Introduction to Explosions and Explosion Safety

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Lecture - 32

Rupture of Pressure Vessels: Explosion of Cryogenic Storage Vessels
Stratification
Thermal Overfill
Rollover
Condensation Shock
Rupture of Pressure Vessels
Energy Release
Constant Pressure Explosion
Maximum Experimental Safety Gap

Good morning. In today's class we will consider the explosions involving storage vessels, which contain cryogenic fluids. We will also consider something on rupture of pressure vessels after we deal with explosions involving the cryogenics fluids.

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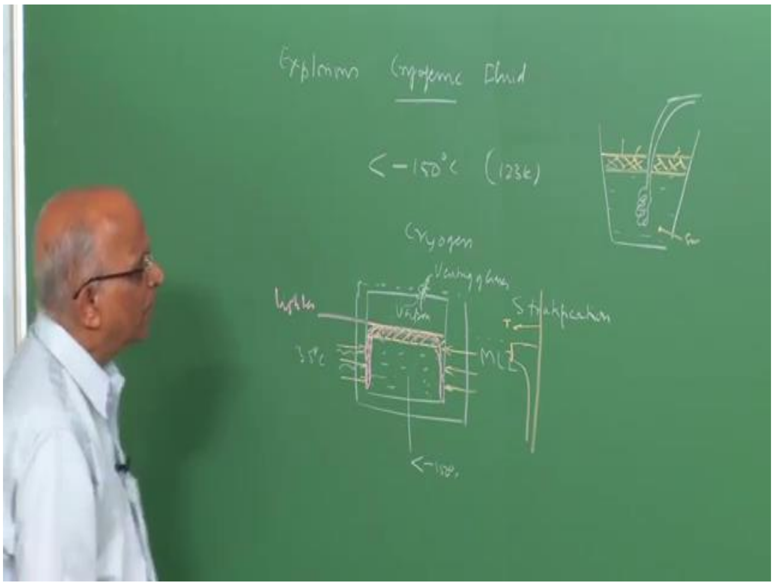

But to come back to the particular point of let us say explosions involving cryogenics fuel let us say, we must first define what a cryogenic fluid or liquid is. You know any liquid which as it is boiling temperature under normal atmospheric conditions, less than minus 150 degree centigrade that is equal to 123 Kelvin is called as a cryogenic liquid, or it is also known a cryogen.

You know, we find these cryogens are important not only as fuel like, hydrogen is a fuel may be LNG is a fuel. It is also used for several other applications in the industry these cryogens are used. And we would like to understand, what are the types of explosions which take place, when they are kept in a storage vessel? Like for instance, let us say, I want to keep a cryogen in a storage vessel apparently, you know this is the cryogen, and we say the cryogen is a low temperature fluid. That means, it is boiling point under atmospheric conditions is less than 123 Kelvin well, the vessel has to be insulated, very well insulated.

Let us say, it is insulated using let us say, double wall construction with vacuum or let us say, with several other, may be foam, may be you have multi layer insulation and all that. Such that, you like to prevent the heat from the ambient, see the ambient is something like a let say 35 degree centigrade. The fluid here is at temperature less than we say, minus 150 degree centigrade.

Therefore, there is always a tendency for heat to flow in and therefore, you give sort of a good insulation multi-layer insulation, vacuum insulation, may be some powdered insulation, maybe some puff insulation, and so on. And therefore, let us say this is it, the vessel is very well insulated. Now, even if you give the best possible insulation, there is always some heating leak which occurs. There is always some heating which is going to take place. You know maybe it is small, but still it is there because of the large temperature differences.

And what does this, what does this heating do? It causes, may be you know when I heat this particular surface over here, little bit of heating. May be the fluid becomes less dense over here because whenever I heat a fluid it tends to become less dense, and the fluid sort of rises up. Here it rises up and therefore, you have something like the fluid, which gets heated in the wall region, tends to rise up because it is lighter in density compared to the original fluid. And it sort of accumulates at the surface.

Therefore, you have the convective currents over here which go and cause the current to go like this. And you have the migration of the heated fluid, which is less dense and you ultimately end up, with something like a lighter fluid on top, may be lighter fluid on top, and may be the heavier fluid at the particular bottom. Actually, the lighter fluid is at slightly higher temperature, and with respect to time, what is going to happen is, you have something like lighter fluid at the top, the heavier fluid at the bottom, and this process of having because of the heating leak which takes place, and in any vessel.

However, well you insulate, there will always be some level of some small heat in leak, which heats the liquid, and you have this process which is known as stratification. In other words, the lighter fluid comes to the top, it is little warmer and therefore, if I were to now, plot the temperature gradient. If I were to let us say plot the temperature gradient over here. What I observe is, yes well, at the top I have temperature which are slightly higher, temperature which is slightly higher, may be on this scale I plot the temperature.

And then, I have the temperature lower. That means I have a warmer fluidon top resting on a, on a relatively lower temperature cryogen. You know, this is not only true for cryogen, it is also true you know at home, if I have let us say, a bucket of water, and I put something like a heater coil in this particular water, I supply, I heat the water. What is it we observe? You know we find that when the water is heated, on top of the water you have hot water at the top or quite something.

In fact, you will find boiling of water takes place, but the temperature of water in depth is going to be smaller. This is also the same thing like stratification, may be the less dense water when it is heated, water when heated gets lower in density, it rises to the top. And you have the warmer layer at top which is called a stratification. Therefore, we find well you have stratification warm layer and therefore, what is going to happen? The gas, that is the vapor, of this particular cryogen which is on top, is also warm. At this particular temperature, it tends to be in equilibrium, and if the more and more warmer fluids comes over here, well gas is generated.

And therefore, in all cryogenic appliances, you give something like a vent wall, through which if the pressure increases well, the vapor gets lost, gets released through this particular vent. And when it gets released, the pressure decreases well, the temperature decreases and you can also control the temperature because, once the vapor is released the temperature decreases, the temperature decreases. This layer is in equilibrium with the vapor here and therefore, you havesome equilibrium type of thing.

But all sudden done, you have to release the vapor in order to keep the pressure in a cryogenic storage vessel constant. Therefore, you have the venting of gases. Before coming to a particular problem, let us take a look at 3 of 4 cryogens, which are used and then, discuss what are the problems, is there any particular problem associated with storing a cryogen in a particular storage vessel, in a well-insulated storing vessel. But as we keep saying, whatever be the type of insulation there is always some heating leak taking place. Therefore, let us put a few cryogens, well we can talk of liquid helium.

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Well liquid helium, as a normal boiling temperature at atmospheric pressure of something like 4 Kelvin. You could have liquid hydrogen, the normal boiling temperature at atmosphere pressure is 20 Kelvin. I could also think of liquid nitrogen, which has the normal boiling temperature at atmospheric pressure is 77 Kelvin. I talk of liquid oxygen, which is at 90 Kelvin, the boiling temperature. And the last one, I talk in terms of liquid methane, and the temperature, boiling temperature is 111 Kelvin at the ambient conditions.

