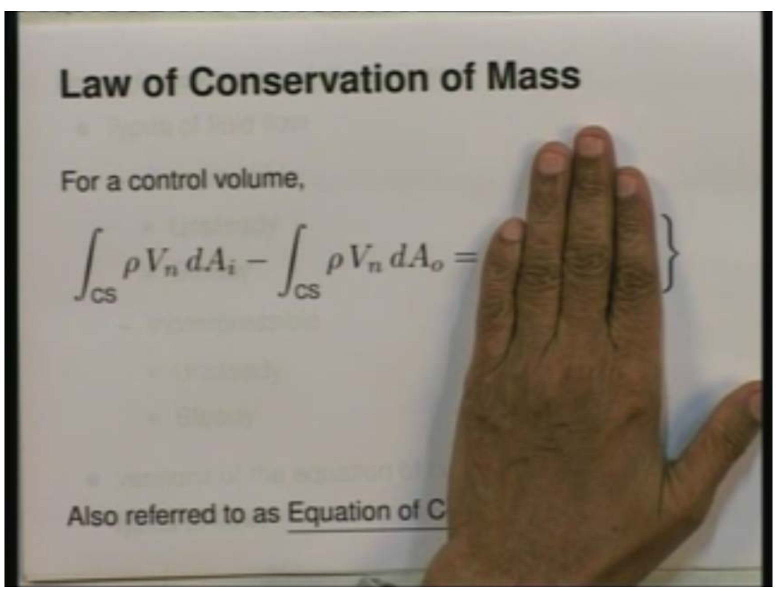

That will be the law of conservation of mass. Now suppose I say the flow is incompressible. The moment I say the flow is incompressible, note the following: the rho in each term can be brought outside the integral, this rho here for the flow entering can come outside, this rho can come outside. This rho stands, rho into dv stands for the mass inside the control volume. This is a fixed quantity and if this is a fixed quantity then it cannot have d dt. So the moment I say the flow is incompressible, the right hand side will be zero and in the left hand side the rho will come outside the integral sign. So the simplification that I will get if the flow is incompressible is: if the flow is incompressible, let me write that down.

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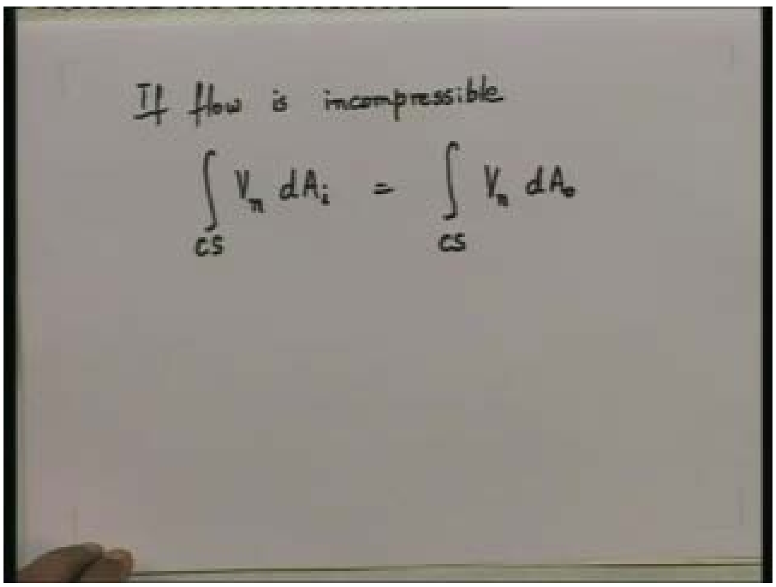

If flow is incompressible, the expression I am going to get is integral over the control surface V_n dA_i is equal to the integral over the control surface V_n dA_o. That is the simple form of the law of conservation of mass that I am going to get and mind you, it doesn’t matter whether the flow is unsteady or steady. So, let me add that. If the flow is incompressible, unsteady or steady, it doesn’t matter. This is the simple form of the law of conservation of mass which I need to satisfy. This is the simple equation that I get. So, we have a general form for a compressible unsteady flow; we have a slightly simpler form for a compressible steady flow and this is a still simpler form which we need to satisfy for an incompressible flow - steady or unsteady.

