High Speed Aerodynamics

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Lecture No. #01

Introduction and Review of Thermodynamics

Welcome to this course on High Speed Aerodynamics, and also often called as compressively aerodynamics or gas dynamics. We already had a number of courses on aerodynamics, in which we have discussed mostly, low speed or incompressible flow. And the first question that comes to our mind that what is special or what is difference in high speed aerodynamics that we need to consider, high speed aerodynamics separately from low speed aerodynamics.

The first and foremost point, that is related with high speed aerodynamics; that here the speed of the fluid or say the gas or air is considerably large then, how large it is that quantification we will be doing later on, but we can say in deeply that, the speed is comparable to the local speed of sound. And then, if you want to maintain a flow at very high speed. Obviously, the pressure difference or the pressure changes that will be associated are quite large. Now once, the pressure changes are large, the gases is likely to change it is density.

Rather, you cannot assume that, the pressure changes are not capable of making any changes in density, which was the basic assumptions used in low speed aerodynamics or incompressible aerodynamics. Or you consider that the pressure changes are so small, that there is no change in density as a consequence. However, when the speed is much higher, then the pressure changes are large and as a consequence, there will be changes in density in the pressure, density of the gas due to change in pressure. And hence, the definition of incompressible flow, that is density changes are negligible due to change in pressure is violated. And the flow cannot be considered as incompressible rather they have to be considered as compressible flow, however density causes a changing of pressure causes a changing density.

Also we know that, all substance and that includes gas also, have certain amount of energy due to its existence. Even a gas at rest, has certain amount of energy which is called the internal energy; which is associated with the random motion of the molecules. Translation, ration and vibration of the molecules which is manifested in the form of internal energy and temperature. Now, flowing gas in addition to these random molecular kinetic energy or internal energy has also a kinetic energy and when the speed is large? The kinetic energy of the gas is also of the order of internal energy.

Even, if the speed is very very high; it can be an order higher than the internal energy and as a result, if there is a change in energy that is from kinetic energy to internal energy. In this case, the change can be considerable low speed flow; the internal energy, kinetic energy is so small, that even if, the entire kinetic energy converts to internal energy there will be hardly any change in the internal energy or temperature. However, in high speed flow since, the kinetic energy is quite large; can even be an order of magnitude larger than the internal energy. To a fraction of this kinetic energy, if it changes to the internal energy; the change in internal energy will be considerable and as a result, the temperature change also be quite large.

So, this provides a coupling between internal energy and kinetic energy or the temperature and the flow field and the two cannot be separated or solved separately; which you saw in the low speed case, that they can be solved separately. That is the temperature equation or the energy equation as we found there, is decouple from the other flow equations, but here, we see that they are completely coupled, that large change in temperature causes a change in pressure, density and not only pressure and density, but also, some other fluid properties that includes coefficient of viscosity or coefficient of thermal conductivity. So, there is a complete coupling between the energy and flow motion.

Some additional features may also coming, when the temperature is very large? That is, when the speed is very large and change in temperature is very large; due to this large change in temperature, chemical and thermal reaction may occur in the gas. Which includes excitation of the vibrational mode; dissociation of the gas molecules; ionization and if it is a mixture of gases then, some chemical combination reaction and many such reaction? In such a situation, some additional features also come into the picture. Of course, we will not discuss any of these phenomena in this course and hence, we will not discuss about them further, also we will be seeing that information high speed flow; the information, that is the disturbances propagates in certain directions on. Which of course, depends on the local mach number? Unlike the low speed flow or disturbance propagates in all directions, at the same rate, but incompressible or high speed flow.

This disturbances will propagate in certain direction only and that directions, depends on the speed or rather to the ratio of the speed and speed of sound. Since, change in temperature, internal energy and simultaneously also, pressure and density or coupled. In addition to the conservation laws, that are always use to analyze the flow or discuss the flow will be needing some thermodynamic concepts also, this is also a specific difference between low speed flow and high speed flow. That in low speed flows, the thermodynamics do not come into the picture explicitly, but in high speed flows, the thermodynamics has an integral part of this.

