Introduction to Explosions and Explosion Safety

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Lecture - 28
Explosions in Closed Vessels:
Explosions in Confined and Unconfined Geometries, Maximum Pressure, Violence And K_G Values in Explosions, Venting

Good morning in today’s class we will look at explosions in confined and unconfined geometries. When we say confined, what is it we mean confined or unconfined.

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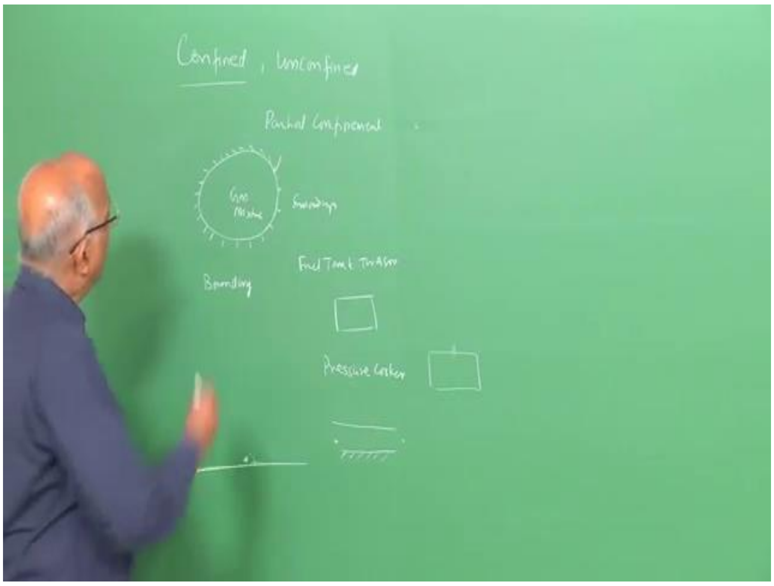

That means when the boundary of the explosive gas mixture what we have is sort of confined, we mean it is it does not allow gas to go and mix with the surrounding. That means, the boundary is impervious that means, the boundaries could be fixed the boundary could move. But as such the boundary isolates the gas mixture and the explosion what happens in it from the surroundings. And it is quite possible that the boundary will give way it may, it may give way and the products of combustion will mix thereafter with the surroundings.

When we say confined, what we mean is? The boundary of boundary containing the gas mixture is such that, it is something like a tank like, let us say we had the fuel tank in the TWA800 flight which we say exploded, and you know this particular fuel tank we presume that the vent is so small that, it is as good as a solid boundary or a storage vessel which keeps the gas within it, and the gas builds up the high pressure and then, it blows off

Similarly, when we talk in terms of, let us say the pressure cooker in the Boston marathon which happened let us say last year. You know the pressure cooker contains the high pressure gases you put a combustible gas, and till it starts leaking it starts venting out the gases well, it is something like a vessel with a fix storage volume. And therefore, and under these conditions when the boundary contains the gases, we say it is confined.

We could have unconfined like for instance, in the open medium I have the explosion taking place in the open medium without any constraints at all then, we say it is unconfined. You know in between confined and unconfined I could also have partial confinement, in which case let us say I have the ground as it were, and its explosion occurs just at the ground or above the ground. The gas could interact with the ground, may be with the blockages on the ground and therefore, it becomes something like a partial confinement.

May be even if I talk in terms of a tunnel which is burrowed through a hill and there is a road which goes through, you know it is a case which is open at the ends of the two tunnel. And I have may be the road going through the tunnel well, it is a case of partial confinement because it is open to the atmosphere, at the same time the boundary is partial boundary and not fully enclosed boundaries. When the boundaries fully enclosed we say well, that is confined. Let us get started with a confined medium, and let us say we look at explosions in a close boundary, explosions in let us say a close boundary.

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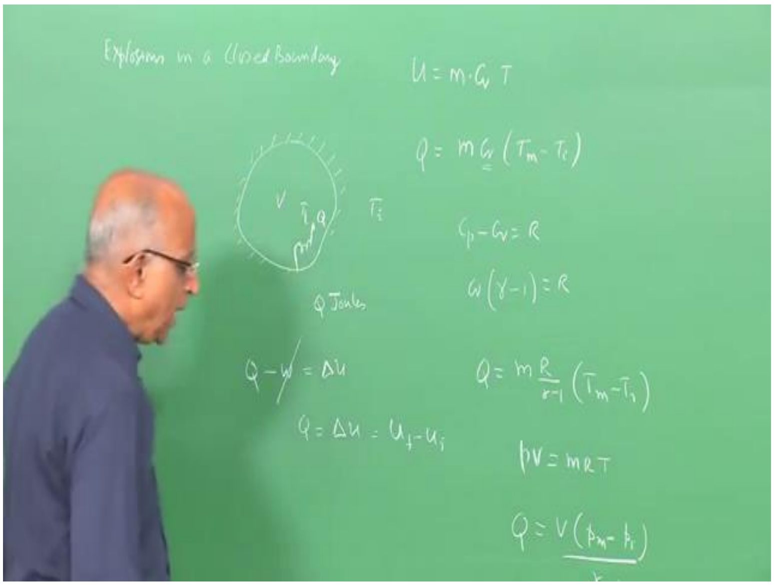

To begin with let us say I have a volume, let me presume that the boundary does not move. This is the boundary I have a volume of let us say some particular flammable mixture of gases volume v. Let it be at the same ambient temperature as the surroundings let us say, T initial let us call it of the gas, which is same as that temperature of the surroundings we call it as T i.

And now, I presume what I do is because of the chemical reactions which take place in this flammable mixture. Let us say some heat gets generated at the rate Q, let us say Q joules of heat get generated. Now, I want to find out what is the maximum pressure which can be reached within this storage volume that is, this fixed volume what is available.

Therefore, what we say is well, you do an energy balance, you say well the heat given is Q, the work done by the boundary is w and Q minus w is equal to the change in internal energy of this particular medium. Well, we say that the boundary is fixed the boundary does not move therefore, Q becomes 0, I am sorry w the work done by the boundary since the boundary does not move, it is 0.

Therefore, I have Q is equal to change in the internal energy of this medium. That means finally, when the maximum temperature is reached, when the maximum pressure is reached I have something like the final pressure minus the initial value of the, I am sorry final internal energy minus the initial value of the internal energy. And what is internal energy equal to? Internal energy is equal to the mass into specific heat at constant volume into temperature. And therefore, I can write that the heat which is liberated by the combustion or by the chemical reactions of the gases. I can write it as equal to m into Cv into the maximum temperature at what it reaches minus the initial value of the temperature.

Therefore, I am able to relate the energy which is deposited or which is released by this particular medium to the change in internal energy. And now I look at this expression Cv, can I, can I solve this to give me the maximum value of pressure because I would like the pressure to be such that, the boundary or the, or the particular case which holds this particular material, or this storage vessel which holds this, does not yield or does not burst under pressure. I am interested in such a pressure such that, the boundary can hold this pressure.