Well, these are the 5 typical cryogens, whose, which are cryogens because their operating temperature is less than minus 150 degree centigrade or 123 Kelvin. Now, if we store some of these cryogens in this particular vessel and let us say if it is not totally pure, what do you mean by not being pure? You know this is an essential part of it, like for instance let us say I store LNG.

You know if I talk in terms of liquid natural gas, and we have been considering this we considered the LNG explosion at Cleveland, we said well, we talked in terms of natural gas explosion at ural. We talked in terms of the liquefied one, which entered the gutters and cause the manholes to sort of rocket up, or sky rocket. Therefore, you know when we talk in terms of LNG, and this LNG, is an important fuel now a days, it is transported all over the world in tankers, not only that it is also transported in pipelines.

And therefore, and it is also stored, it is also stored in tanks. Like for instance of cochin harbor, we get LNG, we then store it in huge tanks. And these tanks are again, as I say well insulated with a vent valve, such that if you have vapor which is being formed occasionally vented out such that, you have this, and what happens? Let us consider this LNG.

LNG is from the gas fields, it is got as a vapor and it contains not only pure, it is not pure methane, it consists 90 percent of methane. It also contains some other substances, and the other substances which contains are in addition to methane the formula should have been CH 4. It also contains some ethane C 2 H 6. It contains some propane C 3 H 8. And also little bit of let us say may be petrol, like for instance gasoline. Well, if I look at the boiling point temperatures, you know well liquid natural gas is stored let us say as a liquid. It is stored as a liquid.

We say, well it also contains some impurities and these impurities are all fuels mind you. It contains some liquid ethane, it contains some liquid propane because the temperature is low. The temperature is of the order of something like 111 Kelvin which, I can say is may be 273 minus 111 which is equal to something like minus 162 degree centigrade because it is below 0 degree centigrade.

You know at this temperature, may be the ethane which is contained over here is also a liquid, propane is a liquid. But the boiling point of let us say methane, is we say is minus 162 degree centigrade of ethane, the boiling point is something like minus 85 degree centigrade. For propane the boiling point is minus 42.4 degree centigrade. And for gasoline it is something like plus 69 degree centigrade. Therefore, when I consider liquid natural gas, which is stored in large quantities, in all over the world, you know you have. This LNG is not pure methane at this particular, at this particular boiling point temperature at atmospheric pressure, but it also has other traces of let us say, ethane, propane, and gasoline.

And therefore, what is likely? Let us consider the problem just I keep the LNG, cryogenic LNG in a particular vessel. And since, it contains some of the heavier constituents. Mind you, C 2 H 6 is heavier than methane, propane is even heavier molecular mass is higher well, gasoline is something like may be C 20 H something therefore, it is even higher. Therefore, when I store these things in a vessel now, I will remove the outer layer, I just say well I store the LNG over here, what is going to happen? The heavier constituents such as say, ethane, propane, and gasoline are all at the bottom because it is heavier.

Therefore, maybe I say gasoline is over here, propane here and therefore, the heavier quantities are at the bottom. And the lighter methane which constituents more than 94 percent is what is at the top. Of course, you have the vent valve over here and some because of the, we talked in terms of stratification. We said well the thing arises and I have a stratified layer on top, this is my stratified layer on top.

Now, what is going to happen? It is not that heating leak occurs only from the side valves, but heating leak will occur also from the bottom. And therefore, when heating leak occurs from the bottom, you already have a dense, denser, relatively denser, may be ethane, propane, gasoline at the bottom. And therefore, whenever some little bit denser liquid is heated by heating leak from the bottom, well it is density decreases. But when it decrease, when its density decreases for these heavier substances, it is density could still be less than the liquid methane on top.

Therefore, even though it is slightly warmer, it tends to still be at the bottom because even though it is heated more than the liquid over here, more than the liquid methane over here, its density is still not less than methane for it to migrate up. And therefore, it continues to get heated till a particular time, when it is density, let us say liquid density of the corresponding heavier constituents becomes less than that of liquid methane. And therefore, you have higher energy or higher temperature over here because, it is more than this. And this layer of heated sort of heavier constituents of gases is known as thermal overfill.

Therefore, now we know when it gets heated because of the further heat in leak, well it rises to the top, and sort of you know when it rises to the top, it mixes with the stratified layer. And this what we call as something like a rollover that means, the heated thermal overfill comes and heats the top layer, which is already a little warmer. But mind you now, the temperature difference here is quite high, It comes to the top, mixes with the stratified layer, and you get a discrete increase in temperature of the surface layer. And mind you, the gas over here is the original stratified layer temperature over here.

And all of a sudden, this increase in temperature is not, is such that the vapor pressure of this is not in equilibrium with the pressure here. Suddenly, there is a spurt in formation of a gas something like a flash vaporization. And this flash vaporization, as we saw in the last class, generates so much of gas, that is not sufficient, that it is not the vent hole, is not sufficient to vent it away, with a result the pressure increases rapidly and you have the burst of the storage vessel.

Therefore, whenever we talk of explosions involving storage vessels holding cryogens, we talk of thermal overfills. That means, the initially that means, the cryogen is not a pure cryogen, may be it contains some substances, some cryogens which are or some other substances, which are relatively denser. And they can be get heated to a more, they can be get heated to a larger temperature, before that density matches with the layer above it.

And all of a sudden, when and or when it gets heated to a level wherein, its density becomes equal, or less than this. Well, it rises up, we call this as thermal overfill, it mixes with the stratified layer on top namely a rollover process in which, thereafter this flash vaporizes because it is at higher temperature and the bursting of pressure vessel occurs.

Therefore, whenever we handle cryogens, which are somewhat impure, you have mixture of some other substances which are there such explosions are likely. But in the case of LNG, well it is obtained as a mixture of some substances, it is not pure methane by itself. And therefore, LNG has to be the storage vessel has to be designed with care such that, the thermal overfill and rollover will not cause an explosion.

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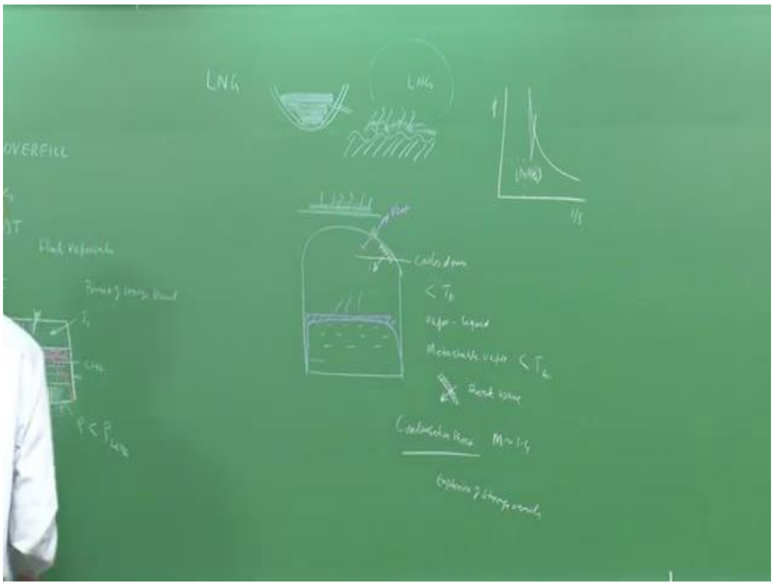

Having said that, it is also important that we talked of LNG on and off during the earlier classes. We find that well, you know we have tankers in the ship, which are designed to take this low temperature fluid across the different oceans. We have the LNG over here, and you know in, if by chance let us say, a ship containing the LNG leaks out. Supposing, there is a leak on the surface of water in a sea then, you have LNG which is being formed, and we said this is very dangerous. Why did we say it is dangerous? Because if LNG leaks over, let us say the surface of the earth because the LNG is very cold, it immediately cools the earth and also may be it tries, it flashes into vapors because, its boiling temperature is very low.