That is because the change in internal energy or temperature is considerable. We know that, in low speed aerodynamics; we can describe the flow by the basic conservation laws which are say, the continuity or the mass conservation law and the momentum conservation law and the energy conservation is the usually decoupled from these two; that is, the mass conservation and momentum conservation can be solved together and the result, can be used to solve the energy equation for temperature or internal energy. We have already mentioned that, in high speed flow that energy equation is also coupled with this set and they cannot be solved separately, they need to be solved together. That is all three conservation laws are linked together.

Now in addition; we also have seen that, the pressure density and temperature are linked together and some thermo dynamical relationship for them is also to be specified. So, what we need? What we saw here? Or what we discussed here? that to solve high speed flow, we need to considered the energy equation in a coupled manner and also, we need some relationship between the properties of pressure density and temperature and to do this; we need to bring in the subject of thermodynamics explicitly, in the discussion of high speed aerodynamics.

So essentially, we will start this courses with just, very new; very brief, review of the thermo dynamical concepts that are useful for discussion in high speed flow. However, as you have mentioned that, we will not consider the very high temperature or very high speed flows, how as? We need to consider the gas as mixture or chemical reactions and other formal reactions, so our thermodynamics will not include those phenomena. Now, when you go for brief preview of thermodynamics? The the law of conservation of energy is one of the principle law of thermodynamics and it brings in the concept of internal energy of a system. Now, what is a system thermodynamically? A thermodynamical system.

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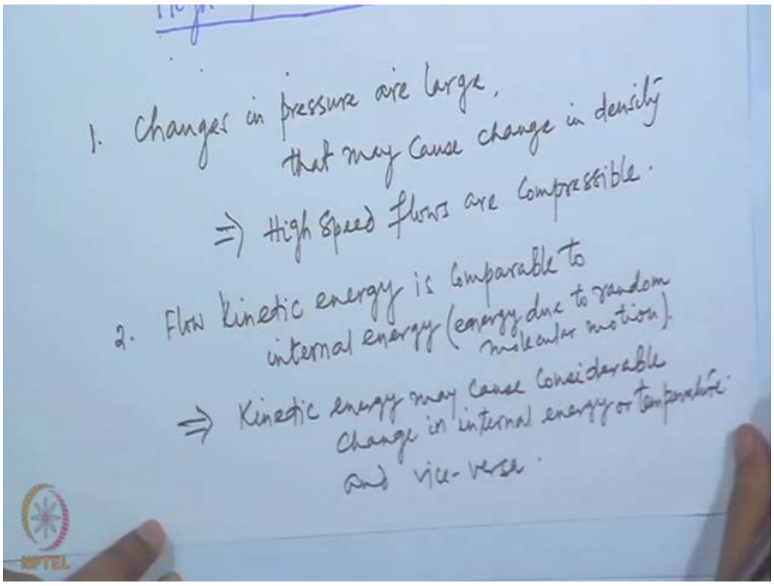

So, let us point out first, what we have discussed that in high speed flow? We have discussed, that changes in pressure are large, that may cause change in density. So, high speed flows are compressible. We also discussed that, flow kinetic energy is comparable to internal energy. (No audio from 13:57 to 14:31) So, kinetic energy may cause considerable change in internal energy or temperature and of course, and vice versa.