We may have, there are situations also in which we make one more idealization in flows and that is we introduce the concept of what is called as one dimensional fluid flow. The one dimensional flow is one in which we idealize the flow and say variations in the parameters of interest to us – velocity, pressure, etcetera - are essentially occurring only in one direction. Let us say it is a pipe flow. A pipe with may be a varying cross-section and the flow is flowing in that pipe and variations are essentially occurring only in the flow direction. The variations in the cross section are negligible.

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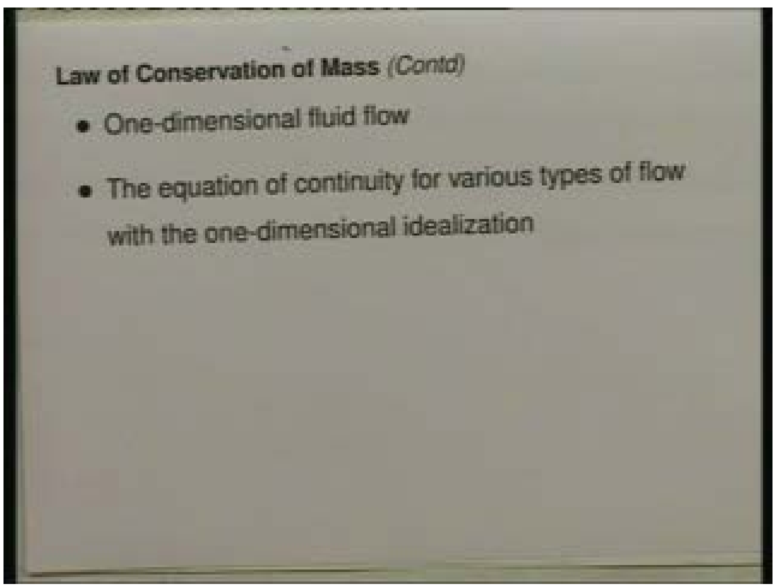

Then we do, we call that a one dimensional idealization and one would get simpler forms of the equation of continuity for the one dimensional idealization. For instance let me just that down. If I make the one dimensional idealization what will I get?

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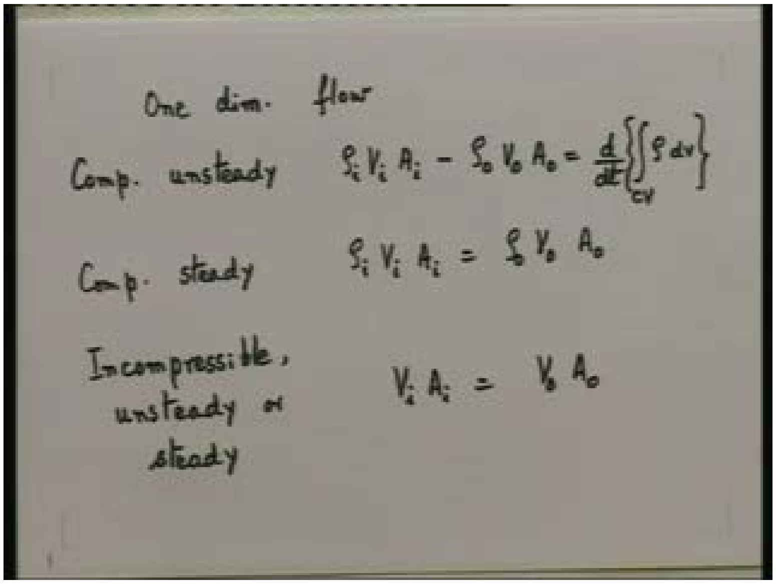

If it is a one dimensional flow, if it is compressible but unsteady, the equation which I am going to get would be - let me put it down and then explain what I am putting down. I will get rho$_i$ V_i A_i minus rho$_o$ V_o A_o is equal to d dt of the integral over the control volume rho dv. Now, compare this expression with the earlier expression that we have. The right hand side is the same what we had earlier but on the left hand side we do not have any integral over the control surface because there is no variation across any of the dA$_{is}$ - at any dA$_i$ - wherever flow is entering it is the same value of velocity with a one dimensional idealization. So, wherever the flow is entering, at that point we say we have got one value of velocity, one value of density. So, the flow entering rate at which flow enters, mass enters will be rho$_i$ Vi Ai; rate at which mass leaves rho$_o$ V_o A_o. So, that is the simpler form.

