Introduction to Fluid Mechanics and Fluid Engineering
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Lecture – 56
Compressible Flows (Contd.)

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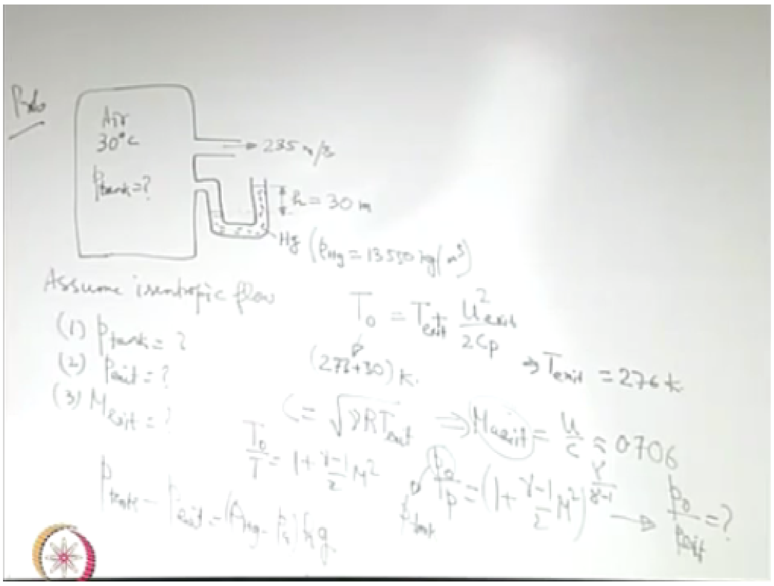

We were discussing about the property variations in isentropic flows and let us work out a few problems to see that how we may evaluate those property variations. So, let us say that we have a tank like this to which is connected one manometer, this tank has air at 30 degree centigrade, pressure is not known, the exit state from the tank is with a velocity of 235 meter per second. The manometer has the manometric fluid as mercury with a density of 13,550 kg per meter cube.

The height that is the difference in the levels of the limbs; of the 2 limbs of the manometer is 30 meter, assume isentropic flow that is given, you have to find out what is the pressure of the tank and what is the exit pressure and what is the exit Mach number, okay. So, let us see how we may work out this problem, so if we apply the energy equation in terms of the stagnation temperature, we have seen that T0 is = Te + ue square/ 2 Cp.

So, when you have this large tank, remember that the properties of fluid; the fluid which is there in the tank is approximately at a stagnation condition, so the temperature; the 30 degree centigrade the air temperature within this large tank, this is the stagnation temperature corresponding to this condition. So, you have T0 is 273 + 30 kelvin, so if you want to find out what is the exit temperature; so long as the flow is adiabatic one, you have Te + ue square/ 2Cp is same as any Te + ue square/ 2Cp.

So, you can use the exit state here, so let us say T exit and u exit; u exit is given as 235 meter per second, so from here you can find out what is T exit. So, if you evaluate that this T exit will come as 276 kelvin. From the T exit, you can calculate the Mach number at the exit because the sonic speed at the exit is root over gamma RT exit. Remember that we are considering an isentropic flow for which this formula is valid.

So, from here you can have the Mach number at the exit is = u/ c and if you calculate that it is approximately 0.706. So, when you calculate the Mach number, you can find out from that the expression of p/p0, so remember that we had an expression of T/T0 or T0/T rather, for an isentropic flow T0/T was 1 + gamma – 1/2 M square and p0/p; so if we know the Mach number at the exit, so from here we can find out p0/p exit by using the Mach number at the exit.

And the remaining relationship between p0 and p exit, so remember p0 is nothing but p at the tank, right. So, the other thing is the difference between the p at the tank and the p exit or the p atmosphere; remember p exit is same as the p atmosphere that is given from this manometer, so p tank - p exit is = the rho Ag - rho air * h * g, from the readings of the manometer. So, now you have 2 equations; one is p0/p exit that is as good as p tank/p exit.

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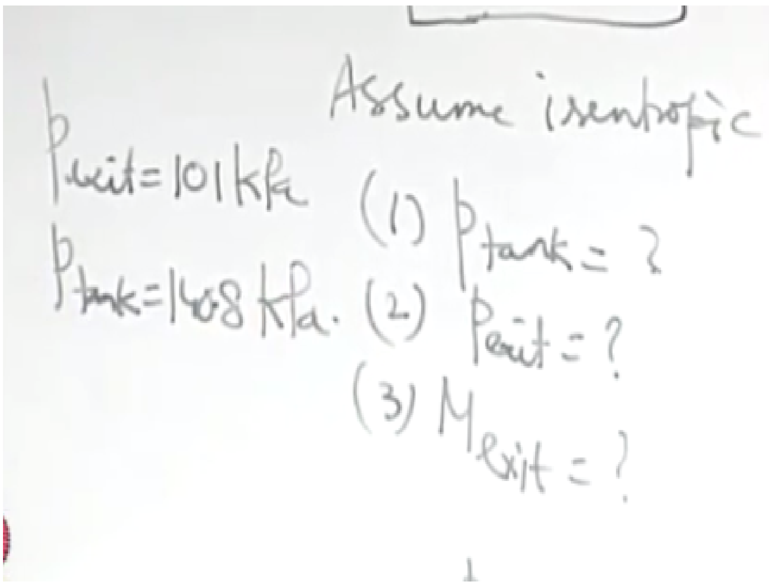

Another is p tank - p exit, so from these 2 equations you may solve for the 2 unknowns; P tank and P exit, so the answer to this is P exit = 101 kilopascal approximately and P tank is = 140.8 kilopascal. Let us work out a second problem to illustrate the use of isentropic properties. So, this problem statement is like this; considered isentropic flow in a channel of varying area with the sections 1 and 2; between the sections 1 and 2.

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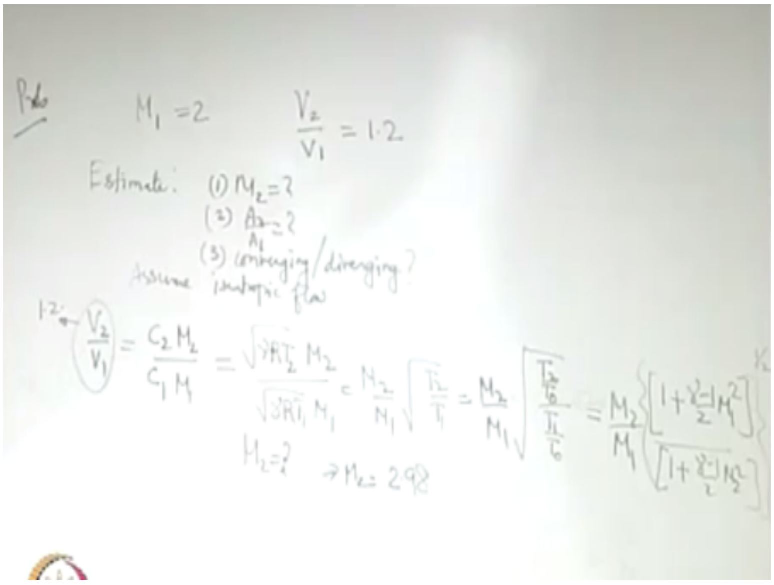

Given the Mach number at the section 1 is 2 and given that V2/V1 is = 1.2 is given. What you have to estimate is the following number 1; Mach number at 2, number 2; A2/A1 and number 3; figure out whether the channel is converging or diverging of course, it might appear to be trivial by looking into A2/A1 but you also have to make sure that there is no other type of variation in between.