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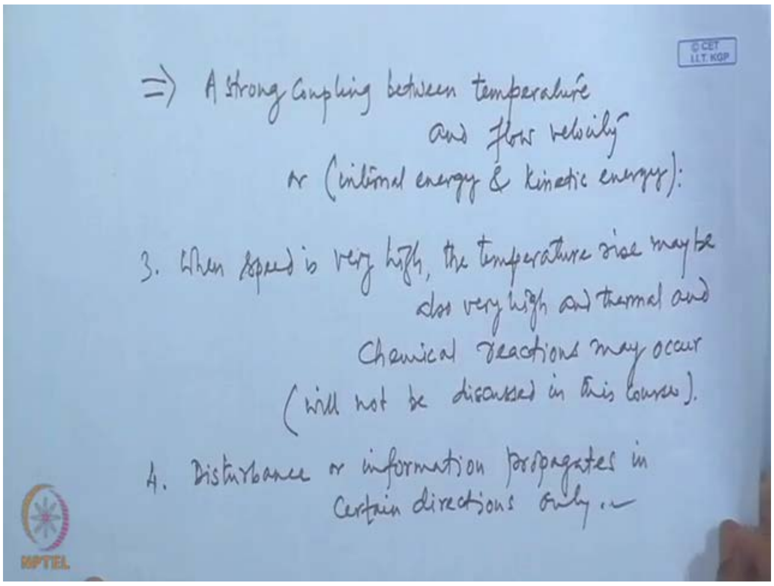

This this implies, a strong coupling between temperature and flow velocity or of course, we can say, internal internal energy and kinetic energy. When speed is very high? The temperature rise may be also very high and thermal and chemical reaction thermal and chemical reactions may occur, but will not be discussed in this course. These are of course, very easy to comprehend from our basic discussion that we had.

However, we have one more very important phenomena, that disturbance or information information propagates in certain direction only. Of course, this is not state forward from this discussion we had now. However, this will be seen later, based on this basic differences what we see that.

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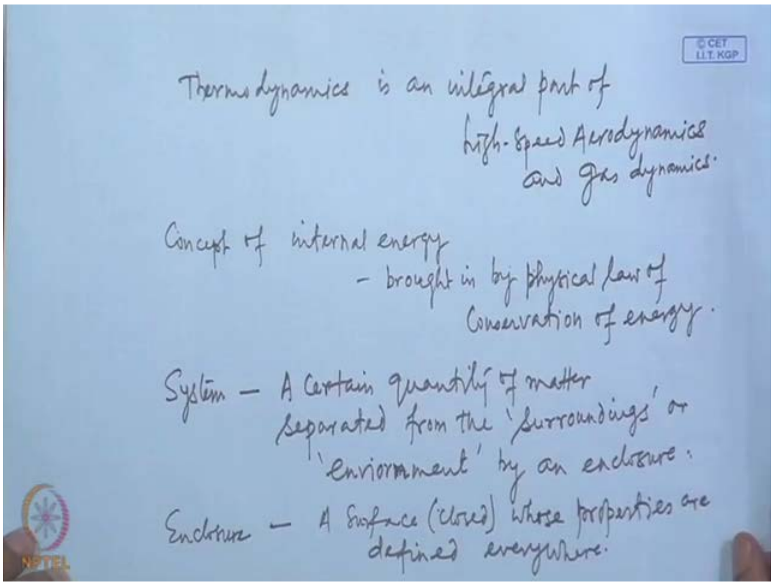

Thermodynamics is an integral part of part of high-speed aerodynamics high speed aerodynamics are gas dynamics. Now as we mentioned, that the physical basis of thermodynamics are formalized in certain conservation laws and the law of conservation of energy is one of the principle law, and this law of conservation of energy into this is the concept of internal energy, so concept of internal energy brought in by physical law of conservation of energy.

Now, thermodynamics deals with what are called as system and surrounding? So what is a system or what is a thermodynamic system? We may recall, the thermodynamic system; it is basically a certain quantity of matter separated from the surrounding or the environment. So, a certain quantity of matter quantity of matter separated from the surroundings or environment by an enclosure.

Of course, this enclosure is just a closed surface with properties known everywhere; it is not necessarily to be physical rigid enclosure. So, enclosure is just a surface a surface or rather a surface; whose surface with properties are defined everywhere. That is, this enclosure; it may transmit heat, work, mass or any momentum or any any such thing.