If it is compressible and steady, you can see straight away that this, I will simply get the one, with the one dimensional idealization, we will simply get rho$_i$ V_i A_i is equal to rho$_o$ V_o A_o and if it's incompressible, if the flow is incompressible, then with the one dimensional idealization. If the flow is incompressible - steady or unsteady it doesn't matter which is, what the flow is steady, unsteady or steady. Then, the statement will simply be - since rho is a constant - we simply get V_i A_i is equal to V_o A_o. So, with the one dimensional idealization, depending on the flow, we have these equations to be satisfied. So we have put down various versions of the law of conservation of mass or equation of continuity as it is called and depending on the problem, one dimensional or multi dimensional, compressible or incompressible flow, steady or unsteady flow, there will be an appropriate equation which must be satisfied. That is the essential point to note.

Now let us move on to the next law, the next set of laws rather. I have Newton's laws of motion. Now, all of you know there are three laws of motion. But it is really the second that is of concern to us because the first law simply says - if there is no force is no acceleration. The first law is in fact integrated into the statement of the second law. We don't really need to satisfy the first law or write down an equation for it. The third law simply says to every action there is an opposite reaction. So, wherever there is a force acting on a body in one direction, the body exerts the same force in the reverse direction on its surroundings, that is what we are saying. It is the second law that yields a quantitative statement. So it is the second law with which we are concerned. Now first for a closed system the second law statement is what I have put down here.

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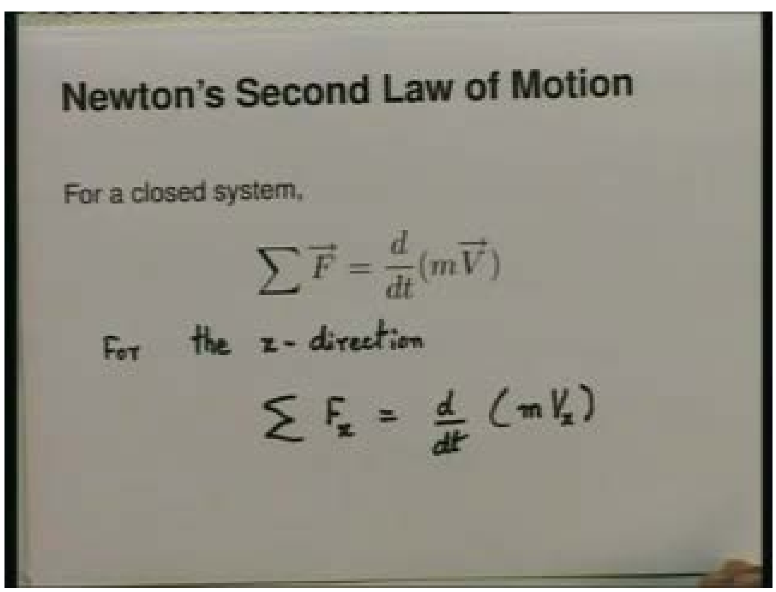

What does it simply say? It says summation of the forces acting on the closed system equal to rate of change of momentum of that closed system. A closed system may be a solid body for instance. This is the statement which all of you have seen. It is, I have put it in vector form so really there are three equations here if I am dealing with a three dimensional situation typically for instance. Suppose, I want to put down for one direction say x direction then I will say for the x direction - what would be statement? For the x direction, the statement would be summation of all the forces acting on the closed system in the x direction equal to rate of change of the x direction momentum of the closed system, of the matter inside the closed system. So, that would be the statement for the x direction. I could put down a similar statement for the y or the z direction or if I am dealing with some other coordinate system like a cylindrical coordinate system, I could put down equations for $r_{theta}z$ and so on. So, it is Newton's second law that we are concerned with and we would need to satisfy this Newton's second law at all times.

