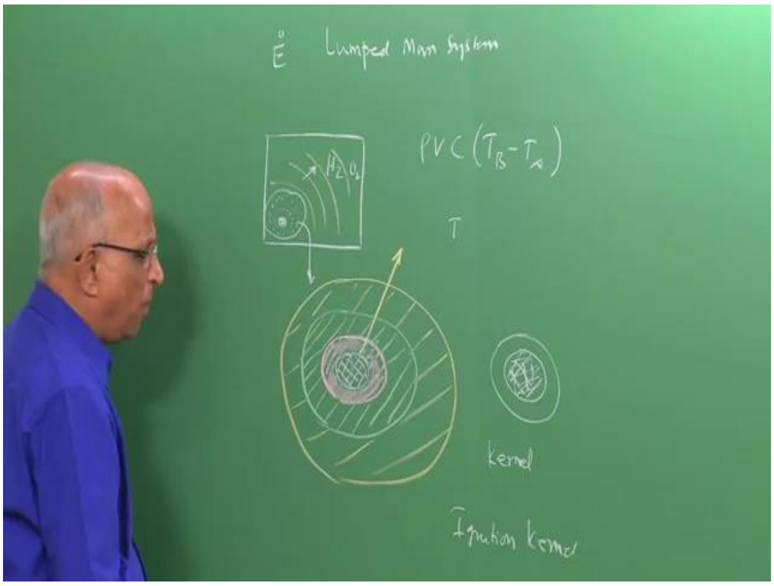
Introduction to Explosions and Explosion Safety

Prof. K. Ramamurthy
Department of Mechanical Engineering
Indian Institute of Technology, Madras

Lecture - 20
Combustion

Good morning. Now, that we have developed a rationale to determine under what conditions a rapid release of energy gets generated in an explosion.

(Refer Slide Time: 00:00)



In the particular context of lump mass system let us go ahead and see whether we can relax this assumption of this lump mass system, and see whether we can understand the explosion a little better. Therefore, in this context, let us restate what we have been saying all along in the lump mass system, we said well the temperature is uniform throughout the concentration is uniform throughout. We assume all events to occur in the special domain at uniformly at all times.

Well, you know, this just may not be possible like for instance. We again go back to this example of a hydrogen oxygen mixture in this particular pone. Let it be at a pressure of one atmospheric pressure, initial temperature being around 300 Kelvin. And I sort of deposit some electrical spark or some energy in this particular small volume. It is not that the entire volume is going to explode like what we assumed in the lump mass system. But all of us know yes from this particular source of energy, which is released.

You know, this energy release heats up the neighbouring volume, the neighbouring volume, and so on a zone of chemical reactions propagates out. Let us take a small look at this, let us therefore, expand this particular portion and maybe sketch it over here, in other words I have a small volume. I show it a little magnified in which I deposit some energy over here in this small volume or in a small volume.

Corresponding to the electrical spark or some resistance heating whatever it is or a match stick I put over here, and I heat the gases over here, what happens the moment this volume gets hot maybe chemical reactions take place. And maybe the temperature goes up still further, and what happens this gas heats up the neighbouring gas around it. That means, in a zone, which now I show in pink over here. The neighbouring gas gets heated by the chemical reactions and heat generated in this small volume. And the heat sort of defuses out the concentration defuses out causing, maybe a chemical reaction in the adjacent layer.

Now, what further happens? This adjacent layer, which is therefore hot and it undergoes chemical reactions heats up the next layer over here. In other words I have the adjacent layer to the one, which was previously heated. Now, getting heated by heat transfer or conduction or convection from this pink zone into it, and chemical reactions occur into this particular zone. And this zone thereafter further heats up the layer around it, and so on and therefore, what is happening this zone, now heats up the other the zone adjacent to it, and in this way from this initial zone of heat release.

You have chemical reactions occurring here, because of heating it causes chemical reactions in the next layer; it causes chemical reactions in the next layer and next layer and so on. You have chemical reactions propagating out from the zone of heat release, there you have propagating out till it fills the mixture. Therefore, it is not that instantaneously as assumed in the lump mass system everything is uniform, but it is going to take some time for it to propagate out this point one, point two.

Let us take a look at the energy release itself supposing this volume is very small. Let us say, maybe this volume is small and the amount of chemical reactions it produces are small such that when it heats the next layer apparently it is going to get cooled because the heat passes on to the next. Therefore this hot zone becomes cool and if the volume is sort of insufficient or if the amount of energy here is insufficient or the amount of chemical reactions here is insufficient to be able to maintain its temperature as it is heating the next layer, what is going to happen this initial volume, which I showed something like this over here.

This initial volume you know, the amount of heat in it will collapse or the amount of temperature in it will decrease, and chemical reactions will decrease, and by the time the neighbouring element gets heated up. Well, it is inadequate to heat the neighbouring element and collapses. Therefore the spark or the chemical reaction collapses, and I cannot longer be able to get combustion occurring in the neighbouring layer.

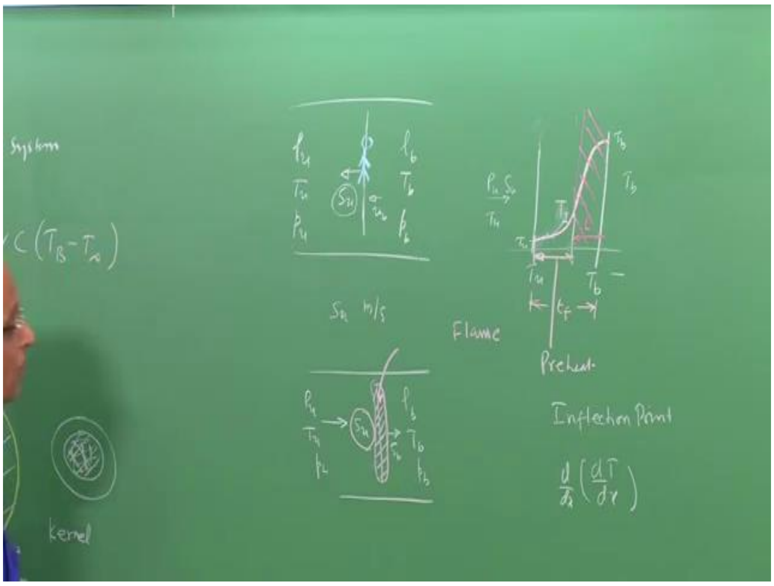
Therefore we say, well I use a spar for igniting a mixture and unless I have adequate quantity of this particular volume or let us say by volume, I mean something like a kernel something like a seed. If I do not have an adequate kernel for ignition, which takes place, well the ignition kernel will collapse and it will not be possible for it to heat the adjacent layer.