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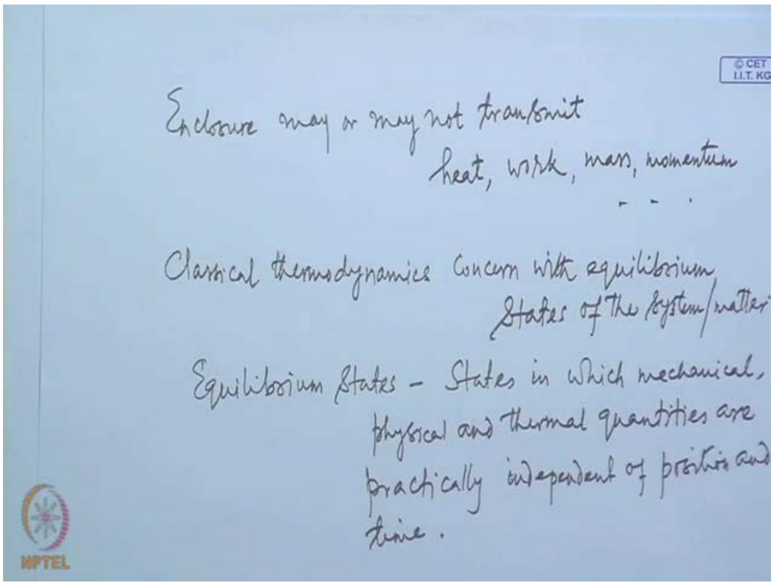

So, enclosure may or may not transmit heat, work, mass, momentum and similarly, other such property. Now, thermodynamics start with defining the system, its surrounding or environment and its enclosure and the changes in any thermo dynamical properties are considered in the, within the system. Now, classical thermodynamics is basically concerned with equilibrium state of uniform matter, so classical thermodynamics is; so let us see, classical thermodynamics concerned with only equilibrium state of matters.

Thermodynamics concerned with equilibrium states of the system; that is the state in which all local, mechanical, physical and thermal quantities are virtually independent of position and time. Equilibrium states that is, the states in which states in which mechanical, physical, and thermal quantities are practically independent of position and time.

So obviously, that thermo dynamical results or the results from the classical thermodynamics can directly be applied to fluid at rest. Now question comes that, if the fluid is flowing, how can the classical thermodynamics be applied? Because now, it is not in equilibrium. So however, it is observation that departure from equilibrium in a moving flow; in a moving fluid or practical or small as regard to the effect, on the thermo dynamical relationship.

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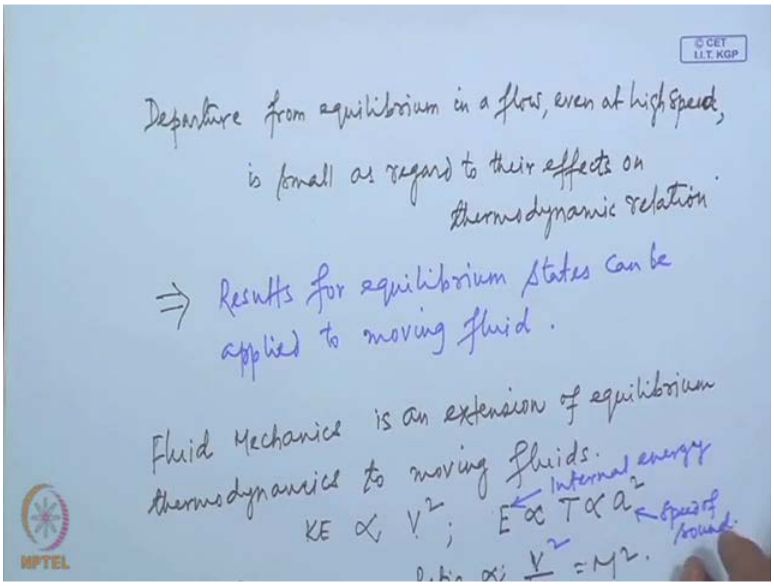

So for a flow, the departure departure from equilibrium in a flow, even at high speed, even at high speed as regard to their effects on thermodynamic relation. That is even though, it appears that the departure from equilibrium is quiet large, but as far as thermodynamic relationships are concerned. The the effect of this departure are quiet small. That is the relations that we derived for equilibrium states can be used for flow also.