Therefore, I say well Cp minus Cv, we have been doing this earlier or rather Cv is equal to Cp by Cv is the specific heat ratio minus 1 into the specific gas constant. Or rather Cv is equal to r over gamma minus 1 and therefore, the expression cube becomes equal to m into r divided by gamma minus 1 into Tm minus the initial value of the temperature.

Now, you know when I, when I look at this particular one, let us assume that the gases are perfect in the sense that the Cp, Cv are constant, and the gas obeys the law pv is equal to mRT. And these internal energy is only a function of temperature, enthalpy is only function of temperature, h minus u is equal to pv therefore, pv is equal to mRT is the ideal gas of the equation. And since, we are considering perfect gases, we also presume Cp and Cv are constants.

Therefore, we have pv is equal to mRT and therefore, I have mR into the maximum temperature is going to be equal to p maximum into v, mR Ti is equal to p, initial into the volume because the volume is fixed. And therefore, I can write Q as equal to p. I take volume outside, volume does not change into pm that is the maximum corresponding to this, pi and this is divided by gamma minus 1.

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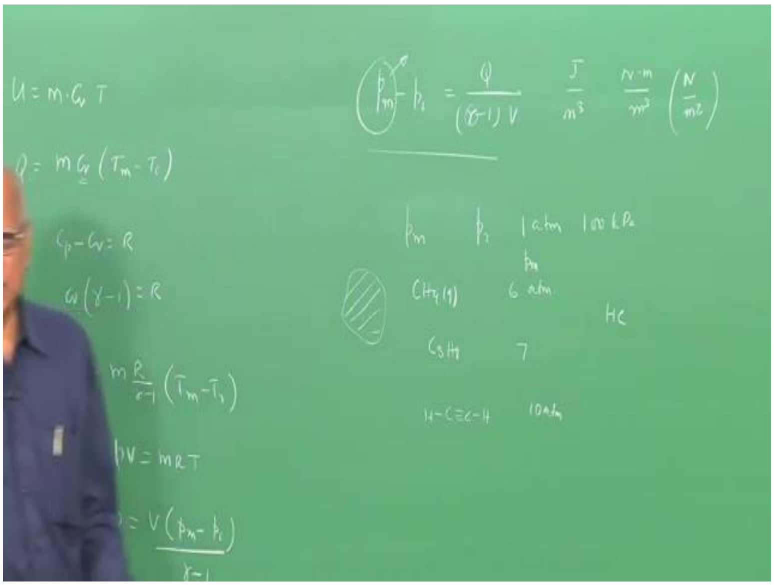

Or rather I get the value of maximum pressure pm minus the initial value of pressure of the gases which are contained here before combustion takes place, as equal to Q over gamma minus 1 into the volume. And let us say if the units are right, Q is in joules, if it is in joules we can also say joules divided by meter cube or rather joules is equal to Newton meter by meter cube.

And therefore, the pressure has units of Newton per meter square and therefore, if we express Q in joules and volume in meter cube, I get that the change in pressure in Pascal namely Newton per meter square. And this gives me the maximum pressure which can be obtained in a particular vessel of volume v in which chemical reactions are occurring.

Well, I get the maximum value of pressure, and in case the pressure of gases exceed the value which the boundary can hold well, the boundary breaks and you have wave which starts. Well, this is how we estimate the maximum value of pressure, and what is it we find? It is a strong function of gamma, you know normally for gases, you know gamma is for air it is 1.44 combustion gases, it is around 1.3, 1.22 of this order.

And therefore, the gamma must be accurate to be able to get the maximum value, and in this case since we presume that the gas is perfect, we also said gamma in the unreacted gases gamma in the reacted gases is about the same. And therefore, this method of estimating the maximum pressure is subject to some errors.

But let us put things together, if we were to do an experiment and calculate, what is the value of the maximum pressure, when the initial pressure let us say one atmosphere that is equal to 100 kilo Pascal. We find that for hydro carbon gases like let us say methane CH 4 gas, methane the maximum value of pressure is of order of something like 5.5 to 6 atmospheres. Whereas, if I consider propane C 3 H 8, which is little stronger well, it is of the order of 7. Normally it is between 5.5 to around 7 for most of the hydrocarbon gases except when we talk acetylene, no mind you we have been always telling that the triple bond in acetylene that is, acetylene C 2 H 2 is a strong gas.

In this case, the maximum value of pm is of the order of 10 atmospheres when the initial pressure is 1 atmospheres, and for all other hydrocarbon gases it is between we let us say 6 to 7 or let us say 5.5 to 7 of this order. Therefore, we tell also, but for hydrogen oxygen again it is higher of the order of 11 to 12 therefore, this pm which we say is the maximum value of pressure under constant volume conditions. That means, if I have a gas which is burning in at constant volume, the boundary does not move, the maximum pressure I get is around let us say 6 to 10 times the initial pressure is what we get.

Now, let us try to estimate this, it is of interest, you know we have been seeing such incidents happening. We talked of the pressure cooker bomb, we talked of the fuel tank and some aircraft exploding and therefore, let us try to estimate this pm for one particular case. Let me take you through a particular case study because in this case we will also learn to do, learn to apply the internal energy of formation. Let us do it for the particular case wherein, I consider let us say a closed volume…

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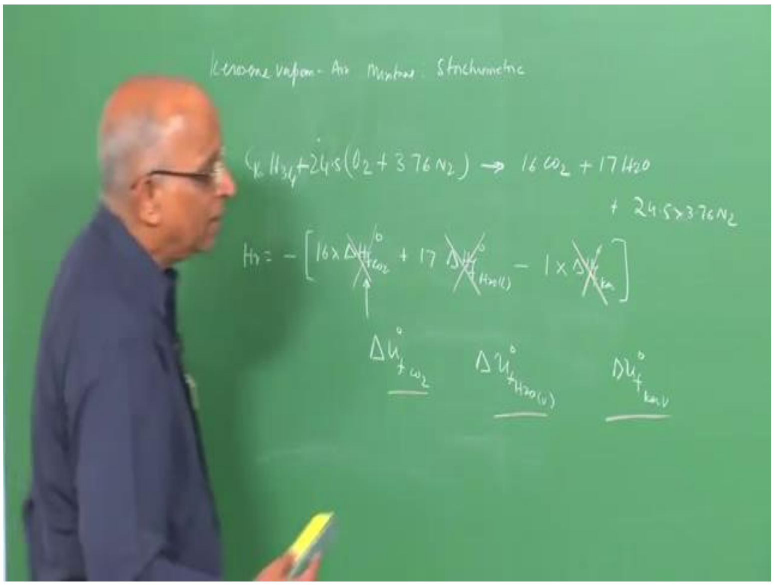

I do not need to specify what is this volume because I find, I want to estimate the maximum pressure, I find maximum pressure is depends on the energy density and therefore, we will not come directly into the picture.

Therefore, we also finds a function of gamma, let us see what is the role played by gamma also. You know, well I have a close volume let us say v meter cube, and it contains let us say kerosene vapor air mixture, just like what the central wing fuel tank in the Boeings 747 TWA800 flight, which met with an accident, what that is the kerosene mixture and lets us assume for the present it is also stoichiometric. We take stoichiometric because it is easier to do, but we know how to estimate the heat release and that is the value of Q there for different conditions fuel leans, fuel rich, and all that.