Now, I have put down the statement for a closed system; let us look at the statement for a control volume. For a control volume, the statement of Newton's second law would be the following - suppose I have some control volume and let me again show you the control volume that we had a moment ago. For a control volume, here is flow. The statement of Newton's second law of motion for such a control volume would be - let me say it in words first before I put it in symbolic terms - it would be net x direction forces exerted by the surroundings on the fluid inside the control volume. I am giving the equation in one direction, say the x direction, so I am saying net x direction forces exhorted by the surroundings - this may be fluid in the surroundings or whatever it is- exhorted by the surroundings on the fluid inside the control volume is equal to rate of change of x direction momentum of the fluid inside the control volume plus rate at which x direction momentum leaves minus rate at which x direction momentum enters.

So, notice now, the moment I go to a control volume approach, I have two extra terms. The first two terms x direction force is acting, is the same as for a closed system. The second term - rate of change of x direction momentum inside the control volume - is the same as for a closed system. But the two extra terms come in because there is flow going in and there is flow going out. So, we say plus rate at which x direction momentum leaves minus rate at which x direction momentum enters the control volume. Now let us, that statement I have given you in words. Let me now give that statement in symbols. What we would get would be the following.

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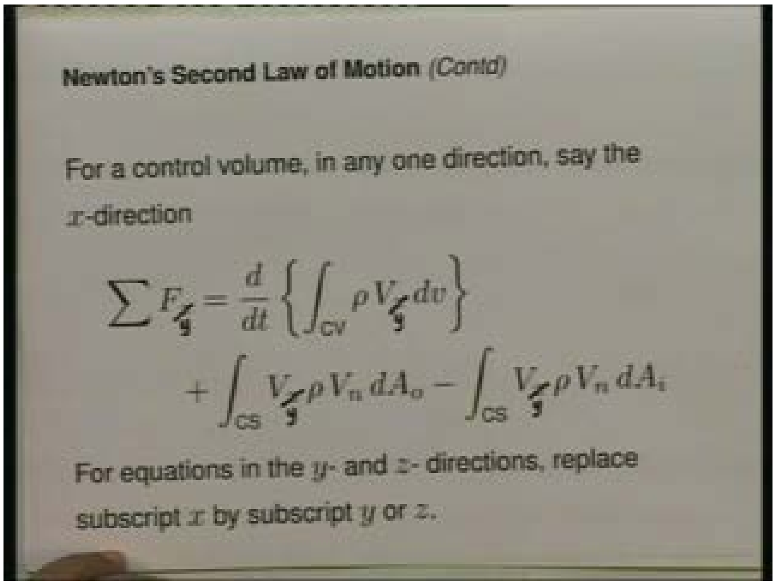

For a control volume in any one direction, say the x direction, the statement of Newton's second law would be summation F_x - F_x are all the forces exerted on this, on the fluid inside the control volume by the surroundings and their x components mind you. So, therefore summation Fx equal to rate of change d dt of - now notice if I want the x direction momentum inside the control volume, take an elementary area dv. What is its mass rho into dv? What is its x direction momentum? rho into d_v into V_x . I want all the x direction momentum inside so I take integral over the control volume. So, I get all the x direction momentum inside the control volume and rate of change of that plus rate at which x direction momentum leaves.

So now, let us go one term at a time here. dA_o ; rho into V_n into dA_o is so many kilograms per second of fluid leaving through the area dA_o. If I multiply it by Vx, I get the x direction momentum leaving through $dA_{o. I}$ integrate over the whole control surface where dA_o exists, I get all the x direction momentum leaving through the control surface. And minus all the x direction momentum entering through the control surface through all the dA_is. So, these are the two extra terms which come in - momentum entering, momentum leaving at the control surface. Now if I want the y direction equation, what will I do? Wherever there is an x, I will have to replace by y. So, just to show you one of them, let us say this is the equation here. This x, if I want the y direction equation this x will be summation F_y this V_x will be V_y, this V_x will be V_y. The V_n stays the same mind you. The V_n is given by the mass flowing in and out. So the V_n is not going to change; all that is going into change is, wherever there is a V_x there is a V_y. And if I want the z direction equation, I need to substitute the subscript z wherever there is a subscript y. So these will be my three equations for the three directions. These are the statements of Newton's second law if I want to use the control volume approach.