So, it has to be either monotonic or it may be area increasing and decreasing and so on, so just A2/A1 is not sufficient to tell you that what is the total shape of the channel in between 1 and 2 that is why the third part of the question and the assumption is an isentropic flow. So, if you see what is given here is V2/V1, let us see that how we may express it in terms of our known quantities.

So, V2/V1 is the sonic speed at 2 * M2/ the sonic speed at 1 * M1, the sonic speed is square root of gamma at T2 because it is isentropic flow, so this is M2/M1 8 square root of T2/T1, okay. Now, T2/T1 may be expressed as T2/ T0 divided by T1/ T0, remember T1 is; sorry, T0 is remaining fixed, this is the isentropic flow, so there is no question of any change of T0, so you can write this as; so if you write for example, T0/T1; T0/T1 is 1 + gamma – 1/2 M1 square/ 1 + gamma – 1/2 M2 square this whole thing to the power of 1/2 okay.

So, in this expression, what is given? V2/ V1 is 1.2, M1 is given, so you have to find out M2, of course this is not a straightforward linear algebraic equation to find out but one may find out by trial and error or by using some software such as the engineering equation solver and so on. So, it is possible to find out M2 from this equation and if that is found out M2 turns out to be 2.98, this is by iterative solution.

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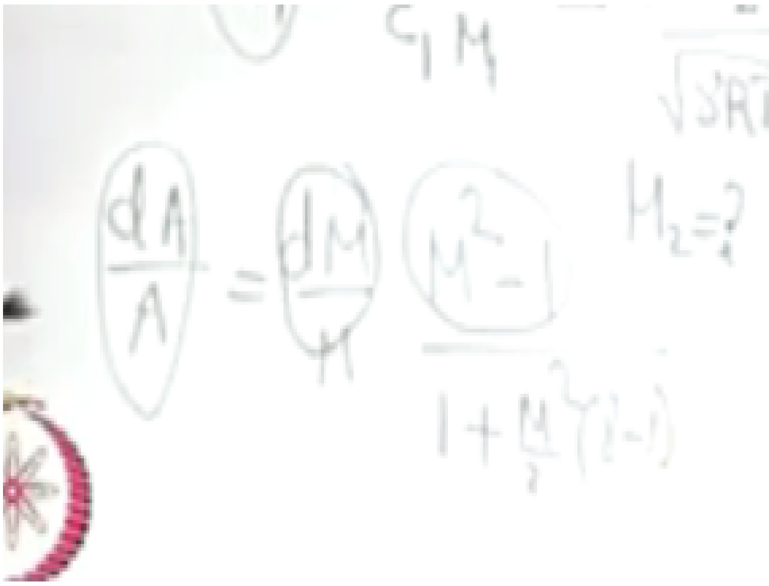

So, when you find out what is the value of M2, so the Mach number at 1 is 2, Mach number at 2 is 2.98 and how the area is increasing, if you want to answer the third part; let us use the expression of dA/A, which we derived in the previous lecture, so let us just write that expression, see dA/A is this one, this is the expression that we derived in the previous lecture. So, if you see here, now the Mach number is between 2 and 2.98, so the M square - 1 is positive.

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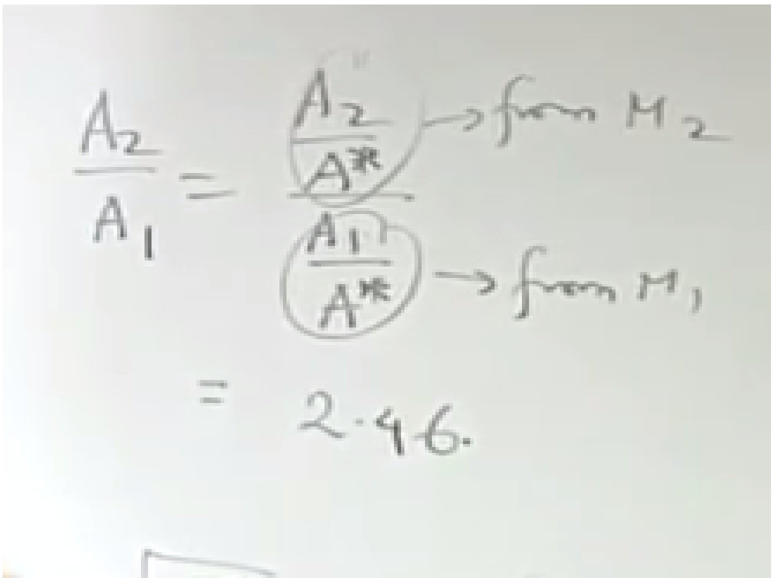

Not only that M is increasing, so from 2 to 2.98, so dM/M is positive, the denominator is always positive that means, dA/A has to be positive, so it is an increasing A, it is a diverging section and how to find out what is the real value of A2/A1? So, A2/A1 is nothing but A2/A star divided by A1/A star, remember what is A star? A star is the equivalent area at which sonic condition could be achieved under an isentropic process.

So, when the flow is isentropic, A star does not change, if it is not isentropic the value of A star will change. So, A2/A star and A1/A star; these 2 may be found out again we have derived expressions for A/A star as a function of Mach number, so from A2/A star value you can find out because you know what is M2, so these you get from M2 and this you get from M1 and if you evaluate those expressions, you will get A2/A1 is roughly 2.46.

If we use the compressible flow tables which are there in the appendix of the textbook, you will find that these values are tabulated, A/A star as a function of Mach number. So, if you have a particular Mach number, you will get A/A star, remember that it is just reproduction of the formula that we have derived in the class for gamma = 1.4 for here, so if it is for any other fluid you should have different tables for different fluids.