But, when it flashes into vapor, it absorbs the latent heat from the liquid over here. And therefore, the rate of evaporation comes down with time whereas, if the spill occurs over water in an ocean, because of the turbulence of the ocean, and also the convection movement of the water below the convection of water, which takes place. You know the spill continues to evaporate. You have a very copious amounts of LNG.

And therefore, LNG requires some caution when we transport it by sea. Or even for that matter, LNG being a cryogen, it has to be handled with care, and there are problems such as, as we say explosions in pressure vessels holding LNG and it has to be adequately designed to hold the additional pressure. Having said that you know we were looking at the explosions involving cryogenic fluid.

There is another instance, or another phenomenon which can again cause the explosions in the storage vessels. Let us take a look, we said earlier that you know, you have the storage vessel. You have the cryogen which is kept in a storage vessel. Now, let us say I have a storage vessel like this, I have vent valve because whatever said and done, you cannot, you cannot avoid the stratification, you have a stratified warm layer at the top. And this keeps on, the amount of stratified layer is shown shaded over here. This is the stratified layer and therefore, the evaporation takes place and therefore you have to essentially vent off the gases right.

You know when you vent off supposing, there is a sudden vent of gases, and if you vent out the gases, what is happening? There will be balance gas because of the expansion that means, the pressure gets reduced, there is expansion, the gas over here cools down. When the gas cools down, well you know it is almost at the saturation temperature, saturation temperature corresponding to this, and it cools down, well it is below the boiling point of the vapor at the particular condition of pressure over here.

And therefore, we expect, when it cools down it should sort of get back from the vapor. It must become a liquid, but the process of condensation that means, the vapor becoming a liquid takes some time. And very often with sudden venting, what happens is you form, something like a metal stable vapor, which is a vapor at a temperature less than the boiling point corresponding to this particular pressure.

In other words, you know it is tending to condense to the liquid, but it is still a vapor and it is there as it is. And therefore, when you have regions, cold regions over here, that is the walls which are cold. And therefore, all of a sudden, this Meta stable vapor cannot exist as a vapor, it is waiting to condense. And therefore, all of a sudden you have condensation taking place and therefore, you have this condensation taking place of the vapor, may be near the surface. And any condensation to condense, you know, you have to reject heat and therefore, the condensation has some heat.

That means, and this heat which gets rejected can drive a shock wave. And such a shock wave driven by condensation is known as a condensation shock. We can readily show this on our Huguenot, namely I have pressure versus 1 over rho. The initial conditions corresponding to the cool down conditions can be shown by the initial conditions P 0 and rho 0. And what is it or let us say 1 over rho 0 because my scale is rho 0 here, I have p 0 into1 over rho 0.

And since, some heat is associated with condensation, I have something equivalent to a condensation process over here, which is let us say meta stable. And when it condenses, I have a heat which is getting generated, I can always form a shock with some particular velocity. And this velocity, the mach number of a condensation shock is in general small, it is of the order of 1.4.

In fact, these are encountered in any process in which, you have a rapid cooling of the vapor, like in wind tunnel you have this problem. In you could have it in the case of the storage vessels, but any way, you know you have a shock, and these shock will increase the temperature, will also increase the turbulence, will lead to more fast vaporization, and this could also be a cause for explosions of storage vessels.

Therefore, we can summarize by saying, well when we consider explosions of may be cryogenic liquids in storage vessels, well the thermal overfill and roll over associated, with different constituents in the cryogen. And secondly the condensation shock could contribute to the explosion. Well, this is about the explosions of cryogenic storage vessels, let us move to the next topic which is let us say something similar, we say well, why cryogenic fluids? You know any pressure vessel can explode. Like for instance…

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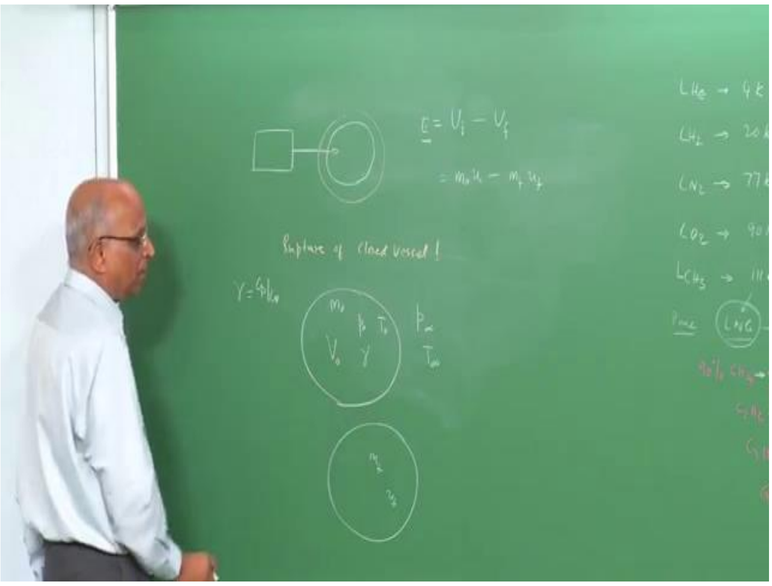

I have let us say a compressor, the compressor is used to charge a storage vessel of air let us say, I keep on supplying the pressure at higher and higher pressure. Well, by chance if my regulation system is such that I supply, I pressurize it to a very high value, well this storage vessel could just explode, could just rupture.

Therefore, we would like to find out, what is the energy released during rupture of a closed vessel? Now, to be able to do that, let us again formulate it, it is quite simple we have done something similar earlier. Let us consider a storage vessel, of let us say volume V. Let us say it ruptures at a pressure P 0, and let us say the volume is also let us say V 0 of this particular pressure vessel.

Let us say that the thermodynamic properties of the gas are such that, it has a specific heat ratio gamma. The specific heat ratio gamma is equal to Cp by Cv, we have been looking at it for the different gases, and we will find well gamma also plays a major role. Let this pressure vessel which explodes at a pressure p naught, let the ambient pressure be p ambient. Let the ambient temperature be also T ambient. Let the temperaturehere be let us say T 0, corresponding to pressure p naught over here.

You know, I want to find out, what is the energy released in this particular rupture, and how do I say? Well, the energy released is in this rupture let us say, E is equal to the initial internal energy which is contained by the gas over here mind you, it is the constant volume explosion.