Therefore, we say well kerosene vapor, kerosene can be represented as do de cane, do de cane is C 16 H 34 plus air. What does air contain? It contains oxygen, each mole of oxygen is associated with 3.76 moles of N 2. And since we are considering do de cane C 16, I am sorry do de cane that means C 16, CN H 2 N plus 2, C 16 H 34, this gives me 16 CO 2 because it is being stoichiometric, I fall, I form completely oxidized products of the combustion plus I have 17 H 2 O, I have 34, 17H 2 O plus I have nitrogen. To be able to find how much nitrogen, I have to get the balance, I have O over here, this takes 16 O 2, 34 that is 17 by 2 O 2. Therefore, this 8.5, 8.5 plus 16 is 24.5 plus 24.5 times O 2 is equal to, I will get here 24.5 into 3.76 nitrogen, and nitrogen in the product comes out here

This is stoichiometric assumption, but in general, if the temperature of the products are higher, what happens is some of these gases like water will disassociate into let us say HOH, may be CO 2 disassociate. And therefore, this gives us an order of magnitude which is quite reasonable let us say therefore, how do I get the heat which is released in the reaction. We have been saying well, the heat of the reaction is equal to minus of the heat of formation of the products at standard conditions, 16 into heat of formation of CO 2 under standard conditions plus I have 17 of heat of formation of H 2 O under standard conditions are liquid minus I have heat of formation of kerosene, which is equal to 1 into heat of formation of kerosene let us say ker, this is the net heat release.

But immediately, we will jump up and tell well heat of formation corresponds to constant pressure. It is the enthalpy of formation. Now, we are talking of a constant volume that means a combustion is happening at constant volume. If it is happening at constant volume well, no work is done, I cannot consider enthalpy, but I must consider internal energy. And therefore, instead of using enthalpy of formation, I should be using something like internal energy of formation of let us say CO 2, I have to use internal energy of formation of H 2 O and mind you, I am not going to form water here, I am going to form vapor, I must use the enthalpy of internal energy of steam and not water over here. And similarly, for kerosene it is going to be I am sorry, internal energy of formation of kerosene vapor at the standard condition, and this is what I must be using.

Therefore, I may not be justified in using heat of formation when I am looking at constant volume of combustion. We made a note of it, I told in passing that yes when we talk of constant volume combustion, it is necessary to use the internal energy of formation. Therefore, but what is readily available in the literature is the heat of formation of substances, that is the enthalpy of formation, and tables on the internal energy of formations are rather rare. It is not readily available, but it is easy to estimate and that is the reason we are doing this problem.

Let us find out the internal energy of formation of CO 2, H 2 O and kerosene such that, we can find out the heat of reaction under constant volume conditions. Let us do that, we take the case of let us say, we start with kerosene.

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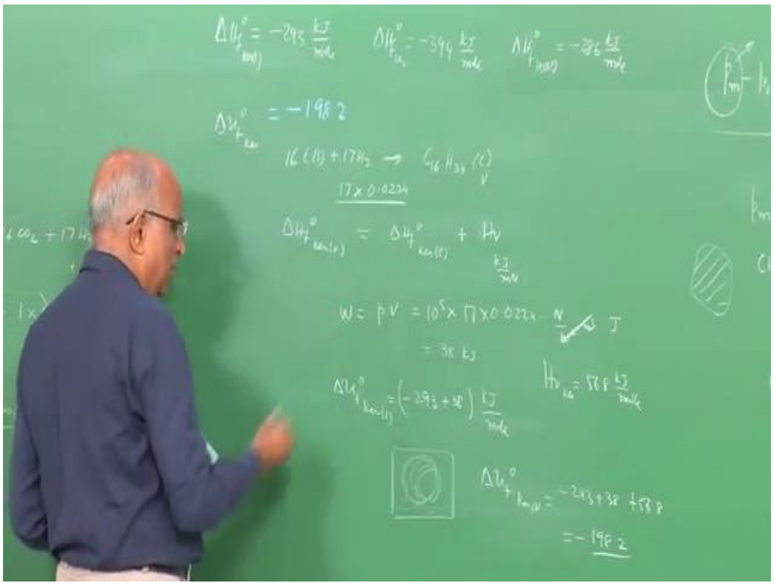

We start over here well, you know the heat of formation, if I go and look at the table for kerosene under standard condition, the value is given as minus 293 kilo joule per mole. If I were to look at heat of formation of CO 2 standard conditions, the value is equal to minus 394, and if I were to look at the heat of formation of H 2 O water, enthalpy or formation at standard condition for water as a liquid, this is equal to minus 286, this is readily available.

I want to be able to find out what is the internal energy of formation of kerosene, and how does, how is kerosene form? Let us go back to the definition, when I formed kerosene and we said that the formation for or the molecular form of kerosene is C 16 H 34, and how do you for kerosene? I take element at the standard state, may be carbon at standard state plus I have 17 of hydrogen at the standard state, I have 16 moles of carbon solid at the because carbon is the solid under ambient conditions, 17 of this and well, I am able to form this therefore, what is happening?

Well, carbon as a solid, has negligible volume, here I have 17 moles and I form well, I form kerosene which is again let us say a liquid, but you know if I were to form let us say, kerosene vapor it is going to be different, let us let us do for the kerosene liquid and then put vapor over here. If I were to form kerosene vapor then, I have a problem in that, you know this is the heat of formation I have for kerosene which is a, which is a liquid over here. Therefore, I must say if I were to take the value of kerosene as a vapor then, in that case it should be equal to heat of formation of kerosene, which is a liquid. And now, you know I have to supply heat to be able to make it into a vapor that means, I have to add the value of the heat of the vaporization that is latent heat of vaporization in kilo joules per mole.

Let us first determine what is the internal energy formation of kerosene liquid? When I look at this, I find well I have 17 moles here, and I have 16 moles here, the volume of the solid is negligible, the volume of the gas here that is, it is under standard conditions I am forming. Therefore, under the standard conditions, under standard temperature and pressure, one mole of any gas contains a volume of 22.4 liters therefore, 17 moles will contain a volume of 0.0224 that is, 22.4 liters, this is 0.224 meter cube.

This is the volume of the gas, here it is liquid, it is negligible volume. And therefore, when I form this particular substance, the volume reduces by 17 into 0.224, and what is the pressure? It is at standard conditions, that is one atmosphere pressure. And therefore, the work which is done by the, by these, by these two substances since, the volume is reducing, work is done on the system. And this work is equal to p into v, constant pressure into the change in volume, which is equal to 10 to the power 5 into 17 into 0.0224 meter cube. That is, we are talking of pascal that is Newton per meter square into meter cube that is so much joules Newton meter, so much joules over here, and this works out to be the work done by the gas comes out as 38 kilo joules, 38000 or joules or 38 kilo joules.