So, results for equilibrium states can be applied to moving fluid. So, what happens that fluid mechanics of perfect fluids are basically an extension of equilibrium thermodynamics to moving fluids? Now, so what we say that fluid mechanics mechanics is an extension of equilibrium thermodynamics to moving fluids? Now, if you want to consider the conservation of energy. As you have already mentioned that, we have to consider the kinetic energy also and if, we try to find a ratio of this kinetic energy say per unit mass to the internal energy per unit mass.

It is basically, a dimensionless quantity and as we will be seeing later, that it is directly proportional to the square root of mach number or mach number is the ratio of the flow speed by speed of local speed of sound. This can be very easily shown that, the ratio between kinetic energy and internal energy is proportional to square of mach number. That is, so the internal energy is of course, proportional to square of the speed, so kinetic energy sorry kinetic energy is proportional to V squared or V is the speed and internal energy which we will be denoting by E. So, the ratio is proportional to a is speed of sound; E is internal energy; so this ratio is V squared by a squared.

Anyway, let us come back to our discussion on thermodynamics. Now, thermodynamics says that, for a pure substance the state of a system can be specified by any two thermo dynamical properties.

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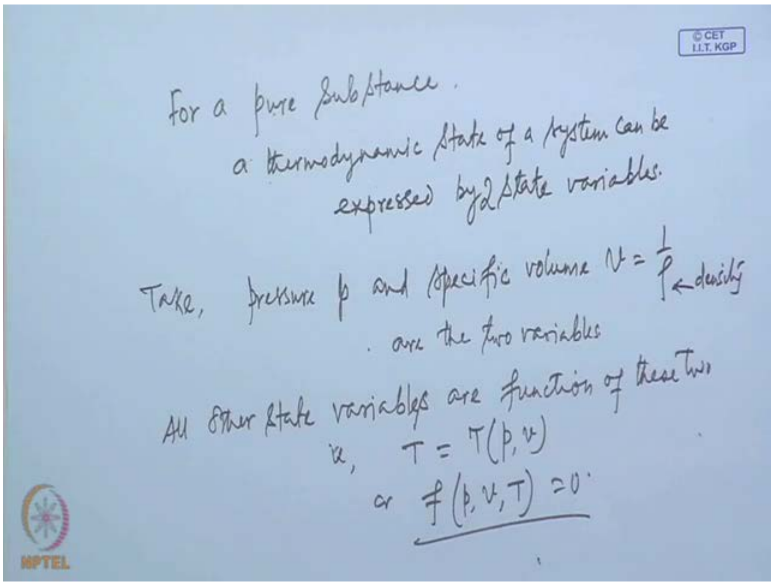

So for a pure substance, for a pure substance a thermodynamic state of a system can be expressed by two state variables. Now, what are state variables? Now, state variables in the thermo dynamical context is defined as those variables which comes back to it original value or original magnitude. If, a cyclic change is allowed to happen in the system, that is starting from one particular state and then, we change the state of course, in such a manner that equilibrium is always preserved and then, come back to the same state at the end. Then, there are certain variables, whose magnitude will again, come back to that original value. So these are called state variables.

Now, for convenience these are usually, take pressure p and specific volume that is volume per unit mass which of course, is reciprocal of the density are the two variables. Then, any other state variables are can be just a function of these two state variables. All other state variables are function of these two. That is, let us say T, as an example T temperature which is also a state variable is function of pressure and volume or we can of course, write; we should also define in this context, the the intensive and extensive variables.

Extensive variables are those which depend on the mass of the system and intensive variables are those which are independent of the mass of the system. Say as an example, pressure is independent of the mass of the system; the temperature is also mass of the system. However, the volume is of course, depends on the mass of the system, but again, if we consider the specific volume then, we have volume per unit mass. Which is of course, independent of the mass of the system? So we see that, for every extensive property which are independent of mass, there is a corresponding specific quantity which is per unit mass is of course, an is independent of mass and hence intensive quantity.