Therefore, I say well that initial of the internal energy over here, minus the final value of the internal energy of the same volume here. And what is this equal to? This is equal to per unit mass, I have small u that is, so much kilo joules per kilo gram, into the initial mass of gas. Let us say, is m 0 over here, m 0 into u i minus when the explosion has taken place in the same volume. I have final mass over here and let us say that the internal energy is small u as so much kilo joules per kilogram therefore, it is equal to m f minus u f over here. Therefore, I want to solve this, I am interested in finding out how much energy is released during the particular rupture. And therefore, let us put these things together.

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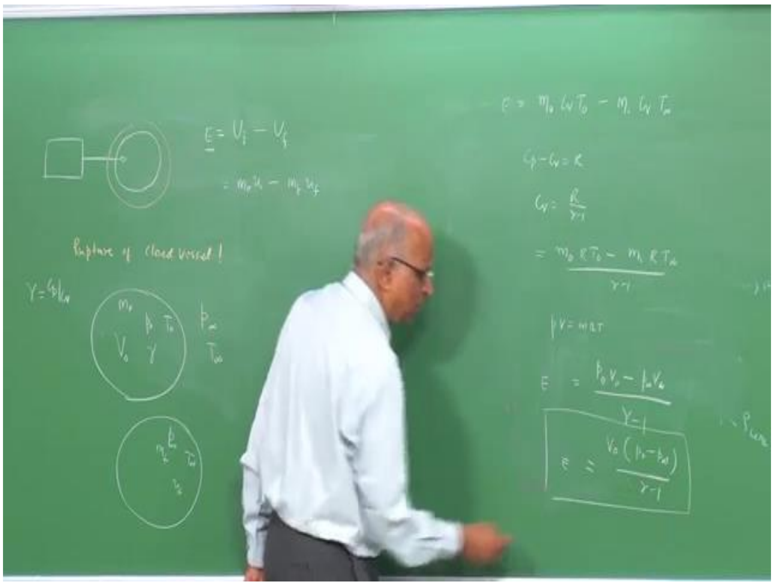

I have E is equal to m 0. You know I can write internal energy, we have seen internal energy is equal to Cv T that means T 0, that is the initial temperature over here. Minus m i into Cv into the ambient temperature because, once rupture has taken. It is the ambient gas which is occupying, this volume well the final pressure is equal to the ambient pressure because, nothing is there over here. We also have well Cp minus Cv is the specific gas constant or C v, I take it in terms of gamma over here is equal to R over gamma minus 1, specific gas constant in terms of kilo joules per kilo gram. And therefore, I can write this as equal to m 0 into RT 0 minus I have m i into, I have R into T ambient divided by gamma minus 1.

Well, what I have said is, I have substituted Cv is equal to R gamma minus 1, and I take gamma minus 1 common in the particular denominator. And here the assumption made is gamma for the gases over here, and gamma for the gases here is same, which need not be so. A high temperature gas has a lower value of gamma gas we shall shortly see.

But, when I look at this particular expression from gas equation, I have pv is equal to mRT specific gas constant. And therefore, I can write this mRT 0 is equal to the initial value of pressure, let us say p 0 is what is said is pressure over here into v, that is the initial volume, the volume does not change. We said that the volume is v 0 minus the final volume is again v 0, mRT 0 corresponds to the ambient pressure over here.

Therefore, this becomes p 0 v 0 minus p ambient v ambient divided by gamma minus 1. Or rather the energy released, if I take v 0 common because the same volume is there, I get v 0 into p 0 minus p ambient divided by gamma minus 1 which is, the energy which is released during the rupture of a pressure vessel.

If I say well, this is there, I find you know, I find that well, you have gamma and you know for air gamma is 1.4. You find the small changes in gamma is going to affect the energy released. Therefore, let us take a look at gamma, what are the factors which influence the gamma? Because you find well, it is not only the volume and the initial pressure, but it is also the value of gamma which is influencing the energy released. And therefore, let us see what gamma represents.

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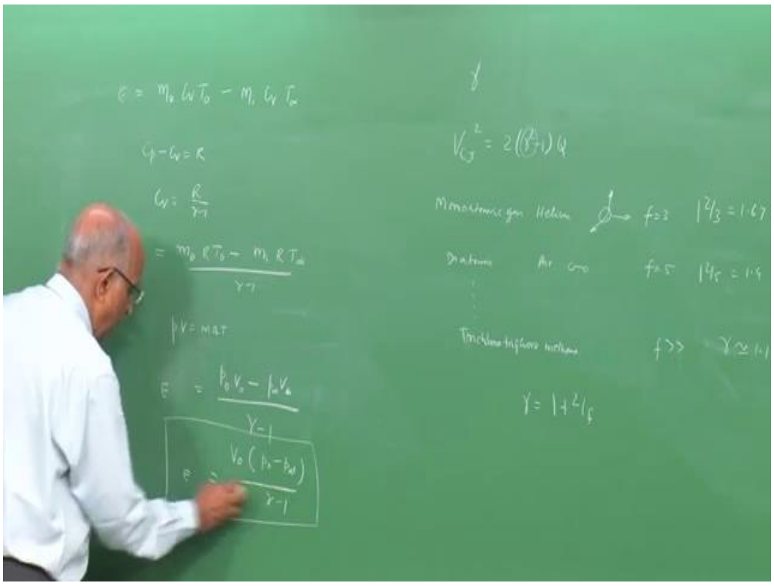

In fact, if you go back and see the ((Refer Time: 29:24)) velocity for a detonation, we also got it as equal to 2 gamma square minus 1 into Q. There also it was a strong function of gamma, and we found well gamma changes between the unreacted gas, reacted gas, we took it to be common, but here also it is sensitive to gamma.

Therefore, I think it is necessary to be a little more clear about what are the factors which affect gamma. Well, let us say if I have something like a mono atomic gas, something like helium let us say. It is a simple gas, you know it just a gas, which as a let us say monatomic, it has only 3 degrees of freedom, it can move in three directions therefore, the degree of freedom it has is 3. If I take a diatomic gas like air, like I have nitrogen, oxygen, and which constituents air, I say it is diatomic.

Well it has, it is double therefore, it has 3 translational degrees of freedom. It can also rotate in 2 direction therefore, the degrees of freedom are 5. Therefore, if I keep on increasing the complexity of a gas like for instance I take something like let us say, trichloro some refrigerant say, trichloro trifluoro let us say methane, which is used as a refrigerant. You know if I consider this, it is much more complex and the number of degrees of freedom are quite large in this case.

It is of the order of something like may be 10, 15 or so. And therefore, you know when I heat a gas again, you know what I do is, I increase the degree of vibration levels of the gas goes up. And therefore, it is degrees of freedom that means, I convert some of the energy into the vibrational modes of a gas, and if it is vibration modes of the gas, the degrees of freedom goes up, if it is rotational mode, the degrees of freedom goes up. And it is possible to connect the gamma to the degree of freedom, as say 1 over 2 by the degree of freedom. This is, this comes from the kinetic theory of gases.