Therefore, we find that the heat of formation that is the heat of, I am sorry, the internal energy of formation of kerosene as a liquid is going to be the value of heat of formation was minus 293 plus 38. This is the enthalpy of formation so much 38 kilo joules per particular mole over here. Because we formed one mole therefore, this corresponds to kg per mole that means, I have to add 38 because the work is done on the system. That means, that is the available work and therefore, the internal energy decreases form minus 293 to something like minus 255 or so.

Now, if in addition, you in the particular example when we took, we found the kerosene liquid has vaporized formed a mixture of kerosene vapor and therefore, this is for kerosene as a liquid. And if I have to take the heat of formation of the kerosene vapor that is, delta u f for kerosene vapor is equal to, for the liquid it is minus 293 plus 38. And now, I have to supply more heat to have to supply the heat of formation to make it into a vapor, and that heat of formation of kerosene that is Hv for kerosene is equal to 56.8 kilo joules per mole, it is readily available in the literature. And therefore, I have 56.8 and therefore, the heat of formation of kerosene vapor I can write it as equal to minus 198.2.

Therefore, compare to the heat of formation of kerosene being minus 293, I have the internal energy of formation of kerosene as equal to minus 198.2. So, I can estimate the internal energy of formation of CO 2 and H 2 O, let us determine this because it is quite illustrative of the method what we must be using, let me do it over here. If I write the equation for the carbon reacting with oxygen to form CO 2 what is it I get?

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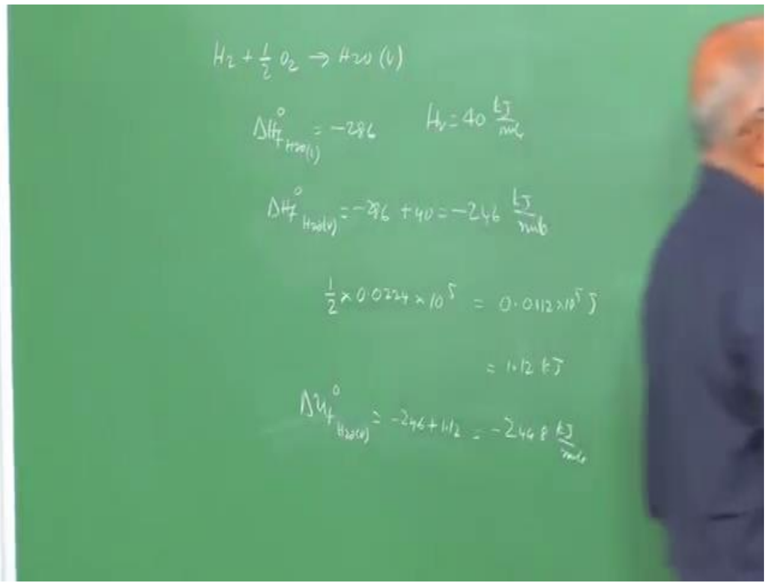

C yes plus O 2 gives me CO 2 gas. Well, carbon is a solid one mole, there is no change in volume and therefore, according to this equation well, I have the heat of formation of CO 2 and a standard condition must be equal to the internal energy of formation of CO 2. And therefore, I presume that the internal energy of formation of CO 2 remains the same as the enthalpy of formation CO 2, 394 kilo joules per mole.

Let us us estimate it for water and since, we said it is not the water which is available, but water vapor which is available in the products of combustion. Therefore, let us find out the internal energy of formation of water vapor at the standard conditions. Now, you know let us write the equation again, H 2 element, half element gives me H 2 O. Well, what happens, there is a decrease in hydrogen gas at standard condition, oxygen gas at standard conditions, water being formed at standard condition, well the volume now reduces by one and a half, but if I were to have H 2 as a gas or vapor then, the volume reduces only by half.

Therefore, if I were to write the value of let us say, the heat of formation of water. We said it is equal to minus 286, if I have to find out this is as a liquid, if I have to get heat of formation mind you it is a standard condition of H 2 O as a vapor well, it is going to be minus 286, the heat of, the latent heat of formation water hv is equal to 40 kilo joules per mole. And therefore, it is equal to plus 40 which is equal to minus 246 kilo joules per mole, and now I find well if I look at water well, I have 3 by 2 moles over here, giving one mole of vapor, there is a decrease by half a mole of vapor.

And therefore, the work done in decreasing the mole by half corresponds to half into, the change in volume one mole is associated with 22.4 liters. Or rather 0.0224 meter cube and at the standard pressure conditions is 10 to the power 5. And this is equal to 112 that is equal to 0.0112 into 10 to the power minus 5 joules or rather this is equal to 1.12 kilo joules. You know the changes are quite small in a large number and therefore, I tell myself well the internal energy of formation of water vapor is equal to minus 246 plus 1.12 may be because the work is done on the system. And therefore, it comes out to be equal to minus 244.8 kilo joules per mole therefore, the internal energy of formation of water I write it over here.

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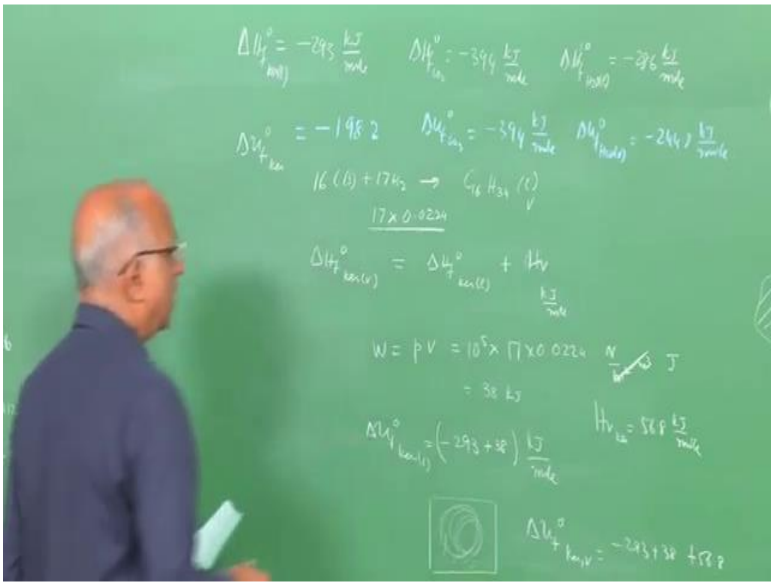

Water vapor using these internal energy of formation, I find out what is the energy released in the reaction similar to what the way we use the enthalpy of formation, or the heat of formation. And therefore, what is the energy which is liberated in the reaction.