Therefore, it is necessary for me from ignition point of view to make sure that the size of the ignition kernel should exceed some threshold value and this is what I want to do. I want to be able to find out, you know, unlike I am not heating the whole thing, mind you I am not having the total mass in this system, which is equal to rho v in rho density into volume into specific heat into the high temperature. That is the burn gas temperature minus the initial value.

That is the, let us say, the initial temperature is same as ambient, I do not need to supply that amount of heat I just need to supply the heat required to really drive or form an ignition kernel, which can heat the succeeding layers and allow the combustion wave to propagate out. But to be able to do this you know, to be able to find the critical size of the ignition kernel and therefore, ignite the gases and have a flame moving out. It is necessary for us to get some idea on the rate or the speed with which the combustion wave, what do you mean by combustion wave zone of the reacting gases and whenever you say, zone of reacting gases. The temperature increases, and therefore the speed at which the zone of the reacting gases move out the thickness of the zones, and some more definitions before I can go and determine the ignition. This is what I do today.

Having specified the problem, let us see, how to go about it. Let us first say well, what is the speed at which the sort of the combustion zone propagates out. That means the speed at which the chemical reactions are going forward to be able to do that. Let us now say, well, I have let us forget about curvatures.

(Refer Slide Time: 07:23)



Let us say, I have a zone of combustion. For I also say, I have a pipe or a some particular medium in which, well, I have the unburned gases unburned gases are at density rho, which is unburned. Well, they are at a temperature T u, which is a unburned gas mixture, and we can also say, well the pressure of the unburned gases is p u into this unburned gas mixture. Like I have the unburned gases here, unburned gases here into which a combustion wave propagates or the zone of reaction propagates.

Well, let this particular zone of combustion, which I now say is planar is propagating at a speed s meters per second. Let us say, s meters per second into unburned gases. Therefore, I can say it propagates at a speed s u meters per second what happens behind the, behind the, behind the combustion front, which moves into this well the gases burn behind it. Chemical reactions take place and the level the density. Let it correspond to the burned gases, let the temperature correspond to the burned gases, let the pressure correspond to the burned gases.

Therefore, the subjects be for pressure temperature and density, if it is b it corresponds to burned gases and the suffix here u for rho T and u corresponds to unburned gases. Well, this is the problem, and I want to determine. Let us say, the speed at which the combustion wave propagates into this medium, and as we did you know, whenever we talk of these waves, which are propagating into a medium.

See, we also told you know, to be able to look at the problem with a wave propagating and things moving, when the wave propagates. Well, I should have some velocity within the medium. Let us say, u in the burned gases behind the wave, which is moving at s u. You know, it is somewhat difficult and the easiest way to do is effect a coordinate transformation such that I imagine I sit on the wave or I am standing on the wave itself. That means, I am looking at this particular problem in the context of the wave stationary.

That means I sit on this wave, and watch the show, if I were to do that, what is it? I get well; I have the same problem now. Well, I have the wave front here, but since I am on the wave in the frame of reference of the wave itself. That is the combustion wave, which is moving or let us say, the combustion front, which is moving into the unburned medium. Now, since I am here, well the unburned gases at a density rho u at a temperature T u at a pressure p u move towards me.

That means, towards the wave in the frame of a reference of the combustion front itself at a speed s u. Let us assume, I have T b temperature of the burned gases pressure of the burned gases, and let us also presume that maybe in the frame of reference of the wave. Let the velocity be s b, well what is it? I am interested in I am interested in determining the value of s u. Well, the problem is posed, you say well behind the combustion disturbance or the combustion, which moves.

I have these are the values and these are the values upstream, but you know can I picture what is really in this frame, what is happening over here, what is this combustion front or the zone of combustion, which we said is moving. We said well something gets heated. I have some diffusion of heat, some diffusion of concentration, which causes the adjacent layer to react adjacent layer to react and so on.

The same thing is happening here, this cause’s adjacent layer to react over here to react over here. That means gases moving more and more of these unburned things are coming over here. It gets heated, can I say what can I expand this out can I have a mental picture of what is going to happen and that is what we call a mind model. I want to have a mind model of what is happening in this particular front over here. Therefore let us, let us try to sort of devise, what would happen? Well, we say, well the unburned gases are moving therefore, maybe initially I have the unburned gases maybe at a temperature T u.

Then, what is going to happen? Well, at the exit I have all burned gases. Now, let us, let us try to expand it out, let us try to give some thickness to it. Let us say initially the temperature is T u on the left hand side on the right hand side. Well, the temperature is T b and what is going to happen into this particular one, which is represented of this particular line over here, what is happening? I have rho u and at speed s u that means this is the mass flux, which is entering this particular one, and what happens.

The moment it enters initially, it is at a temperature T u and when it enters. Well, you have the hot products of combustion on the right hand side, well it is going to get heated and the temperature will sort of begin to increase. Well, the temperature begins to increase and what where does it end up ultimately. The temperature should be T b corresponds to over here. Let us say that the temperature is T of the unburned gases on the left hand side, and what is going to happen? Well, the temperature increases from T u and you know, it increases to a level where in sort of the chemical reactions begin to take place. And once the chemical reactions begin to take place chemical reactions occur fairly fast.

Therefore it reaches this and it comes over here. Therefore this is the way the temperature should change from the initial value on the left hand side. That is the unburned gas temperature T u to the burned gas temperature T b over here. Well, this is the picture, which seems logical, and therefore I can also tell myself. Well, this is going to be the thickness of the flame or the thickness of the combustion front. You know very often, we call the combustion front, which is, which is here or which is moving over here as a flame. That means flame is a region of chemically reacting gases, which generate heat and light and that what we observe.

Therefore, we say, well it we are talking of the thickness of this particular combustion front to be something like this. Well, if I were to use what little we have learnt from the lump mass system, we told ourselves, well the activation energy for most of the substances are high and whatever happens. You know, initially I have something like a pre-heat the temperature increases to some value. Let us say, T c that is the zone in which the cold gases are heated to a particular temperature, which we call pre-heat, and once it has been heated to the to the critical temperature.

That is the auto ignition temperature well there is a spurt in the chemical reactions, and the temperature shoots up like this. Therefore, we are now telling, well initially there is something like a pre-heat followed by chemical reactions in this particular length. Therefore, now I can put something more, I can say, well this is my zone of chemical reactions fast chemical reactions, which I call l. Therefore, I say, well the thickness of the flame is T f my zone of chemical reactions is l, and now can I write an equation for this particular phenomenon?