And therefore, you find that for mono atomic gases such as helium, which is a degree of freedom of 3 it is equal to 1 2 by 3 is the value of gamma which is equal to 1.67. For a diatomic gas it is 1 2 by 5, which is equal to 1.4. And for a gas like Trichloro trifluoro methane or dichloro difluoro methane, it is of the order that is gamma is of the order of around 1.1.

And therefore, for a heated gas, in which it is very hot, maybe the gamma will be very low. And when we talk of a low value of gamma, apparently in my denominator I am having gamma minus 1 therefore, the denominator becomes small number and therefore, the energy released goes up. Therefore, let us do a small problem to find out the sensitivity of the energy released in the explosion of a pressure vessel, with respect to the value of gamma.

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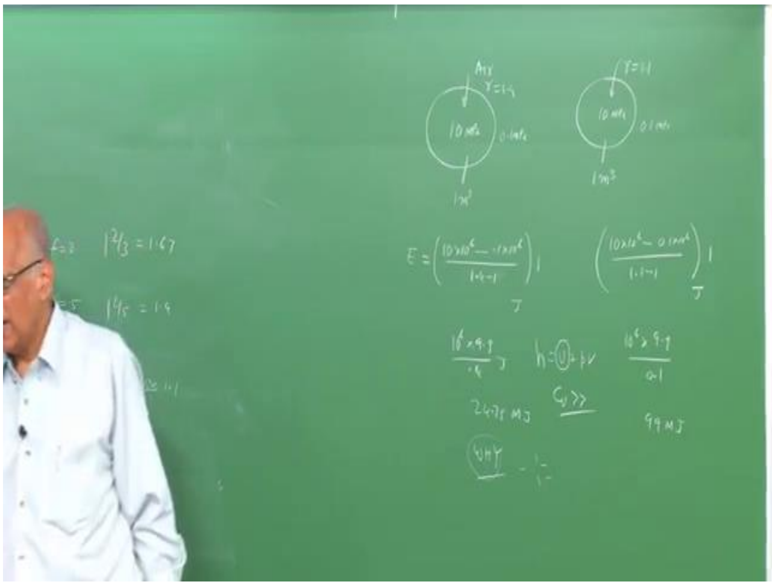

Therefore, let us do this problem, let us say I have pressure vessel which holds let us say air, whose gamma is 1.4 at a pressure of let us say 10 NPA. Let us say the ambient is ambient pressure, ambient pressure is 100 kilo Pascal which is 0.1 NPA. This is in the other case, and this vessel let us say this vessel burst at a pressure of 10 NPA. I also considered another example wherein, for the same volume let us say for the volume is 1 meter cube so, that I do not need to carry the volume. I have the same 1 meter cube vessel, having a pressure of let us say the same pressure of 10 NPA. Ambient pressure is 0.1 NPA as earlier.

But it contains let us say a refrigerant gas, and this refrigerant gas has a gamma, let us say equal to 1.1. Now, I want to find out, what is the energy released in the two cases? I just used my equation, I have, we have derived this E is equal to 10 NPA, that is 10 into 10 to the power 6 Pascal minus 0.1 into 10 to the power 6 Pascal, that is p naught minus p ambient divided by gamma minus 1, and into the volume which is 1 so much joules is what is generated over here. In this case, I have a similar expression, I have 10 into 10 to the power 6 Pascal minus 0.1 into 10 to the power 6 Pascal divided by. In this case gamma minus 1 is equal to 1.4 minus 1. In this case it is 1.1 minus 1 into volume so much joules which is generated.

Therefore, in this case I take 10 to the power 6 outside, 10 minus 0.1 is 9.9 divided by 0.4 joules. And in this case, I have again 10 to the power 6 into 9.9 divided by 0.1. You know if I solve for this, I get a value of the energy released being something like 24.75 into 10 to the power 6, I can call it as mega joules. In this case it is 99 mega joules and therefore, you find, you know the energy released when I have something like a complex gas is much, very much higher for the same conditions compared to air. The question is why this should happen?

Why should an explosion of the gas at the same pressure, same initial conditions, same volume and same ambient conditions release much more energy? The thing is that, a more complex gas because of it is different modes, different degrees of freedom because, of it is structure can hold much more internal energy. That means, the initial internal energy of this gas is very much higher than the internal energy of this gas. And since we are talking of drop in internal energy, well the complex gas gives me much more energy. But why should internal energy change and not the enthalpy?

h is equal to u plus p v, it is this which decides the internal structure which holds the energy. This is just flow work which does not change substantially. Therefore, Cv tends to be high for the complex gas, and since it as high it holds much more energy, this is the logical conclusion. Having seen the values or having estimated the energy released in rupture of a pressure vessel, let us go ahead and try to ask one more question.

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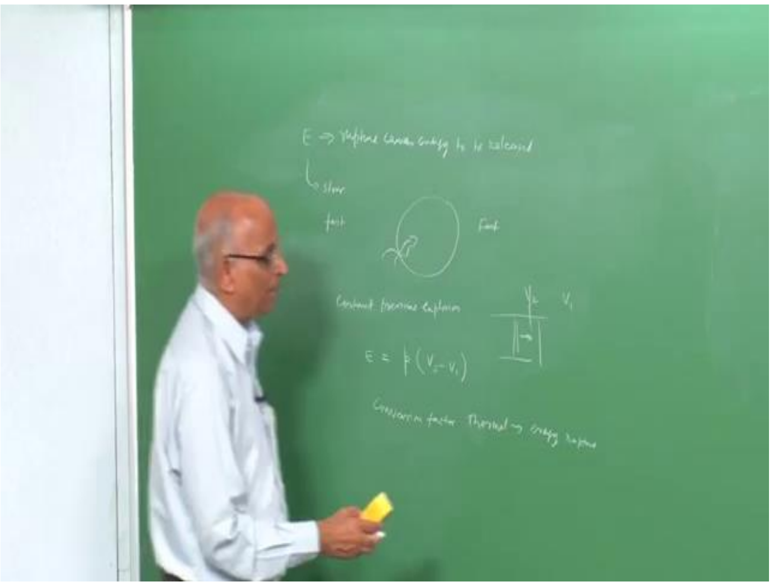

You know, we said energy is liberated in the explosion of a pressure vessel that is the rupture causes energy to be released. And it is this energy which creates a blast wave.

And we will see the effectiveness of the energy released when we talked of TNT equivalence after some three classes.

However, you know let us consider this energy release could be very slow, could be very fast. Whenever, we talk of a constant volume explosion, well it just goes with a bang that means, the energy release is very fast. Compared to a constant volume explosion, if I have something like a constant pressure explosion, what do you mean by a constant pressure explosion?

Well, let us say well, I have a piston, which is driving the gas at constant pressure and the volume increases, well that could also provide some energy with which I could have an explosion taking place. And what is the value of the energy released? Let us say, I have a constant pressure and therefore, I have something like a piston pushing the gases at constant pressure, and let us say there is no change in the pressure of gases.