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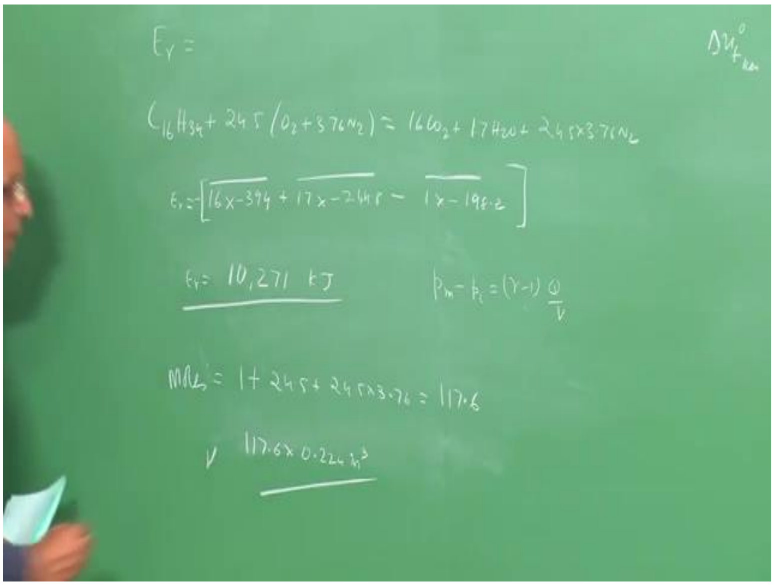

Let us call it energy, which is liberated in the reaction at the constant volume, which is our Q over there for the particular reaction. And that comes out the reaction is we had the reaction here, we let us rewrite the reaction, I think I rubbed it off. We have C 16 H 34 plus, we have something like 24.5, this is a sixteen plus 8 here, 24.5 into O 2 plus 3.76 of nitrogen, which gave us 16 CO 2 plus 8.5, no I am sorry 17 H 2 O plus I have the same thing 24.5 into 3.76 of nitrogen.

And therefore, if I were to write the expression for the energy released in this reaction, it is equal to 16 into the minus internal energy of formation of CO 2 minus 394 minus of this first term plus I get 17 into, for water is equal to minus 244.8 minus for the reactants. It is only one mole over here, these are standard elements, this is also standard element no change over here. And therefore, I get the value as 1 into the value for kerosene is equal to minus 198.2, and you know if I simplify the value of energy released comes out to be equal to the value comes out to be 10271 kilo joules.

You know this is the value of the energy released in the constant values so much kilo joules, but you know if I look at the expression, I am interested in the maximum value pm minus p i is equal to, we found out is equal to gamma minus 1 into the energy released divided by volume, I am interested per unit volume. And the volume corresponds, you know the volume does not change, I had 1 mole of the vapor and I have 24.5 moles of the oxygen. I have 24.4 into 3.76 moles of hydrogen. Therefore, the volume which remains constant is equal to 1 corresponds to moles, how many moles does the volume corresponds?

Let us say the number of moles are 1 plus 24.5 plus 24.5 into 3.76 which is equal to the number of moles is equal to 117.6. And therefore, the volume associated with this is equal to 117.6 into 22.4 liters or 0.224 meter cube, this is our volumes.

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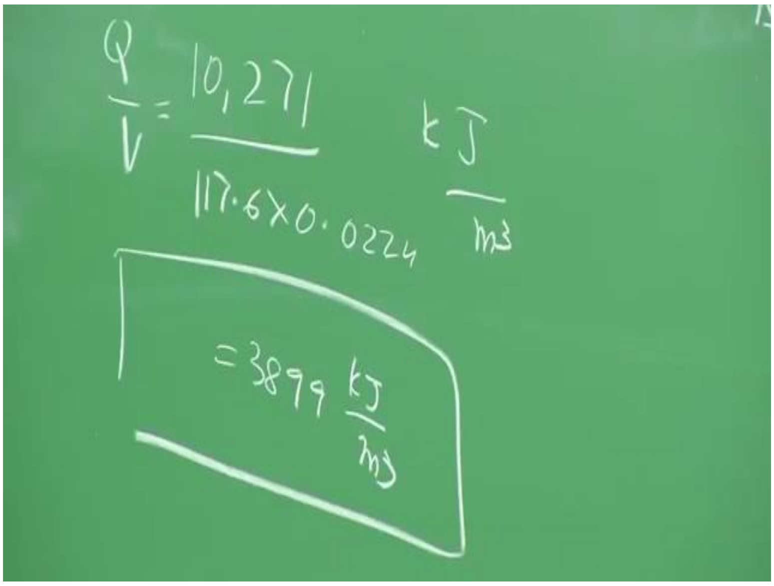

And therefore, if I were to substitute the value of Q by v, it is the heat released per volume is equal to the value of 10 to 71 divided by 117.6, which is moles into 0.0224 so much joules per meter cube. You know we had written the internal energy of formation as kilo joules therefore, it is equal to kilo joules per meter cube.

Therefore, I get the value of Q by v and this Q by v comes out to be equal to something like 3899 kilo joules per meter cube well, I have got the value of Q by v. And now if I, if I were to estimate the value of the maximum pressure, I get pm minus pi is equal to gamma minus 1 into the value of Q by v.

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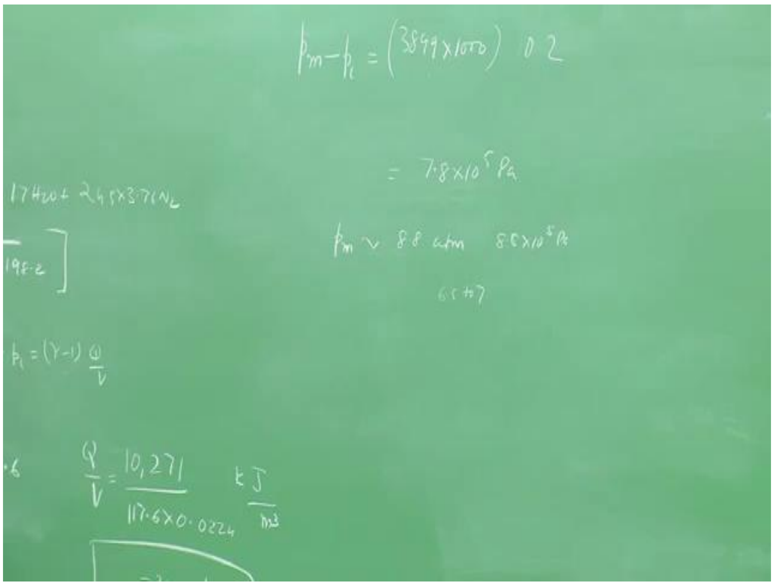

And therefore, I get pm minus pi is equal to 3899, this is in kilo joules that is, 1000 so much joules, in Q by v into gamma minus 1 taking gamma as 1.2 for the mixture since, vapors have a lower value of gamma, it is equal to 1.2 minus 1, that is equal to 0.2. This gives us something like 3.9 something like 7.8, 7.8, you know this becomes 0.2, 7.8 into 10 to the power 5 Pascal. Or rather taking the ambient pressure as 10 to the power 5, you get the maximum pressure is approximately equal to something like 8.8, 8.8 atmospheres or something like 8.8 into 10 to the power 5 Pascal.