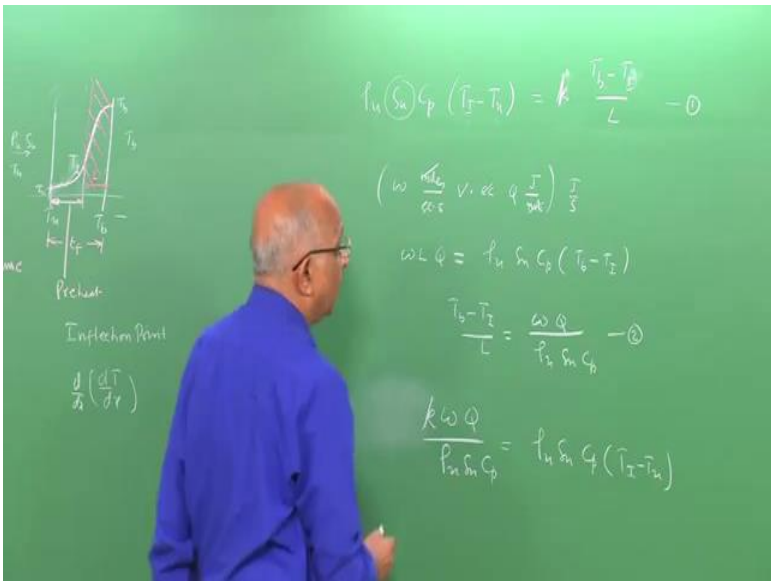
This is the zone of active heat release; well this is the zone in which heat gets released. This is the zone in which heat is getting received such that the temperature goes from T u to T c. Therefore, what is it that we are talking of, we are talking of a zone in which heat is getting released and this heat gets fort of transferred to this zone such that it is able to increase the temperature from T u to T c. Therefore, this zone the pre-heat zone receives heat and you know, you will also observe. You know, whenever we, whenever we receive something, you know we receive something like this. We put our hand and receive something whereas, when you give something you give, you give something like this.

Therefore, you receive something over here, you give something over here. Therefore, in this zone the heat is being given and the heat is being received over here, and the point of this particular zone or the particular contact between receiving and giving is what we call as the inflection point. Well, inflection point is a point at which the concave downwards in this particular zone because it is giving. Well, it is convex upwards or concave downwards and what is receiving is concave upwards and convex downwards.

Therefore, the concave downwards is getting replaced by concave upwards and that is the inflection point that is at the inflection point. There is a sign in d by d T by d x as a function of d x, wherein I say this is my x distance. And therefore, there is a change in the curvature over here. Well, that is the inflection point therefore, rather than carry the concept of critical temperature or auto ignition temperature from the lump mass system. I say, well the temperature here is the inflection temperature over here, which is the junction or point at which the heat received from the hot zone is received over here. This is what is given. I have the inflection point over here.

Therefore, now I know the events which are occurring in this particular line over here which is what I have sketched over here. Can I want to write an equation for it? And what is the equation? Well, I have to write the heat balance the equations. Let us, let us, let us write it out therefore, I say, well I have rho u s, u is the mass flux, which is coming to be able to write the equation that the, that the area what I am considering over here is unity one meter square.

(Refer Slide Time 10:12)



Therefore I say, well the mass which is entering is rho u into S u into 1 that is the, that is the mass flux into 1, which is the mass, which is entering. Let us for the present assume it is at constant pressure C p; we will rectify this assumption a little later. Therefore, this is the thermal mass over here, and what happens in this zone.

Well, the temperature increases from T I to T u in the, in the pre-heat zone. This is the heat, which is getting received over here, and how does it receive the heat. Well, I should have something like a. I have a gradient in temperature this gradient, which gives the heat, and therefore this is equal to again per unit area. I say, well the thermal conductivity is k, and I have the gradient, which is equal to d T by d x at this particular point, which I have approximate as a straight line over here. And write it as equal to T b minus T u by the zone length over here. We said this is the length of the combustion zone or the length of the reaction zone therefore, T b minus T a by l is a gradient, and k into this is the heat flux.

Therefore, this becomes my equation one for heat transfer. Well, can I now you know, I have, I have put it down my aim as we said is to be able to determine the value of as u, but you know, can I explicitly get and expression for T b minus T u, because I find well at least the initial temperature. You know, I do not know, the inflection temperature therefore, if I can somehow get you know here, it should not have been T u, because what is it? I am saying T b minus T I divided by length is a gradient here therefore, should have been T b minus T I. Here, T I minus T u is that is the temperature increase therefore, if I have to determine this.

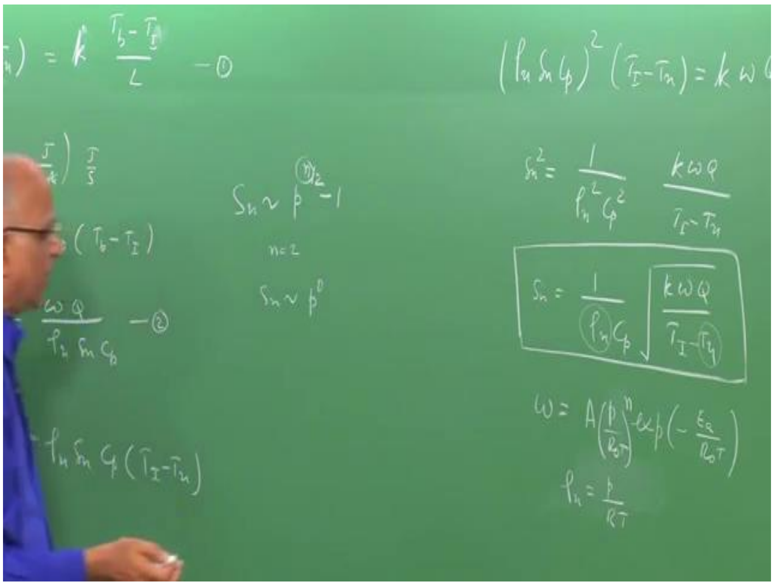
I know well the amount of heat generated in this particular zone, what did we say? Well, the heat generated can be written as the rate of chemical reactions so much moles per c c into second into, we have to multiply by the volume so much c c into. We know, what is the heat generated per mole q so much joules or kilo joules per mole, and this gives me the value in joules per second because what happens mole and mole gets cancelled c c, gets cancelled and joule per second. Well, this is the amount of heat and therefore, the heat, which is generated since I am considering unit area over here.