Let us say the initial volume is V 2 and the final volume is, let us say V 1. That means, I am talking in terms of constant pressure into V 2 minus V 1 which is, the work done which is the energy of the a constant pressure closest what we are talking of. You know what the, if I were to consider this constant volume explosion derived from the thermal energy, which is supplied to this particular volume, and also a constant pressure explosion by the thermal energy supplied, for this particular change. Is there something like this being more effective, this being more effective? I want to find out, what is the conversion factor for the thermal energy into the energy that is the mechanical energy obtained in the particular rupture.

Therefore, let us do this particular problem, it gives us a feel of how much energy, how spontaneous energy takes place in a constant volume and the effectiveness of the explosion.

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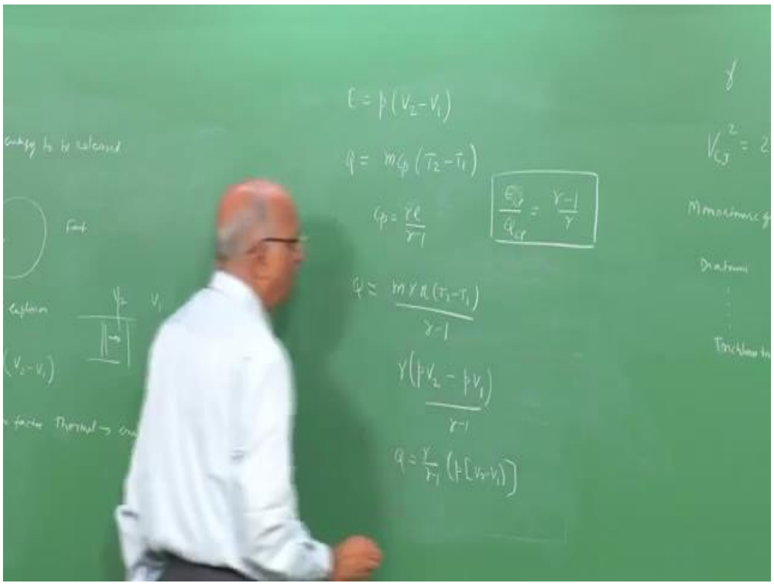

And therefore, when I consider a constant pressure explosion well, we say energy is equal to p into we say, it is equal to the V 2 minus V 1. And what is the heat which is drives this particular explosion? The energy supplied is equal to Cp, that is the mass of the gas into Cp into, I have T 2 minus T 1, or rather T 1 minus T 2. That is the heat, that is this the final temperature minus the initial temperature, and I can write well Cp minus Cv is R therefore, Cp is equal to gamma R by gamma minus 1.

Therefore, the heat which is supplied is equal to m gamma R T 2 minus T 1 divided by gamma minus 1. And now, I do the same thing mRT 2 is equal to the value of pressure being constant. p into the final volume, let us say V 2 minus I have mRT 1, the same pressure into V 1 divided by gamma minus 1 I, we have to take gamma into mRT is the p 2 V 2. I still have to retain this, or rather Q is equal to, I have gamma divided by gamma minus 1 into I have p V 2 minus p V 1, that is about it. That means I have gamma by gamma minus 1 into p into I have V 2 minus V 1.

What is the work done? Work done is equal to p into V 2 minus V 1, this is p into V 2 minus V 1 into gamma minus 1. Therefore, if I take the ratio of the work, or the energy which is released in the particular constant pressure process. Let us say I have E, I say constant pressure process, divided by Q in a constant pressure process. I have p V 2 minus p 1, p V 2 minus V 1 cancelling and I get E by Q is equal to gamma minus 1 divided by gamma.

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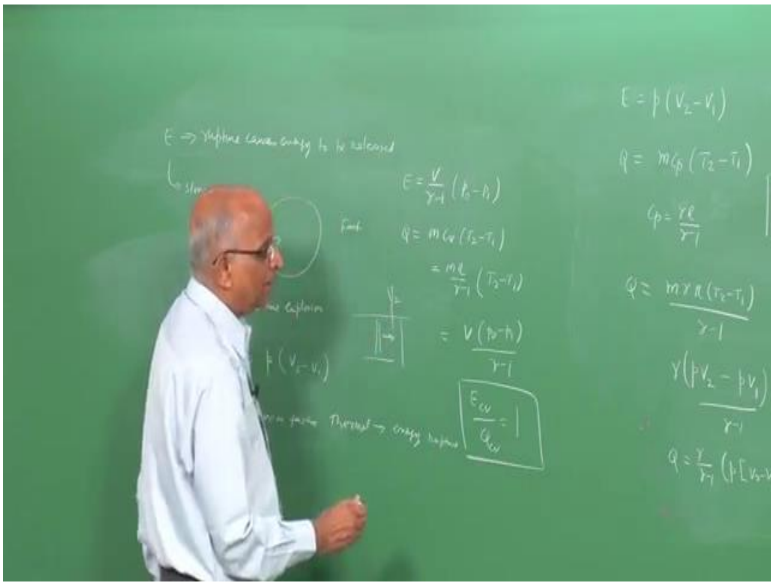

If I do the same thing for a constant volume explosion we found that the energy released in the constant volume explosion is equal to V into gamma minus 1 into we had p that is the p 0 minus p 1 or p ambient.

And we also find that the energy heat, which is supplied to do this, I can write it as equal to I have mCv into the T 2 minus T 1 which I can now, write as equal to mR divided by gamma minus 1 into T 2 minus T 1. Again writing mRT 2 and mRT 1 as equal to p 0 V and p 1 V, I get this equal to V into p 0 minus p 1 divided by gamma minus 1. And therefore, for a constant volume energy released divided by constant volume thermal energy what is required, is equal to V same expression therefore, it is equal to 1.

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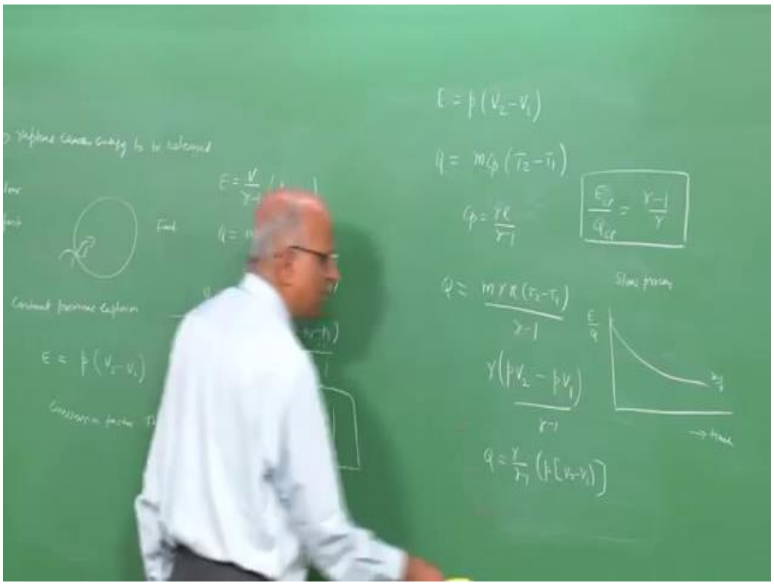

Therefore, we find that the since gamma is of the order of 1.4, the energy released in a constant pressure process, is much lower, and we know that a constant pressure process is a slow process. Whereas, when I talk in terms of constant volume explosion, it is a sudden process. And therefore, now I can plot as a function of time, the value of let us say energy divided by the heat released, I say well for a certain process I have this equal to 1. And as I move towards a constant pressure process, the value I get is gamma minus 1 divided by gamma.