Therefore, we find that the maximum pressure what we are estimating comes out to be, this, it is somewhat larger than the value, which we should we should get. Normally for hydrocarbon fuels like kerosene, we should get a value around 6.5 to 7 atmospheres. But anyway, this is the larger reason being as I said, we have made an assumption that gamma does not change in the reaction, we are also…We did not account for dissociation at high temperatures, but it gives an order of magnitude with which we are concerned about. Now, this value of pm therefore, let us spend a couple of minutes on the type of results what we have, we find that the maximum pressure in the constant volume explosion is that that means the value of pm is normally around let us say 5.5 to 7.5 for most hydrocarbon mixtures.

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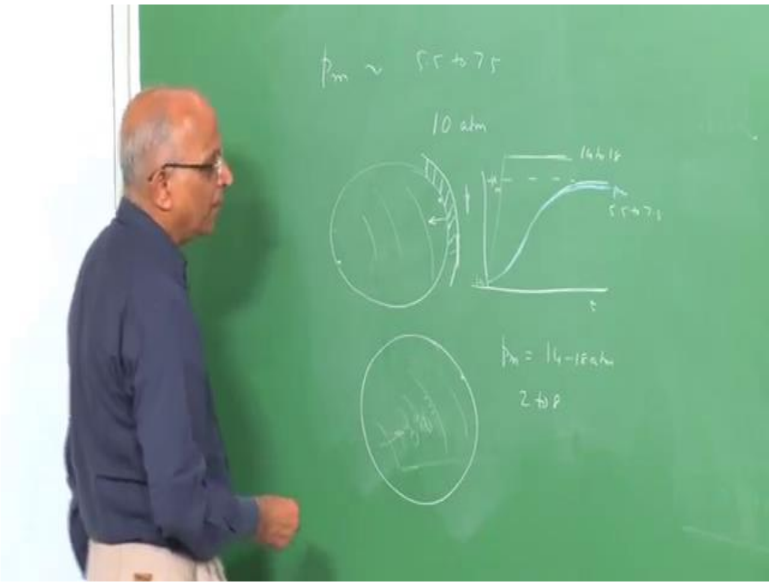

It is around 10 atmospheres when the initial pressure is 1 atmosphere for the acetylene oxygen, and around 11 to 12 for hydrogen air stoichiometric mixtures. It depends on the, it depends on the equivalence ratio of the mixture 0.1 because that is what determines the energetic. You know to some extent, we must also tell ourselves you know if I look at a particular volume, and let us say I initiate a spark over here and then, I am calculating the maximum value, the maximum value of pressure corresponds when the entire gas is burnt. But, if I initiate an explosion at one end, and it goes to the other end, by the time the entire gases consumed, you know the valves of the vessel will cool the final mixture.

And therefore, if I were to plot let us say pressure versus time in an adiabatic conclusion, maybe I will get their maximum value of exposure, which is reached after some time as pm. But if the container you know any container is not adiabatic, what is going to happen, initially it will follow this condition. And maybe it will because of the cooling effect the value of the pm will be lower than the actual value of pm when the container is adiabatic.

Well, this is how we estimate the maximum value of pressure, but when I look at this pressure, this is how it evolves from the initial pressure to the maximum value of pressure, and maximum value of pressure corresponds when the entire gas gets burnt. You know when we did the lump mass system, we assumed that the entire gas gets burnt, but in practice it is not possible because a fling propagates and continues to burn the gas.

Now, this brings us to the next part, you know supposing instead of the flame propagating, supposing I have the same volume, the same gas, but let us say a detonation propagates. If a detonation propagates, the maximum value of pm, which we saw, which we did earlier, we found that it is of the order of 18 atmospheres compared to 5 to 8 atmospheres what we get. Because detonation is a compressing solution we found out with the pressure of gas is quite high, for hydrocarbon mixture it is of the order of 14 to 18.

Therefore, when we talk in terms of detonation, we are talking of a rapid increase in pressure of the order of pb 14 to 18 corresponding to something like 5.5 to 7.5 for hydrocarbon mixtures5 when we are having a flame. And if by chance let us say that the flame initially, I start with the mixture which is initially let us say I have a laminar flame it becomes turbulent, and in the process it converts to a detonation. Well, I can have quite high values of pressure here. There is one more reason which we have to, which we have to one particular phenomenon, which we have to keep in mind.

Supposing, I have an enclosure and I have a shock wave, that is preceding the chemical reaction, that is a detonation tracking the a surface. And if the impedance, mechanical impedance of this surroundings is higher than this, you have a reflected wave which comes out, and we saw that the pressure behind a reflective wave could be anything between 2 to 8 times the initial value. And therefore, you know when we have a detonation well, I could get extremely high pressures at the valves corresponding to the maximum value.

Therefore, we summarize this by telling, if I were to form a flame, I know how to calculate the maximum value of pressure. If I form something like a detonation well, I get the detonation pressure in which case pm is very much greater than what we were talking of the order of 5 to 8 for most hydrocarbon mixtures.

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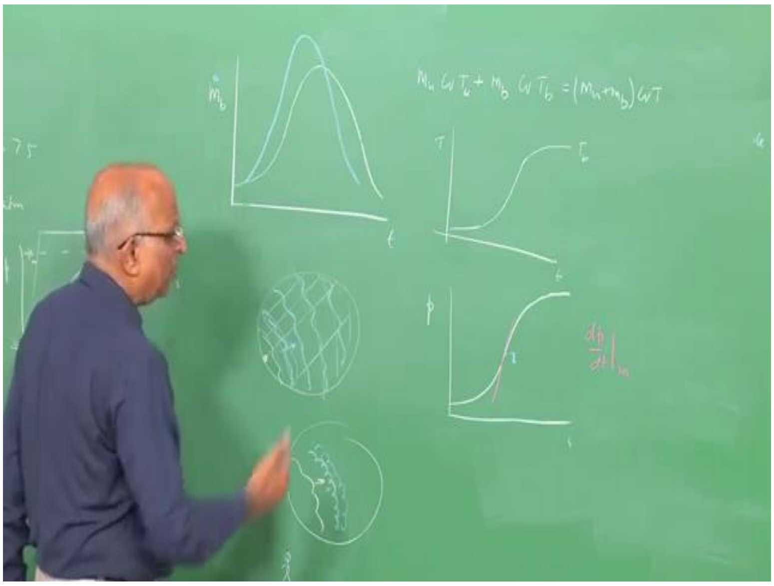

Having said this, see we also, yes we found out the maximum value of pressure, but what is the rate at which the pressure increases? The rate at which the pressure increases, decides the violence of the reaction, how violent it is. Does it just rapidly push it up, does it go gradually? And therefore, I think we should have some handle on how the dp by dT of the pressure time trace changes in a constant volume explosion.

For instance I have a given volume, this volume explodes, I am interested in finding out what is the maximum rate that means dp by dT what is the maximum value which is obtained in this because this is what is going to tell me what is the type of pressure wave which I can get in case the vessel burst. What is this maximum value is something which is of interest to me therefore, let us try to find out what is this value? Let us take a look at this, let us take the look at the pressure time trace and the, and try to conjecture something over here.