Now, let us try to bring in the concept of temperature from thermo dynamical sense, so this is the concept of thermodynamics sorry concept of temperature, comes in this way.

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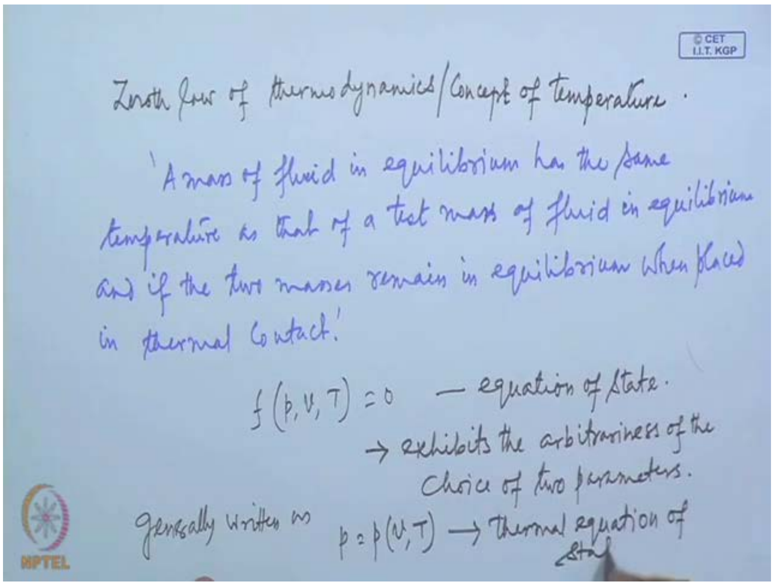

That, which can be called the zeroth law of thermodynamics or the concept of temperature. What you say that? A mass of fluid in equilibrium has the same temperature as that of a test mass of fluid also in equilibrium and if, the two masses remain in equilibrium when placed in thermal contact. That is if you write, let us say a mass of fluid of course, it need not be fluid. It applies to any other substance, a mass of fluid in equilibrium has the same temperature as that of a test mass test mass of fluid which is also in equilibrium equilibrium, and if the two masses remain in equilibrium when placed in thermal contact.

That is, let us say that; we have two masses of fluid both are in equilibrium and we place them in contact such that, heat can flow from one to other and if the equilibrium is not disturbed, that is; if no heat flows from one to the other then, we can say that the both the systems has the same temperature or the property which remains, the which is same for both of the systems is called temperature.

Now we have already expressed that, if we have defined two state properties so for a pure substance, all other state properties are function of these two state properties. Which we have formally written as, f a function of p, v, T is 0 and these are this equation is usually called the equation of state. This also exhibits the arbitrariness of the choice of two parameters. That is, instead of taking pressure and volume as the two independent variables, we can take some other state variables; some many other states variables will be defined subsequently and we can take any two of them to express the third one. This is this relation generally written as p equal to function of v and T and called thermal equation of state.

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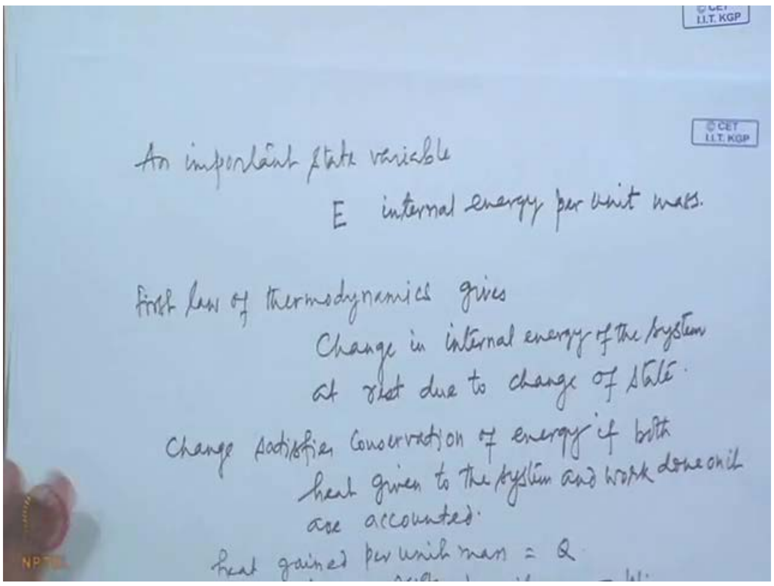