Therefore, the suddenness of an explosion is important to be able to convert all the thermal energy into the mechanical energy. You know this completes what we said is about the rupture of pressure vessel about the energy released, and we found yes now, we can estimate the energy released, but there is one small problem which very often the chemical industries face. And let us quickly go through it. You know the problem is like this.

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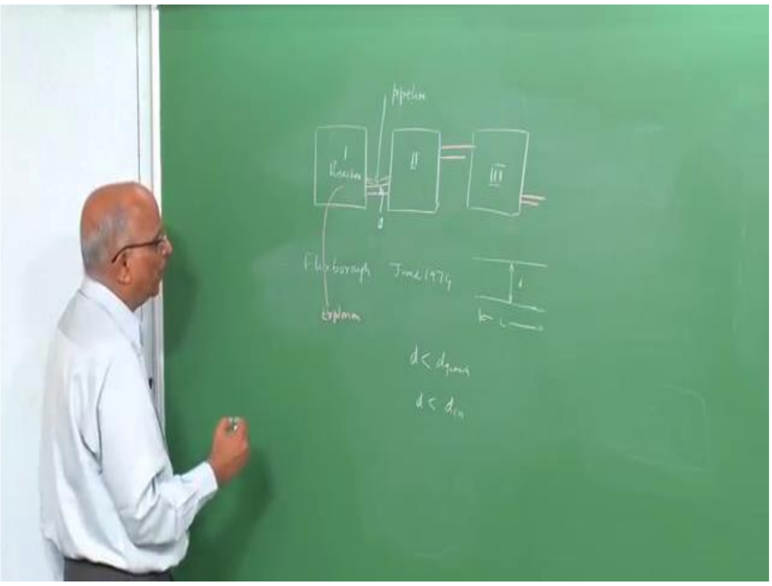

You know, in any chemical plant or in any plant we have a series of reactors. You know we are trying to form some substance like for instance let us go through one particular example. Let us take the example of the explosion which are happened at Flix borough in UK wherein, on June 1, 1974 there was a spillage of, let us say cyclohexene which mixed with air and just ruined or made Flix borough into a ghost city. You know, what happens in a chemical plant? You have somewhat like you have reactors.

Several reactors which are essentially storage vessels, you have let us say reactor 1, reactor 2 over here, I have reactor 3 over here, you have several of these reactors. And all these reactors are always connected by pipelines because from one reactor, I transported to the second reactor, to the third reactor, to the fourth reactor, and so on.

Now, the question is supposing by chance, in one of the reactor, there is an explosion. I do not want my entire plant to get, to get damaged. I would like to still protect my second reactor and third reactor and somehow ensure that the explosion from reactor 1, does not get into reactor 2. Or rather I am interested in so designing this pipeline, which connects my different reactors should be such that, let us say its diameter must be d and let us say it is length must be l. I am interested in the connection having a particular diameter d, and the length l such that, explosion from one reactor does not get into this.

Even if this explodes, can I still save this? This is the question. Therefore, we are looking at this particular connecting or let us say the pipeline. And we immediately say, well I have studied this. If d is less than the quenching dimension. Or rather in the case of detonation, if d is less than the critical diameter, well my problem is solved. Flame cannot travel, but the problem tends to be a little more complex.

There are additional factors which are involved, and that is what I want to highlight now. You know let us say well, in the reactor 1, I want to simplify it, I want to put the scheme as, well I show the reactor through some another geometry.

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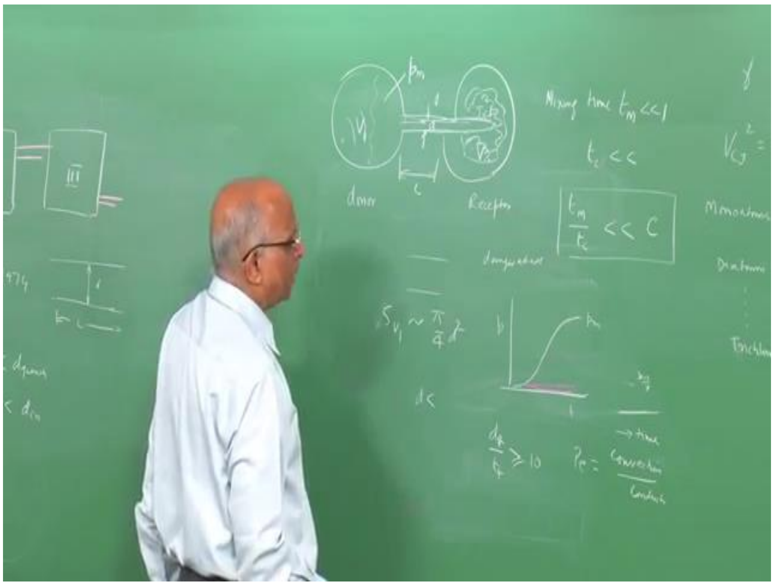

Let us say I have one reactor in which there is some explosion taking place. Well, it is a donor as fast as an explosion is concerned. It is connected to a next vessel, which receives the explosion, I call it as a receptor. Well, I am interested what must be the diameter of this pipeline? And what must be the length of this pipeline? To make sure that the explosion does not travel from one particular reactor to the other.

Therefore, now I tell myself supposing, let us say, that the diameter of this particular connector is such that, it is somewhat same as the surface area of this particular vessel. Or rather if I say volume, and I say mean surface area. If the surface area, cross sectional area of this vessel is same as something like let us say, this diameter is d is same as let us say surface area corresponding to volume 1 is same as let us say pi by 4 into d square.

Well, I have such a huge vent that may be a flame gets started. You know whenever gas is getting generated, you know it really cannot build up pressure here. Because the vent is so large that it just allows the gas to go through. And therefore, in this case there is no danger at all. But to think in terms of a large vent, and why does it happen, the vent area is so large that means, before pressure with time tends to get build up. At the low pressure itself, it starts venting the gases and therefore, you have something like a gas going over here.

And therefore, it is a unburned gas mixture which goes out even if it is burned the, if the diameter is less than quenching thickness well it quenches nothing is going to happen, well it is safe. But in practice it is not possible, in practice d, the diameter or the surface area is going to be very much smaller than this. And therefore, since the vent area is much smaller than the original cross sectional area, this happens like a constant volume vessel, or a constant volume reactor which is exploding.

And in a constant volume explosion, the maximum value of pressure is pm, which we have hydrocarbon we said it is between 5.7 to something like 7 atmospheres. If it is hydrogen, it is of the order of 11 atmospheres. And therefore, I have a constant pressure explosion, which gives me a high value of pm. And therefore, what is going to happen? You have a high value of p m and therefore, the gas comes in here, you know it comes at high pressure, and it expands into this receptor vehicle that means, let us say V 2 as a hot jet.