It is going to be omega o omega. I say is the rate of the reactions into v, which is corresponding to the length l over here, which corresponds to the volume into q, and this heat, why does this, what does this heat, do you know, this heat what does it do? It takes this mass flux maybe the mass flux comes over here, mass flux here, mass flux here, mass flux here is the same therefore, the same mass flux comes here. I have rho u into s u into C p, and what does it do? It increases the temperature from T b burned gases to from the initial value I to this value.

That means I have the mass flux of gases coming over here, which is equal to rho u, rho u s u. I am considering unit area that becomes my mass into specific heat into change in temperature therefore, from this I get the value of the burned gases minus the inflection point temperature. That is the temperature over here divided by l is equal to T b minus is equal to omega into the heat release. That is so much kilo joules per mole divided by rho u s u into C p, this becomes my equation two based on this heat release. This is my equation 1.

Now, I substitute the value of T b minus T a divided by l into this equation, and what is it? I get, if were to substitute it, I get the thermal conductivity k. let us, let us use the small value of k, because capital K is normally used for something like constants. Therefore, I get k into the value T b minus T I is equal to omega q into rho u S u into C p is equal to what is on the left hand side here, which is equal to rho u into S u into C p into, I get T I minus T u. Well, now I have to solve I am, I am interested in finding the value of S u. I solve this, and what is it, I get, well I get rho u s u C p square into T I minus T u.

(Refer Slide Time: 22:40)



Well, let us put that down, I get rho u I get rho u into S u into C p square. I move the denominator on this side into T I minus T u is equal to what I get k. That is the thermal conductivity into the rate of reactions is mole per c c second into the energy generated in the reactions in joules per mole and rather. Therefore, I get S u square is equal to 1 over rho u square into C p square 1. Then, I also get the value of k omega q in the numerator on the right hand side divided by T I minus T u over here or rather the value of the speed at which the combustion propagates into the unburned gas medium so many.

Let us say, meters per second is equal to rho u into C p into, now I take under root on this side k omega q divided by T I minus T u. Well, this becomes my expression, this is the rate at which the flame is propagating into the unburned gas mixture or the combustion is propagating into the unburned gas mixture and let us say, what are the things, which are involved here. We say, well as the density of the unburned gas mixture decreases the flame speed increases 0.1. We also say if the unburned gas mixture is at a higher temperature, well the denominator decreases here. The denominator I am decreasing by a by a higher quantity the denominator decreases.

Therefore, when the unburned gas temperature is higher the flame speed is higher, but can I put it in the terms of reaction rate? Well, I find yes, if the thermal conductivity is higher the flame speed higher; if the heat released is higher the flame speed is higher. Can I put it in terms of omega? Let us say, omega as you know the rate of the reaction. We defined it as equal to a c n into exponential of minus activation energy by divided by universal gas constant into temperature over here, so much moles per c c second. And we also know well, we are considering a gas mixture for the present.

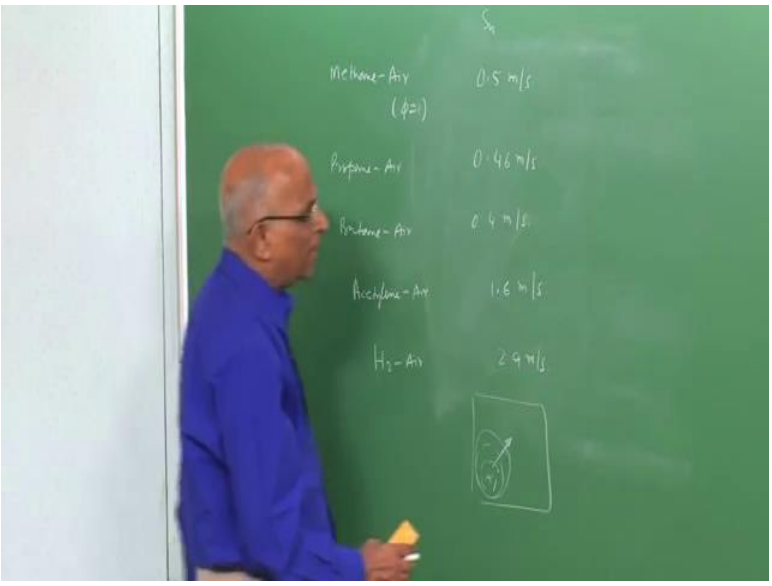
Therefore, I can write p v is equal to n r 0 T or concentration is equal to p divided by r 0 T, because p v is equal to n r 0 T concentration is equal to n over v is the p r 0 T or rather I can, I can now write the rate of a reaction. I replace c by p by r 0 T, and what is it? I get, I get p by r 0 T to the power n over here. I also know well the density of the gases over here. I write p v is equal to m r T or whatever and I get the value of rho goes as p at a given temperature or rather rho u. I can write as equal to the initial pressure divided by specific gas constant into temperature, and therefore mind you this is universal gas constant or not joules per mole Kelvin.

This is specific gas constant in terms of joules per kilogram Kelvin and therefore, what is it, when I look at this is I get omega to the power half. That means, I get p to the power n by 2, I get this is p over here or rather I get the flame speed. Let me just write it here, itself S u versus p to the power n by 2 minus 1 because here I get p to the power n here. I have under root sign p to the power n by 2 minus value of 1, and mind you see.

We also told most of the chemical reactions, we consider have n is equal to 2 or rather if we have n is equal to 2, the flame speed goes as p to the power 0 or it is independent of pressure. If, it is going to be independent of pressure, well I know that the that the speed with which a combustion front moves into an unburned gas medium is independent of pressure increases with the increase in the temperature of the unburned gases increases with the amount of heat release increases with conductivity and so on.