Now another important quantity, that describes the state of the fluid is the internal energy per unit mass internal energy per unit mass and already you have seen, that the internal discussed that this internal energy is basically, the manifestation of the random molecular motions and essentially, this is the kinetic energy of the molecules moving at random; moving in translational rotational and vibrational motion and that total kinetic energy associated with all the molecules in a system. Which are moving at random is manifested as the internal energy of the system.

Now, now the first law or the conservation of law; first law of thermodynamics gives change in internal energy of the system at rest, change in internal energy of the system at rest due to change of due to change of state. Now, the change is such that, the conservation of energy is satisfies, when we consider both heat given to the fluid and work done on the fluid? Change satisfies conservation of energy if, both heat given to the system and work done on it are accounted. Let us say that, heat gained per unit mass is Q and the work done on the fluid is W per unit mass; heat gained per unit mass equal to Q, work done on system per unit mass equal to W. Then, the first law simply says that, (No audio from 53:11 to 53:41) first law of thermodynamics so in our earlier equation of state, or we considered pressure, volume, and temperature. If, we consider internal energy that is, if we write the equation of state as caloric equation of state.

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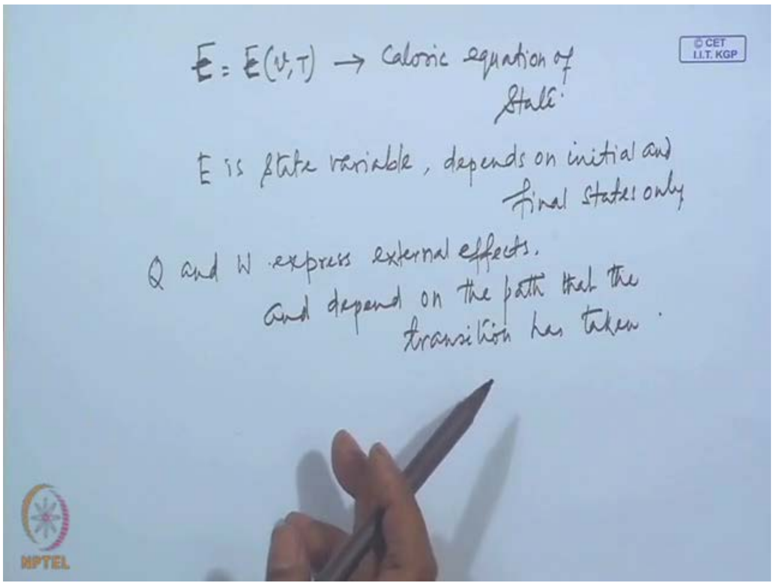

Now we see here that, we have defined internal energy is sorry that E is a state variable that is change in E depends on the initial and the final state. However, Q and W that is the heat added and work added are external effects and they depend on the particular way, in which the transition as between the two states is made. So, E is state variable depends on initial and final state only (No audio from 55:38 to 56:13) and depend on the path, that the transition has taken; that is the amount of heat and work that are required. Of course, depends on how the change has been brought in? From starting from one initial state to second, final state.

The energy internal energy depends only on these two states irrespective of, how these transition has taken place? While this heat added and work done on it depends on, how these changes have been brought in? What are the intermediate states through which the process has come? And however, these change in or the Q and W would be such that, that the sum total will be independent of the path.

We will continue this discussion in our next class of review of the basic thermodynamics, and some very basic relationships coming out from thermodynamics, which will be useful for our future discussion, in High Speed Aerodynamics?