Well, what happens let us say mass of gas which is getting burnt as a function of time, you know if I say mass of gas is getting burnt. Initially I had total unburnt gases, I form a flame and this flame keeps propagating out, this flame propagates over here, propagates over here, propagates after some time over here, and these are the different instances of time. Therefore, now if I were to tell I am interested in the rate at which the mass of gases are getting burnt, the rate at which the mass of gases are getting burnt corresponds to the speed at which the flame is propagating.

Let us say it is a laminar flame, I know how to estimate Su, we have already studied. If the surface area at this particular location of the flame is let us say, Af and the, what is the rate at which it is burning into rho u that means, we are talking this is the speed at which the mass is getting consumed, and the rate at which the mass is burning is equal to Su, Af into rho u. And therefore, if I were to plot this, I find well, I strike a spark over here and what is going to happen well, the area keeps on increasing. But after some time for this particular geometry what I have, that means the area decreases.

Therefore, the mass which burns should be something like this initially it starts off with a small area because I presume that the flame velocity is constant, the initial density is a constant, and this is the way it should burn. But as the gas burns it is pushing the unburned gases ahead of it that means, well I have the mixture which is burning here, the flame pushes the gas ahead of it. And to an observer who is standing outside and watching this flame he will find that the flame is moving faster because it is moving along with the moving gas and therefore, it moves faster.

And therefore, the Su increases, if by chance this flame becomes turbulence you have high intensity turbulence, it forms wrinkles on it, the mass burning rate increases. And therefore, as the flame propagates, you know what happens is the velocity of flame also increases, in addition to this, this is only with area increase. And therefore, in general may be it will increase and come down like this is. This is the rate at which the mass burning rate changes. And you know if I look at the gases what gives me the final temperature, the final temperature is the unburned gas into Cv into T plus I have burned gases which is Cv into the burned gas temperature.

This is what gives me the value of mu plus mb into Cv into the temperature over here, I presume that the specific heat does not change, and this is the mean temperature of the gases which are mixed together. I presume they are thoroughly mixed, I get a mean value of temperature. And therefore, what is it I get? This is the initial value that is the unburned gas temperature, this is the burned gas temperature, this is the mixing cup temperature, this is the mixing temperature over here. And therefore, when I do this since it is proportional to their mass of gas getting burnt, and the rate at which the mass gets burnt keeps increasing, I get the value of temperature as a function of time initially it starts with this, and then it reaches the peak value it increases. And thereafter it stabilizes and reaches a maximum value over here which corresponds to the burn gas temperature when the entire mass of gas is burnt.

Using this, I can now find out well the pressure of gases again, I am coming back to the same thing namely the pressure within the container as a function of tank starts off and goes to a high value. And the maximum pressure corresponds to the point of inflection that means, that region wherein I have maximum taking place, and thereafter anyway the slope changes, that means the curvature changes, this becomes the inflection point, and this is the value of the maximum dp by dT what we get. That is the slope at the inflection point gives me the value of dp by dT maximum.

And therefore, I can find out the sort, I can use this expression estimate the value of dp by dT using conservation. But as you see somewhat approximate, we are just dealing with the energy of the burned gases, we are dealing with the energy of the unburned gases which are ahead of the flame and then, arriving at the mean mixing temperature, and from the mixing temperature I estimate the value of dp by dtm, that is the maximum value.

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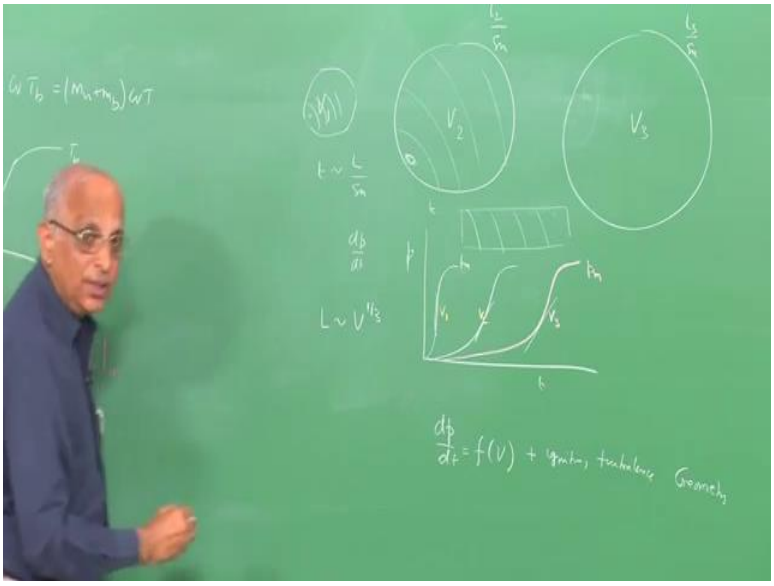

Supposing, I have a certain volume of gas let us say I have a small volume of gas v1, I have a slightly larger value of gas v2 and still I have still a fixed volume which is v3, which is still larger. Now, between these three, will the value of dp by dT for the same gas, under the same condition of ignition, same condition of turbulence, same condition of propagation, will it be same or different? When I look at this particular expression here, I have a small volume, and what is going to happen? The flame gets started over here, it traverses in a slightly because the length the flame has to traverse is much smaller. In this case, the flame has to traverse a slightly larger distance, in this case the flame has to traverse much larger distance.

Therefore, in the three cases if I were to plot the value of pressure versus time, for the small volume well it traverses and reaches the value of pm, and anyway the maximum pressure is only gamma minus 1 divided by the energy density Q by v, volume does not come, pm is independent of the volume. When the volume is slightly higher, what is going to happen? It is going to traverse a slightly longer distance and still reaches the value of pm.

If I have a still larger volume, let us say this is v1, this is v2, if the volume is going to be much larger well, it is going to traverses much larger volume and reaches the same volume of pm, this is volume v3, well we find, well in this case the value of dp by dT is quite steep. In this case, it is shallow, in this case well the inflection point is somewhere over here is still shallower. Therefore, we find well the value of dp by dT is equal to a function of the volume of the gas.

Mind you, it is not only the function of the volume, but it also depends on the turbulence level in the mixture, the type of igniter what I have. If I dump lot of energy into the medium well, the gas gets heated, the flames will be higher. Therefore, we find it is function of volume plus it is also a function of the ignition source what we have, it is also a function of turbulence in the medium, it is a function of type of gas which is used, but in addition, you know we also find well in the addition to turbulence ignition with volume of the gas, it could also depend to a large extent on the geometry of the vessel itself.

For instance if the, if the head is spherical well, this is the way the flame propagates, this is going to be something like a vessel with a long l by d, that is aspect ratio is long well, the area is not going to change significantly as the flame propagates. And therefore, it depends on the geometry therefore, dp by dT is the function of all these things then, how do we express it? Can I put the volume here and say dp by dT in this case is going to be different?

Therefore, we look at the problem again, we say yes, you know to be able to propagate in a small volume, the time taken for flame travel in this case is small, in this case the time taken is larger, in this case it is still larger, and what is the time taken? It depends on the mean length over which the flame propagates divided by if the flame propagation speed is let us say, Su and it is constant and it is l by Su. In this case, it is going to be equal to the mean length divided by let us say the same value, it is the same condition over here, it is equal to let us say l3 by Su.