We have this particular relations and therefore, let us try to get some feel for the, for the speed is it one metre per second is it 100 metres per second to be able to do that. Let us take, let us, let us put the values down or people have put the values down, and let us see what are the values of the flame speeds that we get. Therefore, I quickly go through a few cases maybe 2 or 3 gases. Let us try to get a feel for the speed with which the combustion moves into the unburned gases. Well, I give these values, the values are, let us say,

(Refer Slide Time: 27:43)

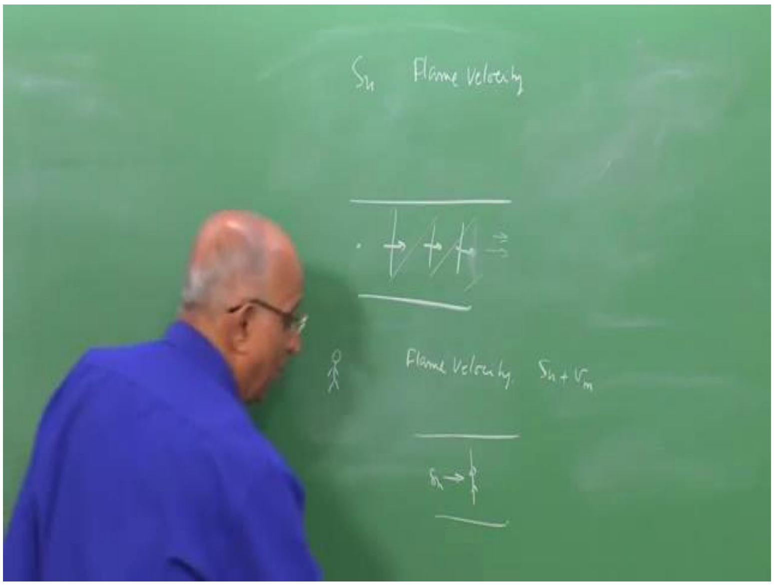


I have, I have methane air, let us consider stoichiometry. That means, we say equivalence ratio is one at this equivalence ratio the value of S u is something like 0.5 per second. If, instead of methane I just jump to propane air again at the same stoichiometry stoichiometric mixture 5 equal to 1. I have that is equivalence ratio 1 is equal to 0.46 meters per second. If, I go to butane air C 4 H 10 mixed with air in stoichiometric proportion the value is 0.4 meters per second.

Therefore, we find for these alkenes, the speed is around 0.5 meters per second; mind you it is quite slow maybe if I have a fire, which is coming forward. You know the inference is I can run much faster, and therefore I can save my skin from the fire, which propagates out from an ignition source. Well, let us put down 1 or 2 more, let me put down value for acetylene, see acetylene we said is higher energetic, and therefore it has a value of 1.6 meters per second. And if I take the last one maybe hydrogen air system the speed is around 2.9 meters per second.

You know, hydrogen is a very light gas, if it is a very light gas the value of rho u that is in the denominator, we have rho u is small and this speed is higher. Well these are about the speeds and therefore, we have done something now, see we are now able to find out, if I have a gas mixture, and if I sort of ignite it, and if by chance I have a combustion wave, which I am able to create. I am able to find out the speed at which this combustion front propagates out, when I say combustion front propagates out. You know, if we go back and look at the text books on explosions or even on combustion.

(Refer Slide Time: 30:00)

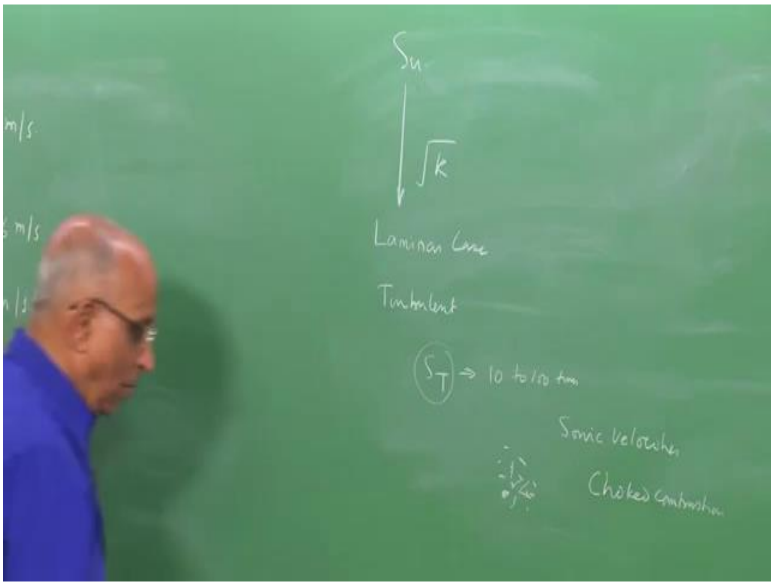


You will find people talk in terms of flame velocity, is flame velocity same as the combustion front, which moves or we say the value of the value of S u, which we said is the velocity with which the unburned gases are moving towards. The front is it same as the flame velocity. Let us go back and look at a particular experiment.

Let us say, I have a tube in which gases are there, and then I ignite the gases, and form a flame, and this flame moves out at a given velocity. Now, when the observer is standing over here outside a stationary observer he watches the flame go by and he defines this as the flame velocity, now what did we tell ourselves? You know, when I talk in terms of that the speed S u what did I presume I said I am standing on the combustion front, and I am looking at the speed with which S u is coming towards me.

Therefore, S u is equal to flame velocity only when the gas ahead of the flame is stationary, but if this is also moving at some velocity, what is perceived S flame velocity is a much higher velocity because it is with reference. See I do not take care of this, I presume here that it is stationary, and therefore I calculate this. Therefore, flame velocity is going to be the unburned gas velocity or the unburned speed plus the velocity of the particular medium in the direction at which flame propagates. Therefore, in way we will do problems involving flame velocity, and get this get this concept to be further clarified as we go along.

(Refer Slide Time: 31:49)



Therefore, now we say, well I know, the speed with which a flame or a combustion. Wave propagates and which I call as the unburned gas velocity. Now, if I say, unburned gas velocity, we also find it was proportional to under root k. That means the thermal conductivity, you know whenever something is moving see I can, I can not only have the transfer of heat by conduction. It could also happen by convection and especially something is very turbulent, what could happen.

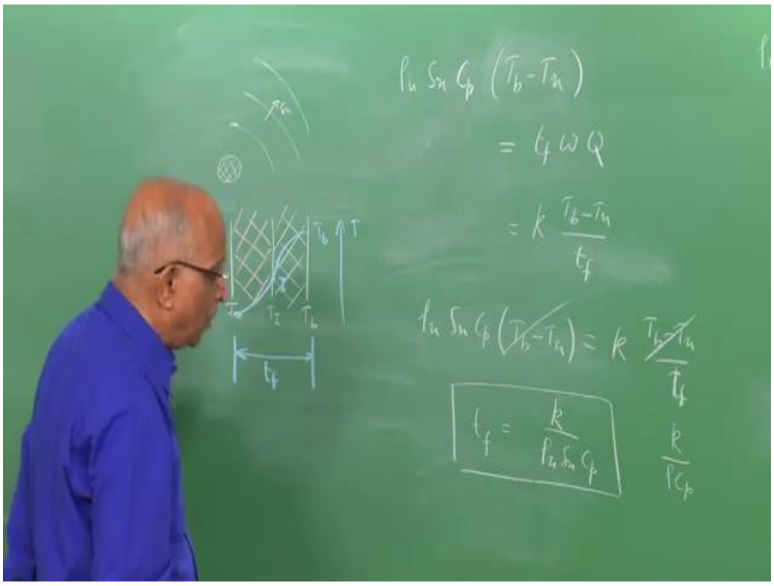
Well, I could have an equivalent conductivity, which is very much higher. Therefore, I can also say, well the S u, which we have learnt so far or which have been able to develop. So far based on this mine model is only good for a laminar case in which the transport of heat is by molecular conductivity k over here. If, it is going to be turbulent, well I can use similar expressions, but I must also take care of which increase the value of the thermal conductivity.