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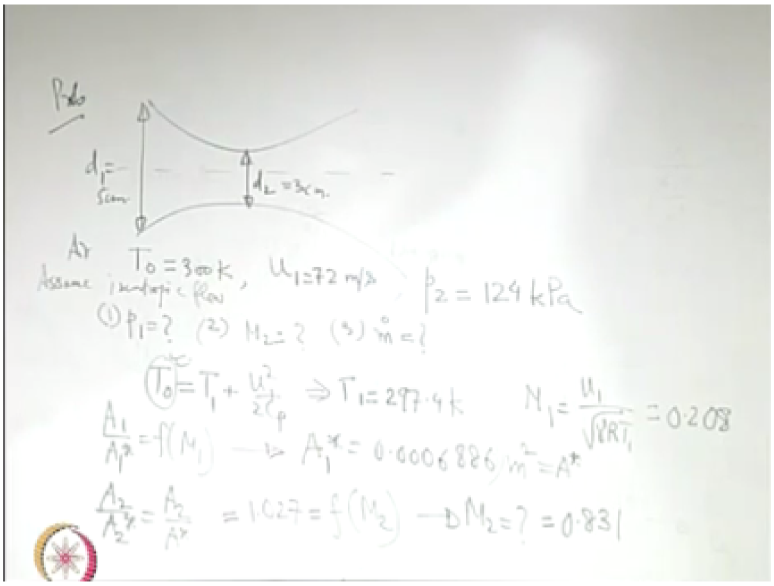

The table which is there in the appendix of your textbook is for air, so you may either use the table or you may use the formula to find out these expressions, okay. Let us work out a third problem, so it is given that this is the shape of a duct with the diameter at the inlet as 5 centimeter, diameter here that is d2 is 3 centimeter, the fluid is air with a stagnation temperature of 300 kelvin, upstream velocity u1 is given as 72 meter per second.

The pressure at the throat that is p2 is 124 kilopascal and assumes isentropic flow; from that find out what is P1, what is M2 and what is the mass flow rate, okay. So, first of all we know u1, so if we know what is the sonic speed at 1 then we may find out what is Mach number at 1, to find out what is the sonic speed at 1, what we should do; we should find out the temperature at 1 and to find the temperature at 1, we should use the energy equation.

So, T0 is - T + u square/ 2 Cp, so from here you know what is T0 that is given, you know what is u1 that is given, Cp of air is known from that you can find out what is T1, so T1 is 297.4 kelvin. So, once you know T1, you know M1 that is u1/ square root of gamma RT1 and that turns out to be 0.208. Once you know M1, you can find out A1/A1 star, it is a function of M1 only, okay.

So, when you find out this one from here, A1 is given; A1 is Pi d1 square/ 4, this function of Mach number is known, so from here you can find out what is A1 star. So, the value of A1 star is 0.0006886 meter square if you calculate that is what you will find out. Now, what is A2/A2 star? A2/A2 star is nothing but A2/A star remember, A star remains same so long as it is the isentropic flow.

So, A star has already been calculated, this is A1 star is same as A star and A2 is Pi d2 square/4, so by putting these values, you will get these as 1.027 and this is a function of M2 and from this you can find out what is M2 by referring to the table of isentropic flows. So, M2 is; if you calculate this, this is 0.831. Once you know the Mach numbers basically you know everything because then you can use the expressions for P/P0, T/T0 like that.

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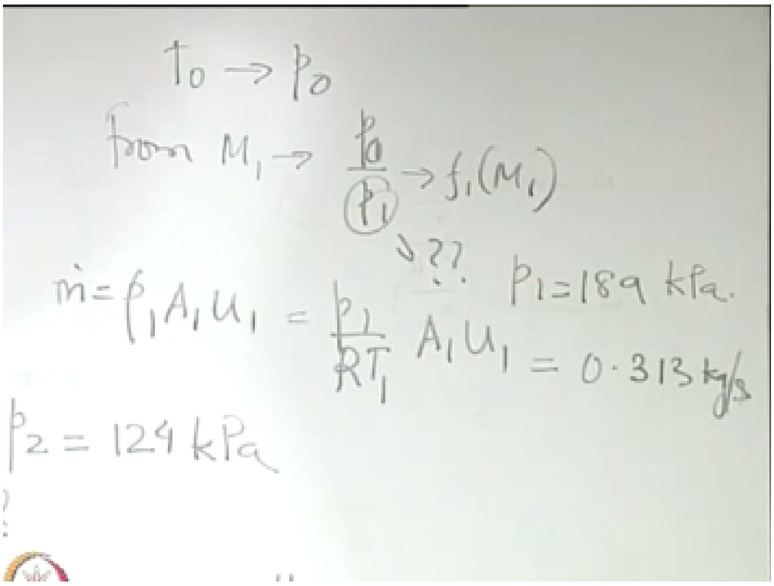

So, you can calculate P1/P0, you know T0, therefore you know P0, from P0, you may now calculate P0/P1 as a function of Mach number at 1, so from that you can find out P1. So, you can find out P1 not from this one but from Mach number at 1, so from so T0 will give you P0, I am just outlining the procedure from the Mach number at 1, you have P0/P1 as a function of Mach number from this, what is P1.

So, P1 if you calculate it is 189 kilopascal and the mass flow rate, it is you can write rho 1 A1 u1 just as an example, you could also write as rho 2 A2 u2; rho 1 is P1/ RT1 * A1 u1, all these things you know, so you may substitute the values to get the mass flow rate which is 0.313 kg per second okay. So, we can see that how you may utilize the properties of isentropic flows to calculate different quantities, pressure, temperature, mass flow rate under different conditions.

Now, as we discussed in the previous class that it is not always true that one would have an isentropic flow or one may even think of an isentropic flow; isentropic flow is something which is not a reality in any way but real flows in certain cases may resemble very close to isentropic flows but if you see that under certain cases even that approximation of isentropic flow will not work.

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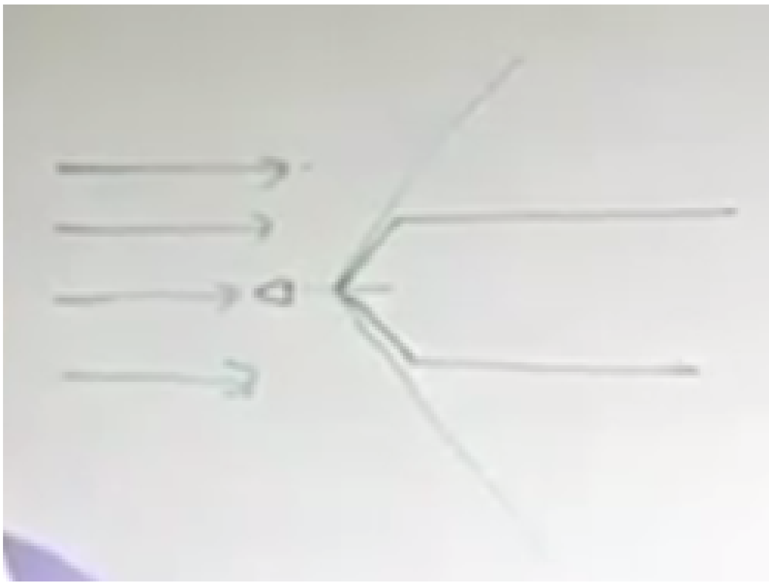

When it will not work, it will not work when there is an abrupt discontinuity in the flow, so how that abrupt discontinuity may be possible? Let us take an example, let us say that there is some aircraft which is moving with a very high speed, so when it is moving with a very high speed, it is say moving with a supersonic speed and therefore all the disturbances are confined within the Mach cone.