Now, I talked about the forces exerted by the surroundings on the control volume but let me describe them a little. What are these forces?

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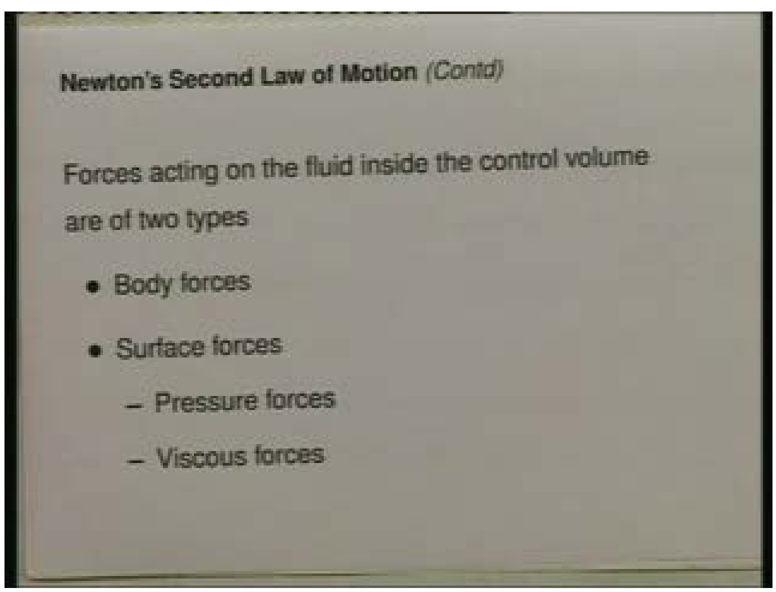

There are two types of forces that we are talking about here - body forces and surface forces. The body forces that we have acting are forces which are caused because of action at a distance. These are forces proportional to the mass of fluid in the control volume and they are caused by action at a distance, for instance, the force of gravity. The force of gravity which acts on the fluid inside the control volume is proportional to volume of fluid inside the control volume and it acts because gravity acts from a distance. In this case if its x direction equation, I will need its component in that x direction.

Surface forces on the other hand are sources acting at surface of the control volume. So, let us just look at that for a moment. Suppose for instance, this is a surface; let me just draw a control surface.

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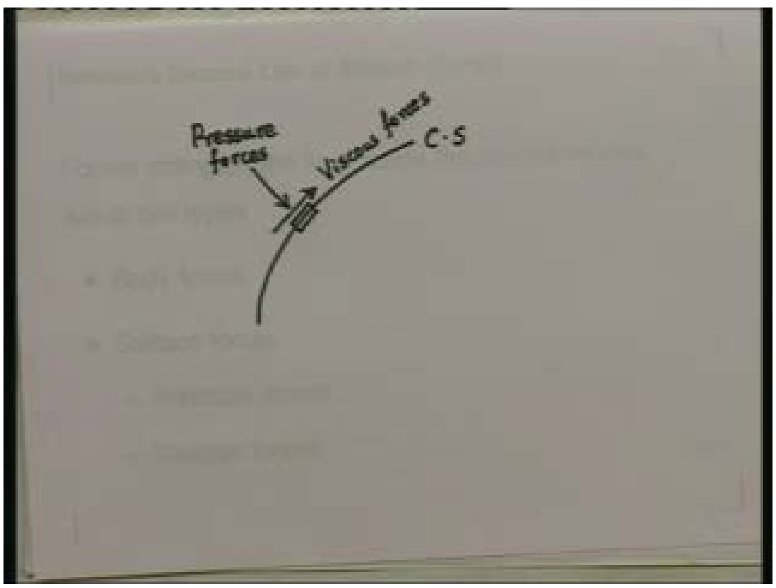

Suppose for instance, this is a control surface and let us take some elementary area on this control surface - it is a dA_i or a dA_o ; doesn't matter. Now on this elementary surface, the forces exerted by the surroundings on the fluid inside the control - volume there would be pressure forces and there would viscous forces. These are the two surface forces acting - pressure forces and viscous forces. So, when we say x direction force is acting what we mean is the components of this pressure and viscous forces in the x direction acting on this dA_i and summed up over all the dA_i which comprise the control surface of this control volume. That is what we mean by the forces acting, exerted by the surroundings; surface forces exerted by the surroundings on the fluid inside the control volume.