Therefore, you know the time taken, that is the mean time taken corresponds to the length of flame travel, and what is this characteristic of length? The characteristics of length goes as volume to the power 1 by 3. Because volume has units of meter cube, length has units of meter and therefore, I can tell myself if the condition of ignition, if the condition of turbulence, and if the geometrical constraints are all the same for a given mixture.

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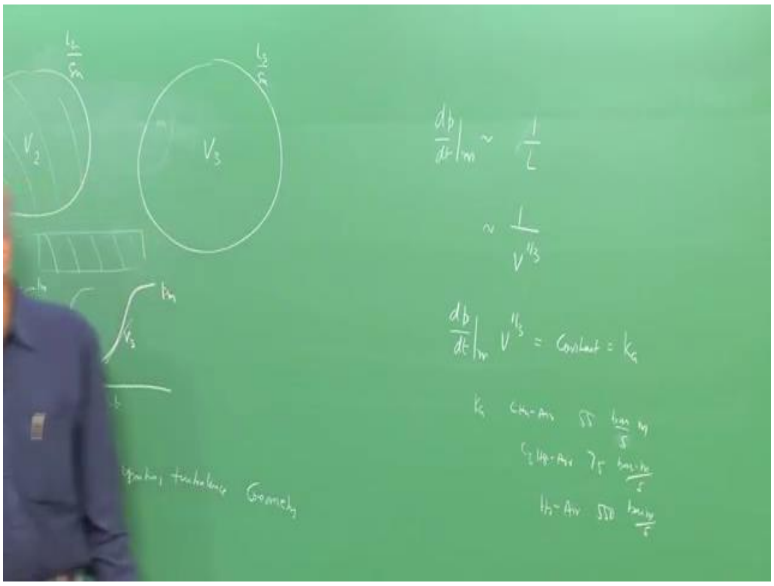

I can always write the value of dp by dT maximum, as a function of length that means, it depends on the length and we find as the length keeps decreasing, or the volume keeps decreasing, what is going to happen? The length keeps decreasing and therefore, I get sharper spike or therefore, it goes as 1 over l, not directly as l or rather it goes, length goes as v to the power 1 by 3. Or rather I get dp by dT maximum into b to the power 1 by 3 is something like a constant, and this constant is known as a kg value for a given gas mixture.

It kg as we now the, now say function of the igniter, function of turbulence, function of the geometry, but it is a constant for a given gas mixture under these conditions also being constant. And this kg value is what I wanted to specify, when we consider methane air mixture stoichiometric, the value is around 55, we are talking of pressure by time, that is bar by second, you know unfortunately the unit of pressure used is bar, it is something like bar per meter into volume 1 by 3 is bar meter per second, bar per second into meter 55 bar meter per second.

If I consider propane air C 3 H 8 air, it is of the order of 75 bar meter per second, if I consider a gas like hydrogen as stoichiometry, it is something like 550 times, I am sorry 550 bar meter by second. Therefore, this gives us the violence of the gas being generated, that is the maximum value of dp by dt, I use this particular expression.

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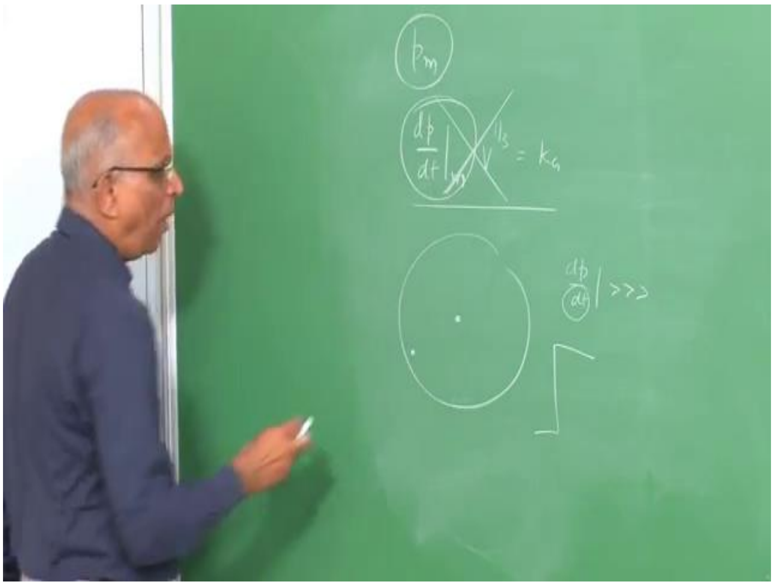

Therefore to summarize at this point, we can say well we have estimated the maximum pressure in constant volume explosion namely pm. We have also estimated the value of dp by dT maximum, and this we find is equal to 1 over 3 into 1 over 3 is a constant for a particular gas having the medium, having the same turbulence ignition source being similar, and the geometry being similar. Values of this are available in literature, using this I can find out for a given volume what is the severity, or the rate of pressure rise in the explosion.

This is what is used, but in general I can tell if I can ignite the gas at the center because the length of flame travel is lower well, the dp by dT or the violence is going to be larger then, if I am going to ignite the gases at the valves. We also find a few things, you know if we have may be depending on the geometry, depending on the blockages, if by chance what is going to happen. If there are blockages or if the flame becomes a detonation in its travel well, the dp by dT maximum for a detonation is going to be very much higher and I cannot use this particular formula.

Because this formula is only true when I have a flame which is propagating, and if a detonation propagates well, the velocity of propagation is so high that I get a spike or a rapid increase in pressure.

Therefore, now the question comes if I have a high value of dp by dt, or if I have high value of pm, how do I control this? You know in practical cases it is important for us to be able to restrict the maximum value of pressure and also control the rate of pressure rise, and for that you know we use the following in vessels of constant volume we put vents.

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Like we allow the gases to go out, or you put something like a diaphragm which we call as a burse diaphragm, or you have something like a explosion doors. In other words, I have a volume over here, I put something like a burse diaphragm, which if the pressure exceeds some limit, it goes away and what is going to happen well, I have the pressure versus time. In the case where there is no such diaphragm or a vent which is allowing such gases to go, I have the pressure increasing like this.

Supposing at this pressure, the diaphragm burst what is going to happen well, the pressure is going to droop like this, I can control my value of pressure. This is the value at which the diaphragm gives way, this is my maximum pressure and this is how you control the pressure in cases wherein you are restricted by the container to hold some particular gas pressure.

Well, we leave it at these things that we estimated by the rate of a flux of gases from either the explosion door or the burse diaphragm, and we can always find out what is this and do the particular problem. Well this is all about explosions in a confined geometry. If we talk in terms of unconfined geometry, we have already done it, we found out that the that the value of the time taken for chemical reactions let us say, the energy release for when the activation energies are large, spikes like this. This particular spike in the energy release, even in an unconfined geometry we said can cause an explosion. Well in the next class, we will deal with dust explosions and we will find well, the same criterion applies there also.

Well, thank you.