So, outside the Mach cone the disturbance is not felt, so let us say that you have sort of this as a bounding envelope within which the disturbance is there. Now, if you consider the streamlines which are there in the upstream, they are not still feeling the presence of these disturbances because the disturbance cannot propagate to all points. Now, suddenly when these come and encounter this point of or these locations of discontinuity then they will feel the presence of the disturbance.

And therefore, there will be an abrupt change in properties, so such abrupt change in properties will be possible here with a condition that on one side, it is supersonic flow and on another side what will happen, we will see; we are not predicting that it is either subsonic or supersonic or whatever but one important thing we can predict that there may be a sharp discontinuity, so that on one side, it is sort of the disturbance is failed because of the supersonic nature of the flow.

On another side the disturbance is not failed, so to say that is an extreme example but you may also have such discontinuities not that on one side disturbance is totally failed on another side the disturbance is not at all failed but there is a sharp discontinuity across that which means that there will be an abrupt change in Mach number across that. The question will be that; what is the length or what is the thickness over which this discontinuity occurs typically a few molecular mean free paths?

So, roughly like of the order of 0.1 micron like that so, it is for all macroscopic calculations, it is as if like a sharp front over which these discontinuities in the flow properties is going to be there, we will see that mathematically, we might initially have possibilities of several types of discontinuities but from the second law of thermodynamics, we will try to predict that some of these discontinuities are feasible and some of these discontinuities are not feasible.

But we have to first appreciate that there is a possibility of such discontinuity in a flow typically, in a supersonic flow we may visualize that why such a discontinuity might occur. The second thing is that when the discontinuity is occurring, what is the front over which the discontinuity is occurring? The front over which the discontinuity is occurring this type of discontinuity is known as a shock.

So, when you have the front over the discontinuity that is occurring that front may not be oriented in a direction normal to the direction of the flow but there are special cases, when the front of the discontinuity is oriented in a direction perpendicular to the direction of the flow and in such a case, it is known as a normal shock. If the front of the shock is oriented at an oblique angle with respect to the direction of the flow, then that is known as an oblique shock.

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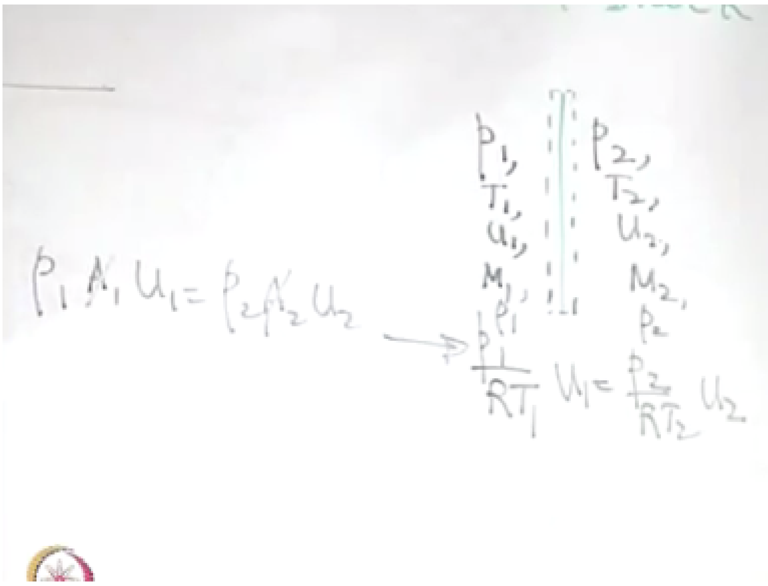

So, in the purview of this course, we have only normal shock, so we will be discussing only the special type of shock where the shock front is perpendicular to the direction of the flow. So, let us take up that case known as normal shock. So, when you have a normal shock, let us say that this is the shock front, so what we are having; we are having a discontinuity in properties across the shock front.

So, let us say on one side the pressure is P1, the temperature is T1 maybe the velocity is u1, the Mach number is M1, another side P2, T2, u2, M2, even you may write the density rho1, rho2 like that so there is a change in property. One important thing we should keep in mind that we also considered a wave type of motion; a weak wave type of motion where there was some discontinuity across the two ends on the front.

What is the difference between that and the shock wave? The big difference is there, the discontinuity was only infinitesimal that is if the pressure here was P maybe here was P + dP like that so that was a differential change or so to say a smooth change, here it is an abrupt change. So, difference between P1 and P2 is not differential, difference between M1 and M2 is not differential and that is why these are sharp discontinuities or jumped discontinuities.

So, when you have such jump discontinuities occurring, then these discontinuities occurring at a very rapid rate, so there is a rapid change in the flow properties and when there is such a rapid change, the change is taking place over a very thin region, so that we may consider it to be adiabatic because there is insufficient time to have opportunity of heat transfer during the process but because the process is very fast, it is no more reversible process.

Therefore, it may be approximated as an irreversible and adiabatic process, so if you have it as an irreversible process, you cannot apply isentropic flow conditions to relate M1, M2, u1, u2, T1, T2, P1, P2 like that and that is why we have to make a separate analysis for the shock. So, this is the motivation of having a separate analysis for the shock despite having the well-known property relationships for the isentropic flows.

Now, let us say that we want to apply our basic equations, so the basic equations are still valid, so you have; for example the continuity equation, remember these are one dimensional flows, so if A is the area of the shock front then you have rho 1 A1 u1 is = rho 2 A2 u2; A1 and A2 are the same and you may relate rho1 with P1 and T1, it is important to eliminate one of the variables out of P,T and Rho by using the equation of state.

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$$\frac{u_2}{u_1} = \frac{M_2}{M_1}\sqrt{\frac{T_2}{T_1}}$$

So, you can write this as P1/ RT1 u1 is = P2/ RT2 u2, so this one we will keep in mind, of course u2/u2, you may express in terms of the Mach number and the temperature, so you can also write u2/u1 as M2/ M1 square root of T2/ T1 because u is M * C; C is square root of gamma RT. See, we are writing this with an understanding that in the upstream of the shock and in the downstream of the shock separately, we are using isentropic considerations that we have to keep in mind.