Therefore I can also say the flame can move at turbulent speeds, which I call as S T S compared to S u over here. The turbulent speeds are generally around 10 to 100 times faster, because the transport of heat from the ignition source or into the succeeding layers is very much higher. The transport by diffusion of the concentrations is very much higher with the result that the turbulent velocity flame speeds are very much higher.

In fact maybe towards the end of the course, we will see or maybe towards maybe another 5 or 6 classes maybe we will see that we can have turbulent velocities, which can reach something like the sonic velocities, which we will sometimes refer to choked burning or choked combustion because sonic corresponds to choking anyway we have to do all this. Let us, let us now come back we say, well it is possible to turbulent propagation and in we have turbulent propagation of the burning gases. I say, well I have turbulent speeds at which it goes, with this background on speed of propagation.

Can I go back and say, what is the thickness of my flame? See, we also said, yes I am interested. Let us, let us again not lose track of the problem.

(Refer Slide Time: 34:09)



I have a particular volume; I want to find out what is the critical ignition kernel such that a flame propagates out. We are now able to find out the value of S u or we say, well S T will be much larger than S u. Can I also find out the thickness of the flame, which propagates out, because that will help me to do this problem? Therefore, I am interested in the thickness of the flame.

Let us again put the diagram of the flame as we looked at it earlier; well I say rho u into S u comes here. It increases in temperature from T u to an initial value T I to the burned gas value T b over here. Therefore you know, what is happening? This is the zone length L in which chemical reactions are occurring. This is the zone in which pre-heat is taking place and you have. If I plot the temperature, what is the temperature distribution, something like is the inflection point over here, T I the inflection point over here. Well, what is it? This the scale is up for the temperature is T b over here, T u over here.

This is the type of progression, what do you find? Now, if I were to get the thickness of the flame, well I am looking T the thickness of the flame to be over here. Thickness of the combustion front T f over here, I want to get an expression for it. Therefore, in a similar way I just put down the values. Well, I tell myself well the heat transferred. Well, let us, let us put it down here. I have rho u, rho u into S u is the mass flux, which is coming and what happens I am, I am interested in the total, I have C p into, I get the value of T b minus T u, which is the total, and what is it?

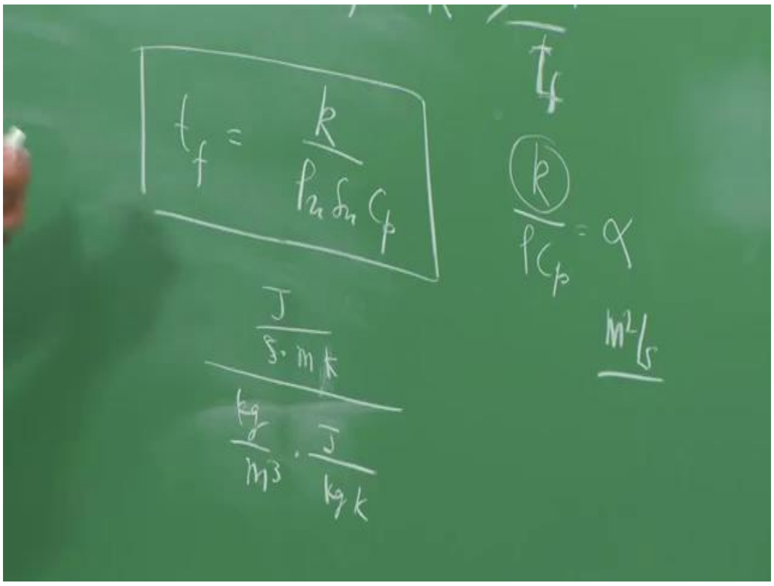
You know, this is the total heat, which is, which is, which is being generated in this and this heat is what is available here. And therefore the total heat is going to be equal to the heat, which is generated, which is equal to T f into omega into q. But the heat, which is generated, is also the heat, which is conducted away. I can write it as equal to k into, if I assume the gradient to be T b minus T u and the thickness of the flame front as T f. This is equal to T f and therefore, what is it? I get, I get now the value of rho u into S u into C p into T b minus T u as equal to.

Well, this is common to this I get the thermal conductivity into T b minus T u into T f and therefore, on the left hand side. I have T b minus T u on the right hand side. I have T b minus T u. I can knock it off over here, and what is it? I get, I get the value this mind you is equal to the thickness of the flame, small T f is equal to. I bring it on this side. I take the rho S u C p on this side I get rho u into S u and C p over here. And therefore, I get the expression for the thickness of the flame to be k divided by rho u S u into C p.

Now, well this is the thickness of the flame, but we must be able to get a idea of the thickness. This is the 0.1 m m, is it 1 metre, is it 1 centimetre? And therefore, let us take a look at this particular expression, when I say k over rho C p, when I say the expression of k over rho C p, we call it as thermal diffusivity alpha, and what does thermal diffusivity actually represent?

It says, how much heat is there in a given substance, and out of this heat content of the substance, how much gets diffused out by conduction? That is what that is the rate at which heat leaves the inertia of a system, and therefore compared to the heat, which moves out how much is heat is contained within the system. That means how much heat gets diffused out of the system. We call it as alpha and k by rho C p as alpha, and if you look at unit of thermal diffusivity, we have unit of thermal conductivity, and what is conductivity watts per metre Kelvin, that joules per second by metre Kelvin divided by rho, that is Kelvin over here. Your rho is kilo gram, rho is equal to kilo gram per metre cube density specific heat again joules per Kilo gram Kelvin.