Now, just like the earlier case for the law of conservation of mass, we can have some simpler versions also of this statement that we put down. The general statement that we put down earlier for the x direction was for a compressible and steady flow, a general situation. Suppose the flow is steady; in that case if you go back to that equation. Let me just for a moment show that. If you go back to that equation, in that case what is going to happen is simply the following.

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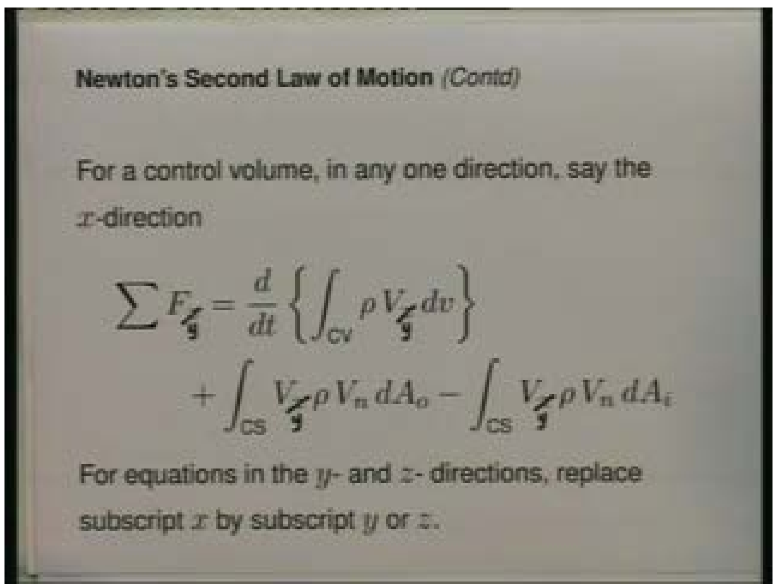

The first term on the right hand side which stands for the rate of change of x direction momentum inside the control volume - this term is going to be identically zero if the flow is steady. If the flow is incompressible, then the rho which is inside the integral here or inside the integral here can brought outside the integral sign. We need not consider it's variation while calculating these integrals so that, these are the simplifications that we will get if we are to have simpler version. Implications we will get if we are to have incompressible flows or steady flows. So appropriately, the equations can be simplified.

Now we move on to the third fundamental law. The third fundamental law that we are interested in is the first law of thermodynamics. Now earlier, I had said the laws of thermodynamics. So, I need to say first of all why we are only going to look at the first law. We have the first law and the second law. The first law is a statement of conservation of energy. The second law is a statement from which we define entropy and it is an inequality. So, in general, the second law will not give us an equality statement because we are not dealing with reversible situations but will give us an inequality situation and generally we will not be interested in it. It is not that we cannot write down the second law for a closed system or for a control volume but while we are studying heat transfer, atleast in this course, we are not likely to need it and therefore I am not going to put it down.

We are going to focus only on the first law. What is the statement of the first law? You have already done this so I am repeating what you know for a closed system.

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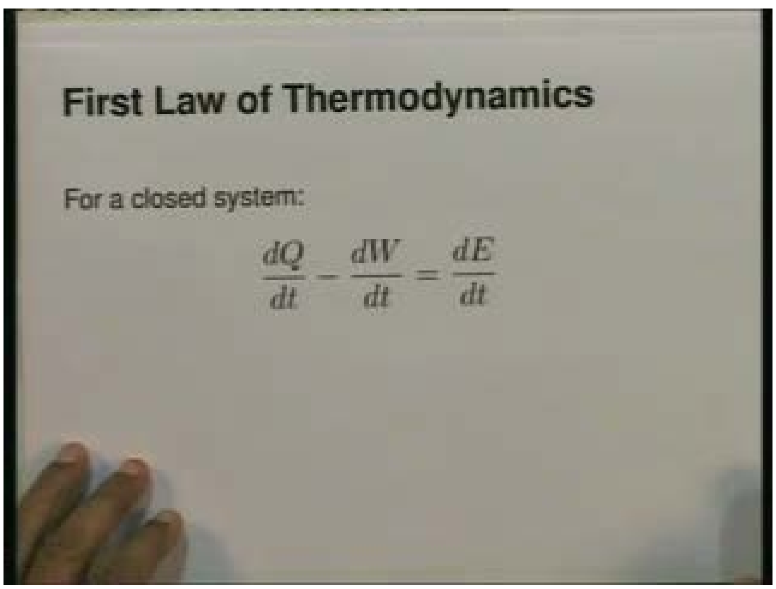