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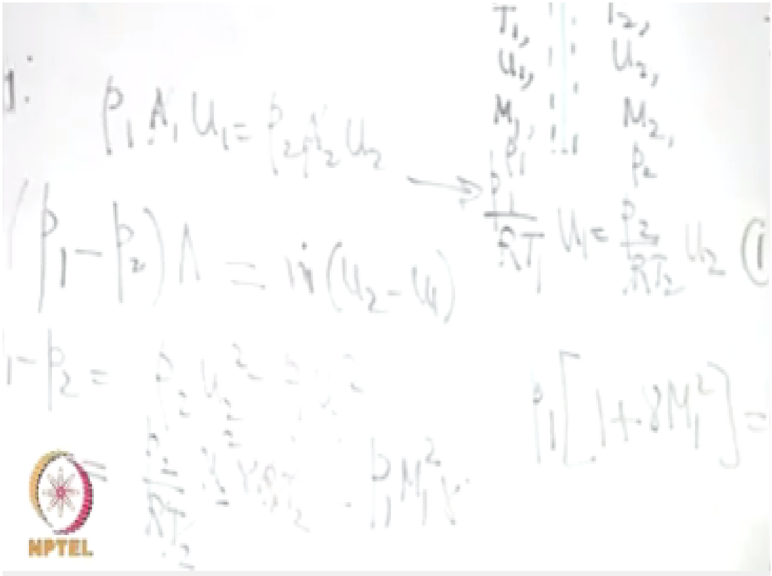

But in between the upstream and the downstream, the flow is not isentropic, so this is what we get from the continuity equation then maybe momentum equation; momentum equation, so the resultant force that acts on the control volume P1 – P2 * A is = M dot * u2 – u1, M dot is rho * A * u, so in place of M dot, you can write rho1 A u1 or rho 2 A u2 either way and then if A gets cancelled from both sides, it is possible to write P1 – P2 is = rho 2 u2 square – rho1 u1 square okay.

Now, in place of rho, you write P/RT, so P2/RT2, in place of u square, it is M square * gamma RT, right, so R * T gets cancelled out, so this term becomes gamma * P2 * M2 square remain, the other term therefore will be P1 M1 square * gamma, right. So, from here you can write P1 * 1 + gamma M1 square is = P2 * 1 + gamma M2 square. So, from this we have an expression or relationship between P1 and P2, which is solely expressed in terms of the Mach numbers at 1 and 2.

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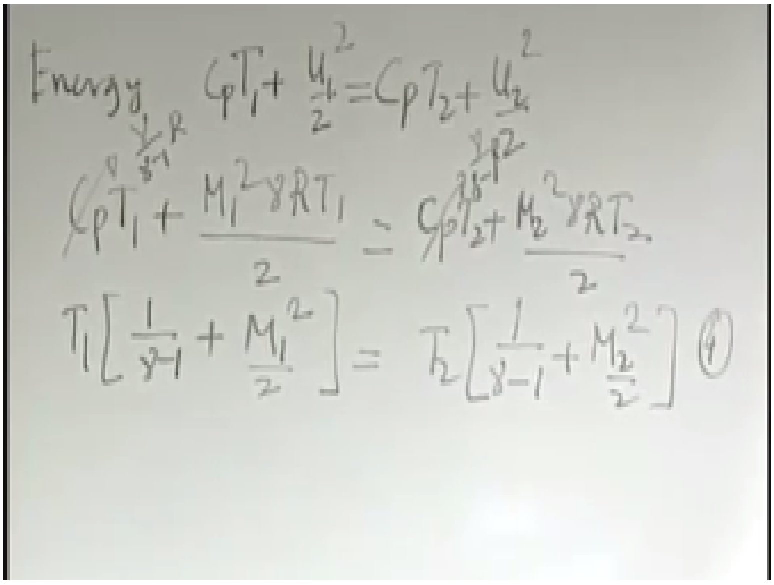

So, we will keep this equation in mind, let us say this is equation number 1, this is equation number 2, this is equation number 3. The next important equation is the energy equation, so let us see that what we get out of the energy equation. Energy equation will give what? T1 +; Cp * T1 + u1 square/ 2 is = Cp * T2 + u2 square/2. Remember, this is adiabatic and that is good enough this is first law of thermodynamics, we do not require any reversible or irreversible condition here.

So, you have Cp * T1 +; in case of u1 square, we will be using the expression of the Mach number that is u1 square is M1 square gamma RT1/2, okay, you can write Cp in terms of gamma and R, so that is gamma/ gamma – 1 * R, right. So, this will become gamma / gamma – 1 * R, this is gamma/ gamma – 1 * R, so gamma * R will cancel, so you will have T1 * 1/ gamma - 1 + M1 square/ 2 is = T2 * 1/ gamma - 1 + M2 square/2, okay.

So, let us be careful that there is no algebraic mistake because we require these calculations for some analysis subsequently. So, we are able to write T1/T2 also in principle as a function of M1 and M2 just like what we could do for P1/P2 and therefore, rho1/ rho 2 also we will be able to do and u1/u2 also in terms of M1/M2 because T2/T1 also is expressible in terms of M1/M2.

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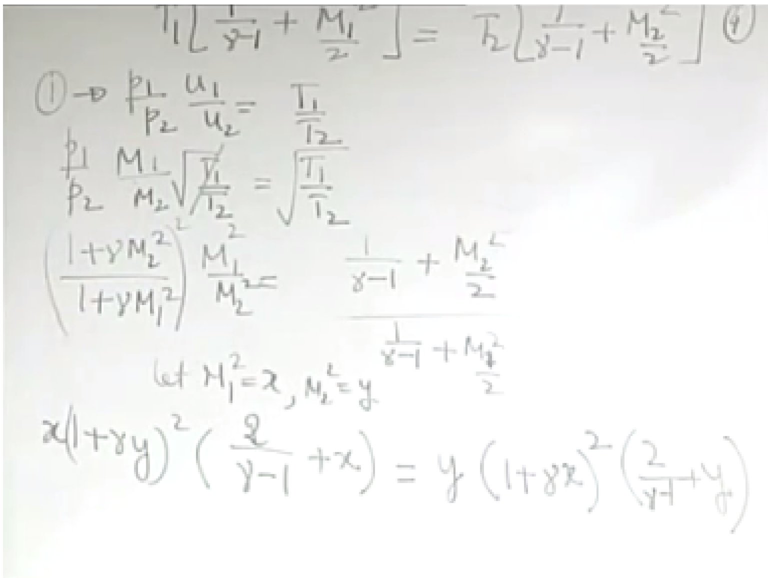

So, let us refer to the continuity equation that is equation number 1 form, so you have P1/ P2 * u1/ u2 is = T1/T2, right and u1/u2, you can write in the next step from equation number 2; M2/M1 square root of T2/; sorry, M1/; this is u1/u2, so M1/ M2 * square root of T2, then this is = T1/T2, so 1 square root of T1/T2 gets cancelled, only 1 square root of T1/ T2 is there. Now, let us substitute from equation number 3 and equation number 4, where we have T1/ T2 and P1/P2.