If this hot jet comes into this particular reactor over here, and if this hot jet immediately mixes with the cold reactive gas over here, or with the gases in this particular volume, what is going to happen? Well, this jet gets extinguished and therefore, it is not possible for you to initiate combustion over here. And since, I am that means I am talking of, if the mixing of the jet with the gases here is very rapid that means the, mixing time let us say t m is a very small number.

Well, I cannot ignite these gases because it gets quenched. However, if the hot jet comes, and the chemical reaction occurs so rapidly that heat is getting generated, well this also explodes. Or rather if the chemical reaction time, let us say t c of the gases here it is a small number well, this container or reactor explodes. Therefore, we find the ratio of t m by t c, if the mixing time is small well, I am safe therefore, for safety I say well that mixing time divided by the chemical reaction time must be less than a particular value.

And this also therefore, becomes an important parameter. It is not only the quenching distance, and mind you, whenever we do these things, you know we also talked in terms of quenching distance, divided by the flame thickness, or critical tube diameter for a tube detonation, let us let us concentrate on flame d q by t f.

We said is of the order of something like 5 or 10, or something of this order. We also were able to put the quenching diameter in terms of a Peclet number that means, the convection heat transfer, divided by the conduction heat transfer. You know, but it is very difficult to theoretically determine this particular diameter.

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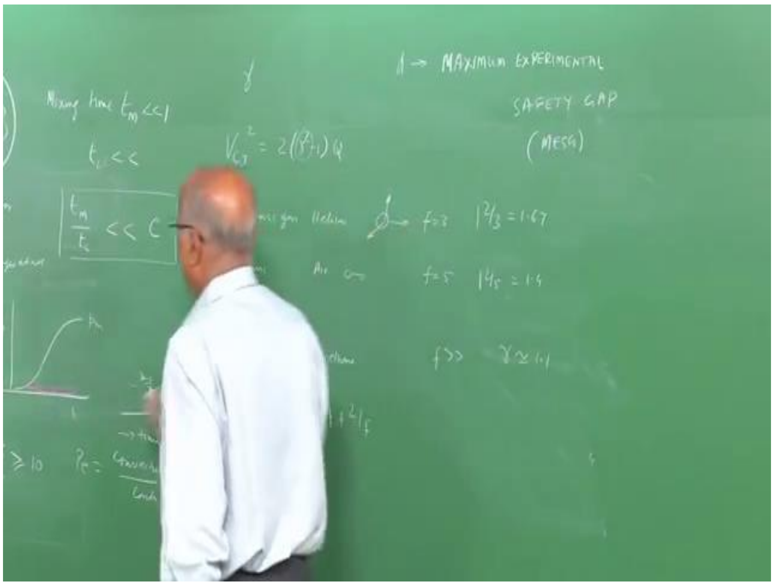

And in practice, what is done is, we derive it from experiments and the diameter so, derived from experiment is known as maximum experimental safety gap and it is known as MESG. It is derived for the different gases and we know what must be the type of diameter what is used. It is also necessary that the length must at least be of this diameter, such that, the heat losses and the active radicals lost to the walls will quench it.

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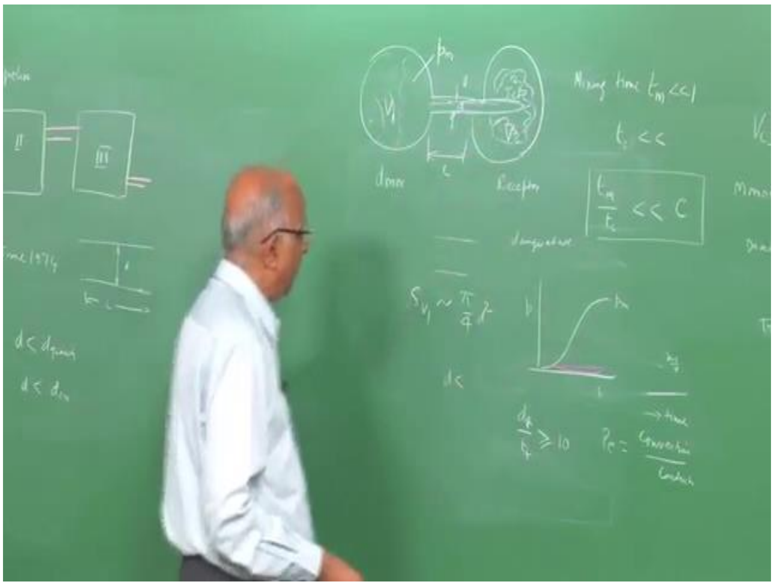

And in practice we use the maximum experimental safety gap, but in addition to the safety gap we must also look at the phenomenon by which things take place. The relative size of this relative to this volume, the mixing times, and chemical reaction time, in order to make sure that explosion in one vessel does not get into the other vessel.

Well, this is all about explosions in the cryogenic vessels, rupture of pressure vessel, and also, something on containment of explosions in a particular reactor, and not spreading to the other. In the next class what we do is, we go to a slightly different topic. We have been restricting ourselves to gas phase and dust explosions. We will take a look at the condensed or the solid explosives in the next class. In the next two or three classes, we will deal with condensed explosives.

Thank you.

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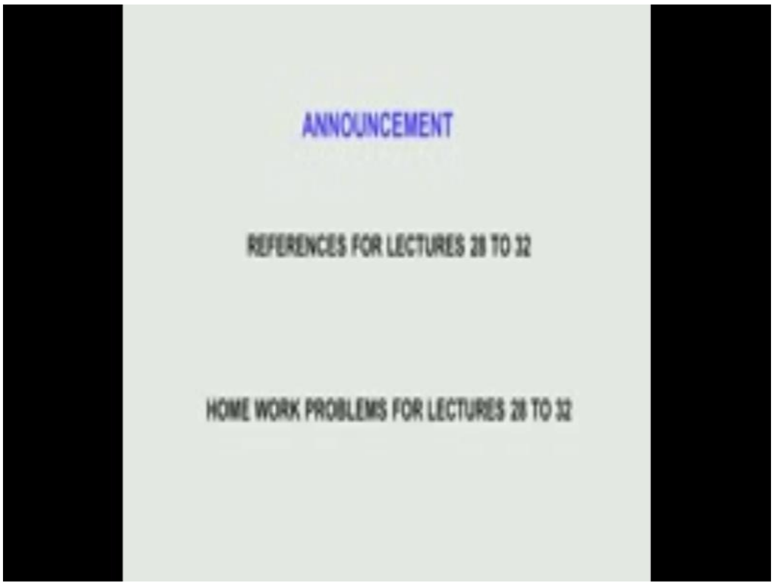

ANNOUNCEMENT

REFERENCES FOR LECTURES 28 TO 32

HOME WORK PROBLEMS FOR LECTURES 28 TO 32

An announcement please, the lectures between numbers 28 to 32 covered the different categories of explosions. The references for further reading on these lectures namely, those between lectures 28 to 32, and a set of home work problems pertaining to these specific lectures are given in the downloads of this video course.