The first law says - the rate at which heat enters the system dQ dt minus the rate at which work is done by this system dW dt is equal to dE dt where E stands for the energy of the system. By energy we mean the energy associated with internal energy, the energy associated with kinetic energy and potential energy. Of course for our problems, it is the internal energy which is going to be the dominant one most of the times but in general E refers to the sum of, E the energy refers to the sum of internal energy - kinetic energy and potential energy. So, this is the statement for the first law for a closed system. We would be interested in the statement for a control volume. What would be our statement? Now let me again put it down for a control volume - first in words and then in symbols.

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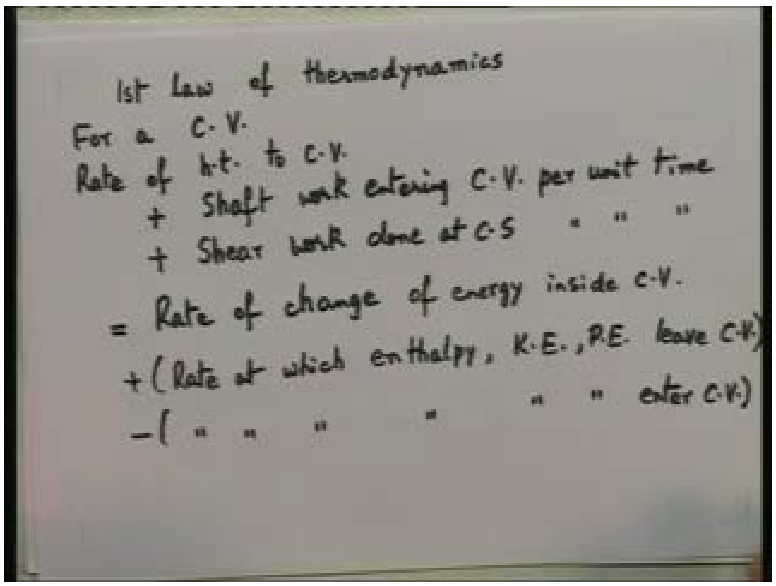

In words, the first law of thermodynamics for a control volume - the statement that we are going to get is first, rate of heat transfer rate ht to control volume plus the work done by the surroundings on the, entering into the control volume. Now we will break up the work as follows: We will say shaft work entering the control volume - suppose it's a finite control volume - there can be shaft work entering per unit time. Then there is work done by shear forces which I mentioned a moment ago plus shear work done at control surface per unit time plus you will say the pressure work but instead of writing the pressure work here, I am going to take it to the other side of the equation and I will tell where I will put it in later, just a moment later. Is equal to rate of change of energy inside control volume plus rate at which enthalpy, kinetic energy and potential energy leave the control volume minus rate at which the same quantities enter the control volume. This would be the statement in word.

Now, notice few things - the extra terms because of control volume approach are right here - rate at which enthalpy, kinetic energy, potential energy leave; rate at which enthalpy, kinetic energy, potential energy enter the control volume and instead of writing the pressure work, work done by the pressure force is out here. We bring it to the, we bring that term to this side and instead of writing here internal energy we write enthalpy; that is really the change that we are putting. This is the convention. One could also write it separately putting the pressure on this side and saying u plus the internal energy plus kinetic energy, potential energy is nothing but the total energy leaving the control volume. But this is the way most people use the statement and so we are following convention; there is nothing sacrosanct about the way it is done. The other point to notice: notice that we have changed our convention for work. Earlier work for the closed system, work was positive when it was done by the system that is why we had a minus sign dq dt minus dw dt.