So, P1/P2 is 1 + gamma M2 square/ 1+ gamma M1 square that * M1/ M2 is = square root of T1/ T2, so 1/; okay, now we have got an explicit relationship between M1 and M2, so to find out that what could be the possible relationship at the end, first of all we may square these expressions. So, if you square this expression, so this is the square; M1 square/M2 square and these square roots will go away.

Our objective is to solve M2 in terms of M1, if you look into this equation carefully, you will see that M1 = M2 is a trivial solution, right because when M1 = M2, each of the terms club will be = 1, so 1 * 1 = 1, right. So, M1 = M2 is a trivial solution but not a solution for the shock because for the shock there will be a discontinuity, so we have to look for the other solution which is different from M1 = M2.

Just to help in the algebra, let us say let M1 square is = x and M2 square is = y and let us just expand these terms, so we have 1 + gamma y whole square * x * 1/ gamma – 1, let us write 2/ gamma - 1 + x is = y * 1 +; okay, so this term square * M1 square is x into this term, which is there in the denominator, so we have multiplied by 2 just for simplicity, so 2/ gamma - 1 + x, okay.

So, just check whether this is correct or not because we will proceed again from this one. We will not do a brute force algebra but we will exploit the symmetry on the two sides, so first of all we will calculate the left hand side and we will write the right hand side just by exploiting the symmetry. See, right hand side is the replacement of the left hand side with x replaced by y and y replaced by x, okay.

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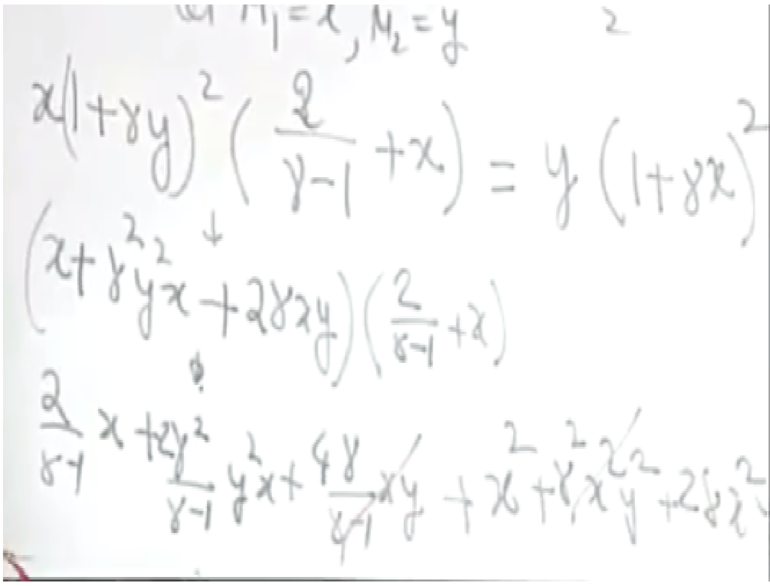

So, here you have x + gamma square y square x + 2 gamma xy * 2/ gamma - 1 + x, this is the left hand side, doing one more step what you get; x square okay, first x; 2/ gamma – 1 x + 2 gamma square/ gamma - 1 y square x + 4 gamma/ gamma - 1 xy, these are the first 3 terms and the next terms are just multipliers of x, so x square + gamma square x square y square + 2 gamma x square y.

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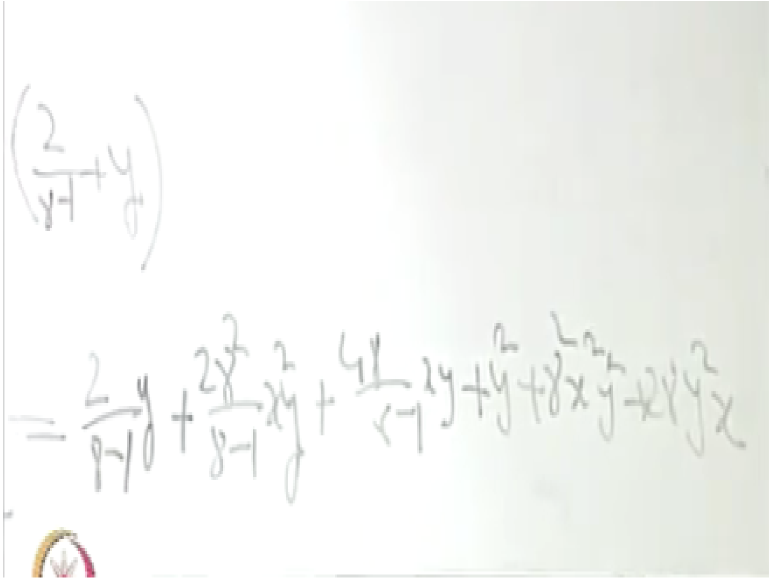

We can straight away write that what will be in the right hand side, x will be replaced by y, so 2/ gamma - 1 y + 2 gamma square/ gamma – 1 x square y + 4gamma/ gamma - 1 xy + y square + gamma square x square y square + 2 gamma y square x, so out of the total 6 terms that you get there are 2 terms which are symmetrical and same in the two sides and therefore they get cancelled.

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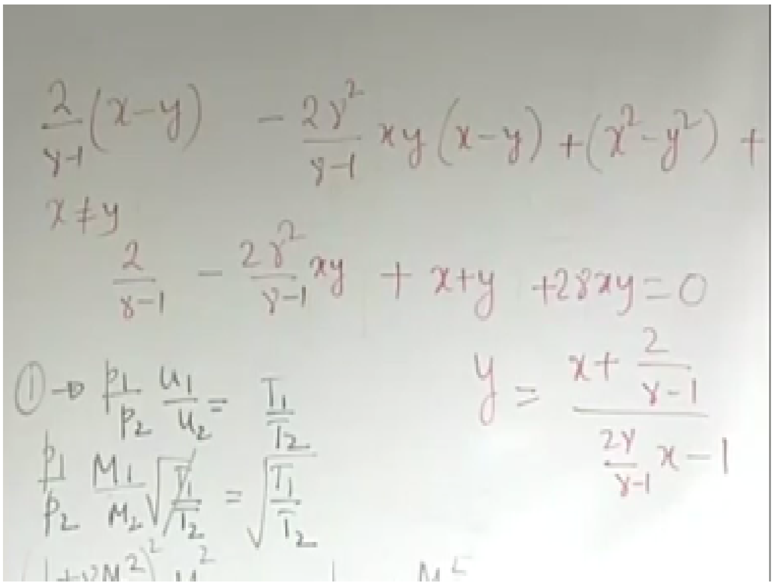

So, one is the term with xy, another is the term with x square y square and then you will automatically get x - y as a common thing because x = y is a trivial solution that we have seen. So, if you take x - y as common with 2/ gamma - 1 as the first term then from the next term, - 2 gamma square/ gamma - 1 xy * x - y + x square - y square + 2 gamma xy * x - y = 0, okay. So, if you consider that x is != y then you have 2/ gamma - 1 - 2 gamma square/ gamma – 1 xy + x + y + 2 gamma xy = 0.