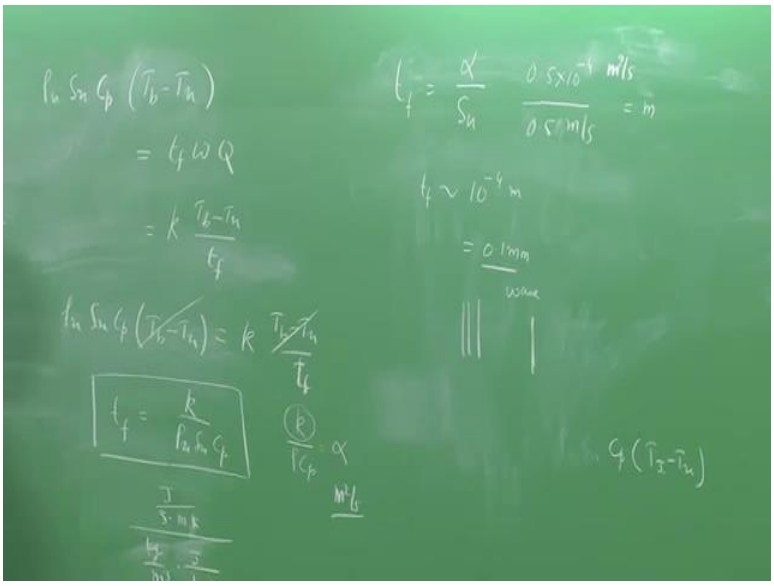
(Refer Slide Time: 38:56)



And therefore, kilo gram kilo gram gets cancelled joule gets cancelled. Metre cube, metre square comes; metre square comes in the numerator. I have left with the second the unit of thermal diffusivity is metre per second. Therefore, you find, I can also write the value of the flame thickness. Let us put it down. I can write the value of the flame thickness T f small t with suffix f as T f is equal to thermal diffusivity divided by the flame speed.

We also already saw, S is typically around 0.5 metres per second for hydrocarbon air mixtures, if you look at the thermal diffusivity of most of the gases at atmospheric pressures is typically around 0.5 into 10 to the power of minus 4 is what we are talking of, is of the or of so much metres per second unit.

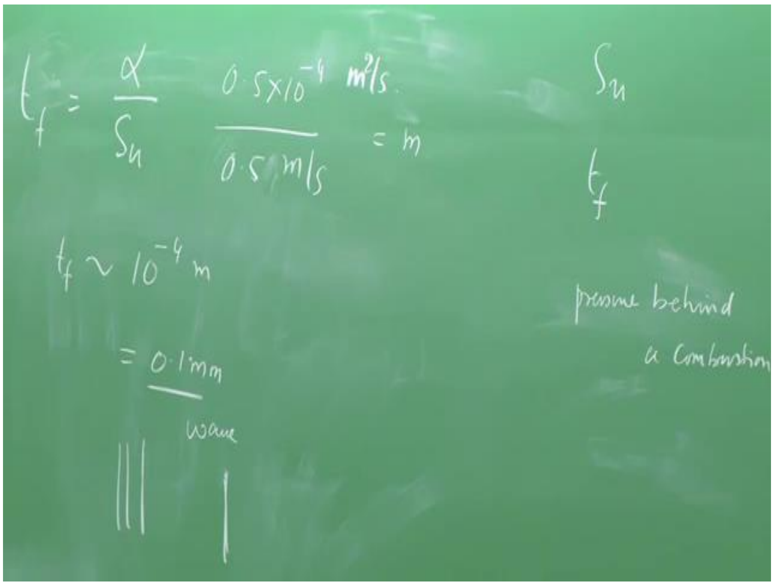
(Refer Slide Time: 39:47)



Being this the value of S u is we said is equal to 0.5 into u h so much we are talking of in metres per second. Therefore, the thickness of the flame is so much metre. Well, the unit is all right and therefore, we say the thickness of the flame is typically around 10 to the power of minus 4 metres or which is around 0.1 metres.

Well, the thickness of this combustion thickness or the thickness of this combustion, which consists of the pre-heat and the zone of chemical reactions, is only of the order 0.1 millimetres. Because it is 10 to the power of minus 4 metre of the order of 0.1 millimetres, and therefore maybe we can also say, it is as good as a wave. You know the flame is so thin that it propagates as a wave. Therefore, we have two expressions, now we derived an expression for the flame speed S u.

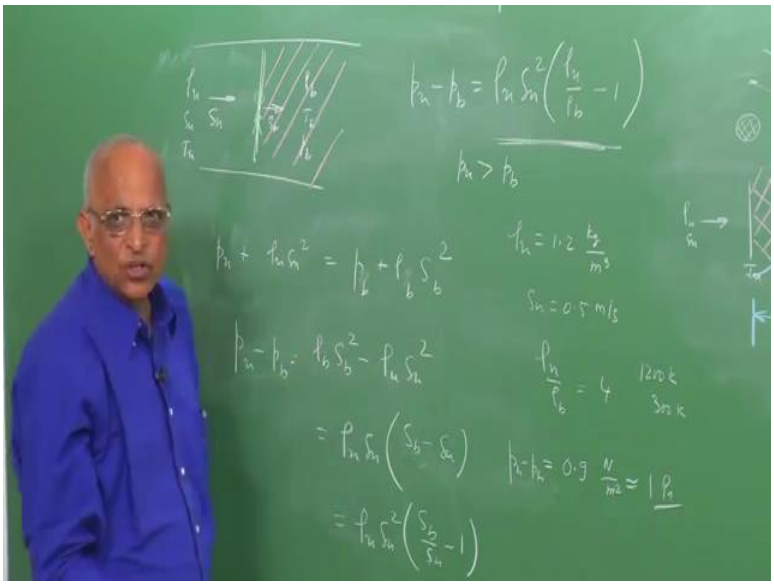
(Refer Slide Time: 40:52)



We also derived an expression for the flame thickness t f. I would like to use these two to be able to find out how much energy, if I do not use the lump mass system, but I am interested in having a kernel of a given size. I would like to know how much energy is required to ignite it, but before I do that one last derivation as regards the combustion wave, what is the pressure generated, what is the pressure behind a combustion front, is what I would like to do. And if this is clear, well I can go back and justify some of the things.

I have been doing today and also have an idea of how to go ahead and model my ignition required my size of my kernel, what I require. And therefore, proceed further with my with my combustion waves.

(Refer Slide Time: 41:46)



Therefore, I tell myself, well I am looking at this. I am, I know, no I have a flame, which is of thickness T f. I have something, which is moving here with the speed S u towards y front, and what is moving is rho u S u and at a temperature T u. And what is here on the right hand side, is what I have the burned gases? And in the into the burned gases the combustion front moves with or the gases are moving towards the combustion front, which is stationary because we considered S u with reference to the with reference to the observers sitting on the wave. That is with respect to the to the combustion front itself. Therefore, gases are moving at us gases are moving are moving away over here.