Now again, it is a convention; the moment you go to a control volume approach, work is positive when it is done by the surroundings on the system and therefore the minus sign becomes a plus sign here, a plus sign here and so on. Just keep that in mind. In symbols, the statement is the following and you can see it straight away flowing from our earlier discussion.

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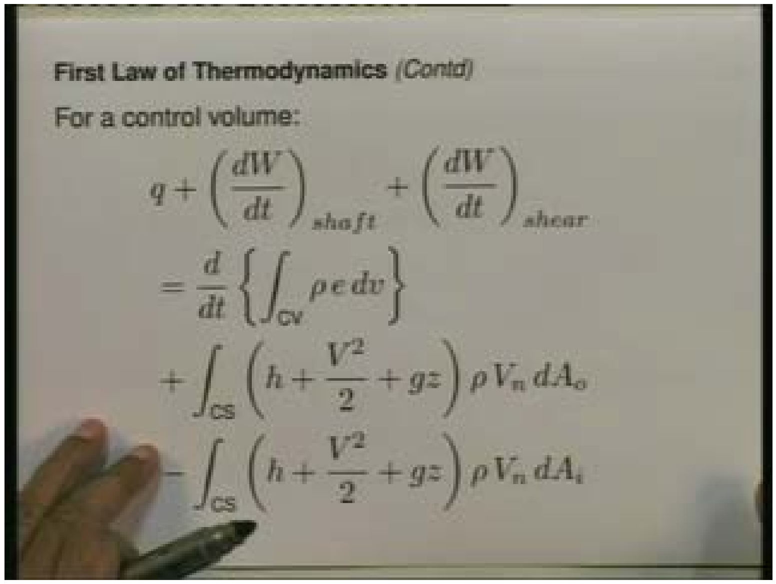

q is the rate of heat transfer to the control volume; dW dt is the rate at which shaft work enters, dW dt - the rate at which work is done by shear forces. Then the first term on the right hand side is the energy inside the control volume and the rate of change of energy, the next term stands for enthalpy per unit mass, kinetic energy per unit mass, potential energy per unit mass multiplied by the rate at which mass leaves rho Vn dAo. Integrate over the whole control surface and we get the total amount leaving per unit time and the total amount entering per unit time. So, these are the extra terms because of the control volume approach.

Let me now, just for a moment again, talk about the simplifications which flow, if I were to have simpler situation. Suppose the same - let me show the same equation again. Suppose it is a steady flow. This is the general statement. Suppose it is a steady flow. In a steady flow, this term, the first term on the right hand side is going to drop out. That is all that is going to be the difference. Suppose, I say it is steady and it is one dimensional. Now notice the change. Now, in addition I need not integrate over the control surface the values of h, V squared by two kinetic energy and potential energy need be taken only as the entering and the leaving values. So the simplification which I will get if the flow is steady and the if the flow is one dimensional is the following - I get q plus dW dt shaft plus dW dt shear, no first term on the right hand side which stands for rate of change of energy, equal to leaving value of enthalpy minus entering value h_0 minus h_i, V_o squared minus V_i squared by two, g into z_o minus z_i ; the whole thing multiplied by the mass flow rate through the control volume. Mass entering rate at which mass enters and rate at which mass leaves is obviously the same and we call that as m dot - so many kilograms per second.

So, now let us sum up what we done today. Briefly, what we done is: after spending the first few minutes describing the various modes of heat transfer in a flat plate collector, we talked about the laws of heat transfer which govern the subject that we are going to study; we distinguished between fundamental laws and subsidiary laws. We said the fundamental laws for us - the law of conservation of mass, Newton's laws of motion and the laws of thermodynamics. And for these, that is, for the law of conservation of mass, for Newton's laws which really came to the second law and for the laws of thermodynamics which meant the first law, we gave statements both for a closed system and for a control volume. And again I went further and said one may have various types of flows – steady, unsteady, compressible, incompressible - and for each of these we said, if we have them, one would get simpler versions of these fundamental laws and we gave those simpler versions which would be obtained. We also talked of a one dimensional situation and gave the simplification resulting from the one dimensional situation.