So, from here, it is possible to write y, explicitly as a function of x, right. So, if you write y explicitly as a function of x, let me give you the final expression that is a trivial war, so y will be = x/ x + 2/ gamma – 1/ 2 gamma/ gamma – 1 x - 1 okay. So, when you get this expression, remember y is M2 square and x is M1 square. The special case that is of interest to us is the case of air.

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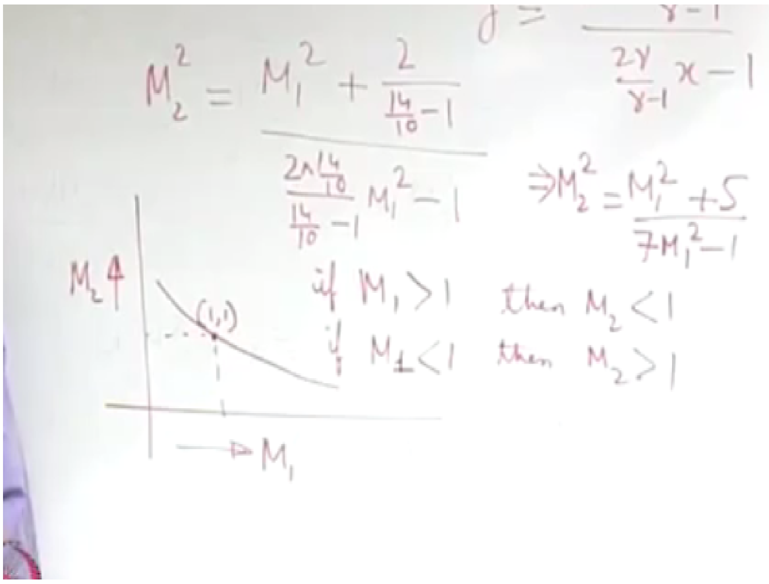

So, air is gamma = 1.4 example, so for air let us write what is M2 square/ M1 square, so M square is = M1 square + 2/ gamma is 14/10 – 1, we will just write it in a fractional form, so what will be M2 square in terms of M1 square? This will be 4/10, so 10 * 2 in the numerator, 20/4 is 5, so this is M1 square/ 5; M1 square + 5 and this will be 7 M1 square – 1. Now, let us try to make a plot of M2 as a function of M1 from this variation.

So, if you make a plot of M2 as a function of M1, just as a sketch; one of the important observations is if you see again from this figure, from this expression when M1 is 1, M2 is 1, so 1, 1 is a point of this variation. So, if you say this has 1, 1, this is one point and the remaining thing if you make a plot, it will be a plot like this just schematically. So, from this what we can conclude is; if M1 > 1, this is 1, then M2 is < 1.

And if M2 is; if M1 is < 1 then M2 is > 1, till now whatever exercise we have done, this allows us with these 2 possibilities but we will see soon that both of these possibilities are not; out of these 2, one is not physically permissible because we have to consider the directionality of the process, we have one process where the Mach number is going from > 1 to < 1, another case going from < 1 to > 1.

So, these 2 are 2 different directionalities of the process, out of these one of the directionalities will be possible, another directionality of the process will not be possible, so what is the direction in which the process will move or is permissible to move will be dictated by the second law of thermodynamics. So, we will now consider that what is the corresponding change in entropy during this process?

So, remember that when you have a change in entropy, you have a change in entropy of the system plus change in entropy of the surroundings, so here there is no heat transfer, so there is no change in entropy associated with the heat transfer with the surroundings, so you have change in entropy with the system that is just S2 – S1.

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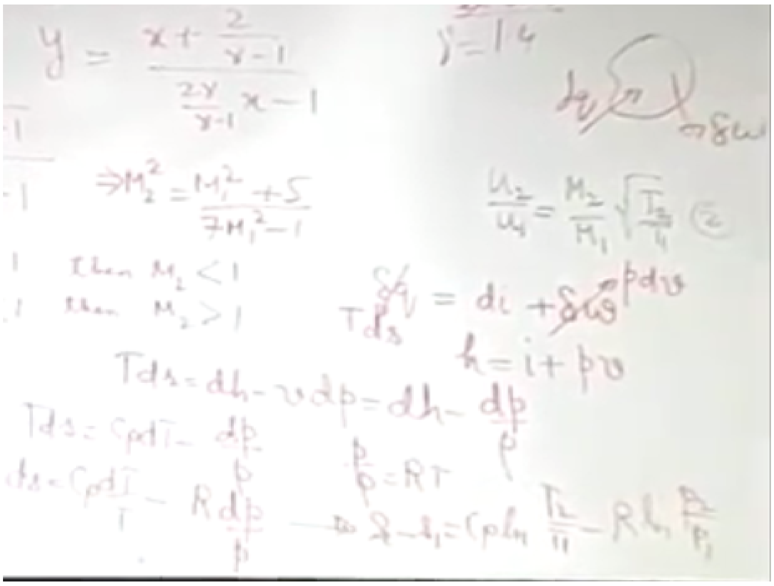

So, just to have elementary considerations on the change in entropy, the first law of thermodynamics in terms of a heat transfer; the heat transfer, remember the convention that we are having this is heat transfer to the system as positive, work done by the system as positive that is the sign convention that we have used, i is the internal energy this is actually the total energy that we should have return.

But we have neglected the changes in kinetic and potential energy in comparison to the internal energy that is why it is d of internal energy. If we consider a process that is a quasi-static one or a very slow one and no other effect other than the pressure and the volume changes then this becomes pdv, where v is the specific volume that is volume per unit mass and if we consider the process to be reversible, then we can write delta q as Tds.

Once we have written this, it is Tds = di + pdv that is valid for any process, so long as we integrate this equation along a reversible path and calculate the change in property by following that path but once the property change is calculated, it becomes independent of the path because these are exact differentials or path independent expressions. So, you may express i in terms of or express enthalpy in terms of internal energy; i + pv.

So, if you combine that what will follow is; Tds = dh – vdp, where v is the specific volume which is nothing but 1/density. So, here in fluid mechanics, we usually refer to that density instead of the specific volume, so we will write 1/ rho, we are using an ideal gas with constant Cp Cv that is a perfect gas, so Tds is = CpdT – dp/ rho. So, ds is = Cp dT/ T -; so when you divide it by rho T; divided by T, it is rho * T, so you have to remember that p/ rho is = RT.