The density is rho b, the speed is S b, the temperature is T u, the pressure is, let us say p b T b over here. If, I write the momentum equation, what is it? I get, well I have pressure upstream, which is equal to p u plus. I also have the momentum, I am considering unit area. Therefore, I say or the flux movement either the flux or I have are. That means, area into pressure is the force. And I now write the total mass, which is equal to rho u into Su into per unit area. I have this into the S u square. This is the result of the pressure and the momentum on this side, which is equal to the value of p s plus rho s into.

I have rho b here, it is p b over here, p b plus o b into s b square over here. Therefore, I get the value of p u minus p b that is the change in pressure from here to the burned gases over here is equal to. I get rho b into S b square minus rho u into S u square, but from continuity I also know that the mass flux coming here is equal to mass flux leaving here or for per unit are I can write as rho u into S u is equal to rho b into S b.

This being equal, I can write it as equal to rho u into S u into, I get S b by S b minus S u. I take this is equal to this without this over here, I am left with S b minus S u, and now I take S u outside in that rho u into S u square into S b by S u minus 1, but S b by S u is equal to rho u by rho b. And therefore, I write the pressure difference. Let us, let us write that out I get the value of p u minus p b is equal to rho u into S u square into. I get S b by S u from the continuity equation is equal to rho u by rho b minus 1. You know, the burned gases are at a higher temperature than the unburned gases. Therefore, this is greater than one.

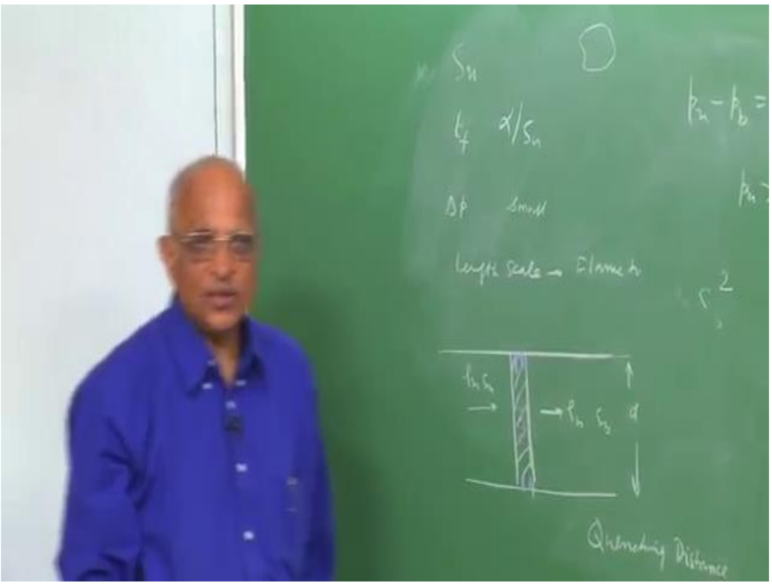
Well, I have the therefore, what is going to happen. Therefore, I say, well p u is going to be greater than p b that means there is a drop in pressure across the combustion front or the combustion wave, and what is the magnitude? Let us, let us put down the magnitude for one specific case. Well, the ambient pressure is something like u h 1 atmosphere 3000 Kelvin. Therefore, the density rho u is typically around 1.2 kilo gram per metre cube. We say well, S u for most of the case is around 0.5 metres per second for hydrocarbon gas mixtures. The value of rho u by rho b, if I say that the temperature increases 3 fold from 300 to 900 or 1000 Kelvin rho u rho b is equal to something like 4.

Let us say, 4 times the increase on temperature that is the burned gas temperature is something like 1200 Kelvin as compared to the initial temperature of something like 300 Kelvin. Therefore, if I substitute these values here 1.2 into 0.5 squared into 4 minus 1. I get the typical value here, if I substitute these values I get the value of p u minus p b is something like 0.9 a Newton per metre square or something like around 1 Pascal. If, 1 Pascal is a very small number atmospheric pressure is something like 10 to the power 5 Pascal.

Therefore, even though there is a fall in pressure, the fall in pressure is very small, and therefore whenever we talk in terms of a combustion front. We talk in terms of a constant pressure process and that is why we are justified in using the value of C p, while determining the flow properties over here. That means across a combustion front there is hardly any change in pressure, but mind you let us keep this clear there is a drop in pressure and this drop in pressure is somewhat small.

Therefore, so far what is it? We did, we have learnt the following.

(Refer Slide Time: 47:18)



We learnt how to determine the value of the flame speed S u which is the unburned gas. That is the velocity with which the combustion front is moving. Into the unburned gas medium, which we said for a stationary medium is same as the flame speed. We also talked in terms of the thickness of the flame, which we said is equal to thermal diffusivity divided by the, by the, by the speed of the combustion front. Also we talked in terms of the pressure drop across a flame, which we said is extremely small, but there is a small drop in pressure across the front. Now, we want to put these things together to be able to relate how much energy is released in combustion. In the zone, we want to estimate the size of the ignition kernel, and to be able to do that.

I want to define one last thing namely is there something like a length scale, which can say, which will not allow. Let us say, a flame to propagate rather. Let us, let me formulate this. Let me say supposing I have a pipe like this. Well, we know now, yes I have a combustion front, which into, which I have. This is stationary, I have rho u S u moving towards it. I have rho b moving at a speed S behind it is there a specific dimension d beyond, which I cannot allow my flame to propagate.

That means, I want to look at maybe, if I have the flame structure over here. I have the flame over here. You know, what is going to happen, I have the walls of the pipe over here, into which maybe gases are moving towards a flame, maybe the flame we are telling is stationary. We are looking at the problem in the frame of reference of the flame, and what I want to do is I want to see, what is the heat, which is getting transferred from the flame to the wall. I want take a look at what is getting generated over here. Therefore, I want to find out the diameter for which a flame is just able to propagate in this is there something like a diameter below, which a flame cannot propagate or rather a diameter by which the flame will get quenched.

Therefore, what I will do is maybe I will take a look at the quenching distance or quenching diameter, and based on this quenching diameter I will put the quenching diameter, along with flame speeds to be able to define something like the critical size of the ignition kernel. I will follow this up in the next class, and therefore to just review what we have done today. We find that we have relaxed the assumption of let us say, a lump mass system, we looked at the ignition of a gas at a particular point and therefore, from this point the flame or combustion wave propagates ahead. We said yes. I know now how to estimate the speed at which the combustion wave propagates.

I know the thickness of the flame; I know that the pressure drop across the flame is extremely small even though I know there is a drop across the flame from the unburned towards the burned side there is a drop. And now we will do in the next class the quenching thickness. That is the quenching distance and thereafter, models the ignition, well.

Thank you.