So, rho * T is P/R, so - R dp/p, okay so you may integrate this expression and find out S2 – S1 is = Cp, remember we are dealing with special cases with Cp as constant, so Cp ln T2/T1 - R ln p2/p1, T2/T1 and P2/ P1 we may write explicitly in terms of M2 and M1 in this case and that also solely in terms of M1 because M2 may be expressed solely as a function of M1, so after doing all that the algebra is too complicated, we will not go into the algebra.

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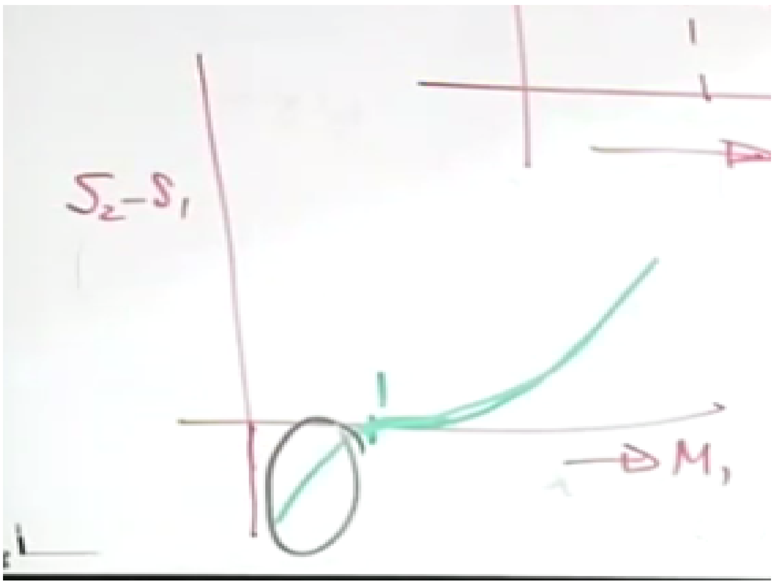

But we may see that what would be the S2 – S1 as a function of M1 plot, in principle we understand that it is very, very much possible to get an expression S2 – S1 solely as a function of M1, so if we make that plot, the plot will look something like this, it will be a plot like this. So, now if you look at this plot, you can clearly see that below M1 = 1, you have S2 – S1 < 0, so this is giving rise to a total change in entropy as negative.

Remember the total change in entropy is S2 – S1 + delta S of the surroundings which is 0 because it is an adiabatic flow, so here S2 – S1 is as good as S net; delta S net. If there is a heat transfer with the surrounding, the delta S net is S2 – S1 + delta S for the surroundings and we have to keep in mind that our requirement is not that S2 – S1 should be > 0 but delta S net should be > 0.

In this case since, heat transfer = 0, delta S net is same as S2 – S1, so from this what we can conclude is that this part is not a physically realistic part of the solution because it is giving rise to negative change in entropy of the system plus surroundings therefore, only permissible part of the solution is that; so out of the 2 cases that we have considered if M1 > 1 then M2 is < 1 this is the permissible solution.

If M1 is < 1 then whatever it is then M2 > 1 is fine but that is not a permissible direction of the process because it violates the second law of thermodynamics, so this is what we say that is not possible. So, from here we conclude that if we have a shock; upstream of the shock the flow has to be supersonic and there should be a change in property such that it has an abrupt change from supersonic to the subsonic state.

Why physically it should occur for a supersonic flow in the upstream and not a subsonic flow? If you see that if you have a supersonic flow, the disturbances are not able to propagate in all directions, so there is a limited zone over which is the zone of action within which the disturbance is propagated. Therefore, there is an accumulation of the disturbances because the disturbances are not able to propagate in all directions at a rapid rate.

So, this accumulation of disturbances gets released in the form of a shock with an abrupt discontinuity, if the disturbances were not accumulated then it would have not been possible to have such a shock with an abrupt discontinuity. So, the shock is like a release of accumulation of disturbances in supersonic flows, so with this understanding we now have an idea that when you have a shock, you have the change in properties; abrupt change in properties.

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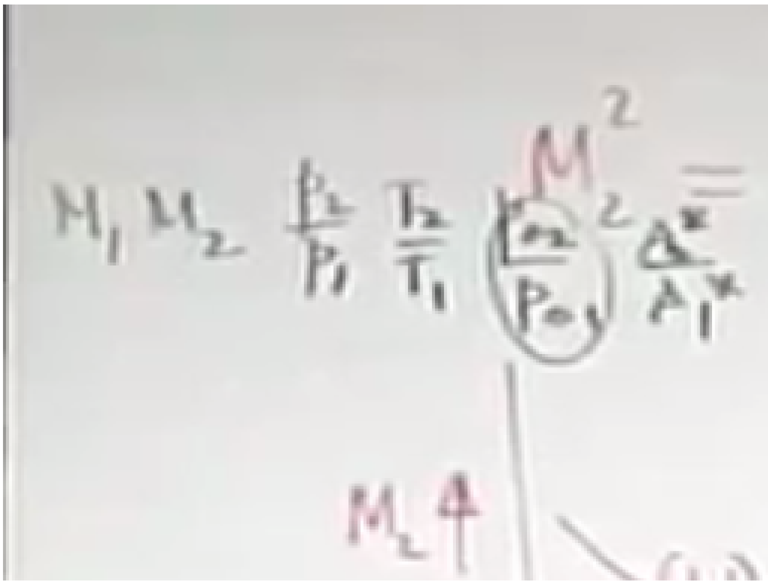

And if you look into the tables of the textbooks that you have, you will find that there are tables corresponding to the shock waves and there are different types of tables depending on whether you are dealing with a normal shock or an oblique shock, so here we are dealing with a normal shock. So, for a normal shock, you will see that the tables will have the following data; the tables will have M1, M2 then P2/ P1, T2/ T1, P02/P01 like this you will have.

So, M1, M2, P2/ P1, T2/ T1 all these fundamentally may be calculated from these considerations and also may be A2 star/ A1 star, all these may be fundamentally calculated from the expressions that we get. So, when you calculate this one important thing you have to keep in mind is that it is possible to express all those in terms of M2 and M2 in terms of M1, there is a change in stagnation property across the shock.

So, P0 is the stagnation pressure which would have remained the same in an isentropic flow but if it is not isentropic, there will be a change in P0, so there is a ratio P02/p01, which is! = 1, so across the shock there is a change in stagnation properties because the shock; across the shock the flow is not isentropic, there is an abrupt discontinuity and because of that you have difference in A star also.

So, A star changes across the shock because A star is an equivalent; A at which sonic condition is achieved by following an isentropic process, across the shock it is not isentropic, so in the downstream of the shock, it is a different isentropic condition and that is why you have difference in A star. So, let us stop here with this lecture, we will continue again in the next lecture. Thank you.