Combustion in Air Breathing Aero Engines

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Lecture - 29
Limit Phenomena I

Welcome back. So, so far we have in this course we have discussed a many things like, we have discussed chemical equilibrium. We have discussed chemical kinetics, different kind of theories of to obtain the reaction rates the reaction rate constants as such. And we have discussed the oxidation mechanism of practical fuels as the mechanisms by which pollutants are being formed.

Then we have discussed different kinds of flames, we have discussed laminar non premix flames we have discussed droplet combustion. We have discussed laminar premix flames thermodynamics premix flames structure you have premix flame speed. And then gone on discuss the different chemical structure of premix flames, but of course as you know that these are all the last things the flames that we have discussed those are like steady state flames.

So, those tell you about the propagation characteristics, those tell you about the stabilization characteristics about the temperature. But they do not tell you how to get them that is how to ignite them or how to extinguish them or what can causes the extinction. So, for a practical engine of course, we cannot start with a flame of course, when you have a and when you start the engine you have to ignite it somehow, and we have to understand once again we will go to the actual ignition problem in an engine later.

But for now we have to first understand that what are the basic principles which can lead to ignition which we call thermal explosion, that is there is no of course, explosion involved here in. It is just ignore a rapid rise of rapid it is of course, in this rapid rise of temperature and that is taking place. And use this thermal explosion we will go to the a scurf concept we will go to extinction flammability limit, and flammability limit is and the concepts of flammability and flame stabilization. We will mainly not mainly go on to these topics here extinction.

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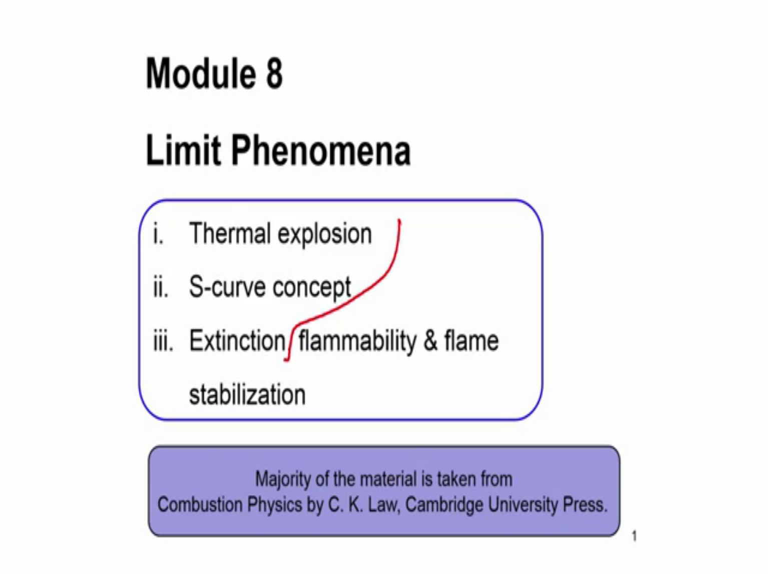

Module 8

Limit Phenomena

i. Thermal explosion
ii. S-curve concept
iii. Extinction, flammability & flame stabilization

Majority of the material is taken from Combustion Physics by C. K. Law, Cambridge University Press.

And the flammability we will just discuss, and the flame stabilization we will take up later.

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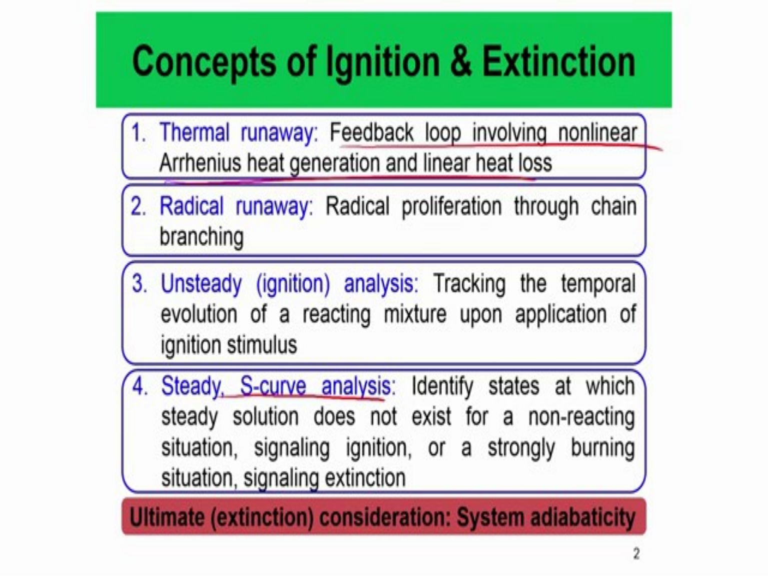

Concepts of Ignition & Extinction

1. Thermal runaway: Feedback loop involving nonlinear Arrhenius heat generation and linear heat loss
2. Radical runaway: Radical proliferation through chain branching
3. Unsteady (ignition) analysis: Tracking the temporal evolution of a reacting mixture upon application of ignition stimulus
4. Steady, S-curve analysis: Identify states at which steady solution does not exist for a non-reacting situation, signaling ignition, or a strongly burning situation, signaling extinction

Ultimate (extinction) consideration: System adiabaticity

So, what is what do you mean by explosion? By explosion a thermal runaway of course, as I said there is no actual explosion involved it is just a thermal runaway, but the temperature can rise quickly in a given mixture, because of the combustion reactions. And it is essentially caused by a feedback loop involving non-linear arrhenius heat generation and linear heat loss.

So, what I mean by that? So, after you ignite if the if there is this some it this temperature slowly increases, now as the temperature increases this heat is conducted and the to the sound is regions or not conducted that local temperature increases, in the local rate of reaction increases. So, once the local rate of reaction increases temperature further increases and this further increase temperature actually again increases the reaction rate. But at the same time as the temperature increases the heat loss also increases. Because the temperature difference to the surrounding also increases. So, the heat loss increases. So, the on one hand you have this highly non-linear a arrhenius heat generation and on the other hand you have a linear heat loss.

So, it is the balance of this that that tells us whether in a given state of mixture we may be able to have an ignition at all possible which can be obtained by thermal runaway. Then there is a radical run away. So, there is a radical if the radicals are produced at a fast rate through the chain branching reactions, then also you can have this different then also you can have this then also you can have this, this a radical runaway and it can lead to ignition. And we will first also a unsteady ignition analysis that is tracking we will track the temporal evolution of a reacting mixture upon application of a ignition stimulus. That is what at, how does the ignition actually happen take place. How much does the fuel concentration change in that amount of time, etcetera? And on what parameters does an ignition delay time would depend on theoretically.

So, we will consider a theoretical analysis, and then we will do a steady analysis, by using this S-curve analysis and we will identify the states at which the steady solution does not exist or it will exist for a non reacting situation. We would consider a ignition state and we will consider a strongly burning state which will signaling extinction. So, we will do the S-curve analysis just like that Z-curve analysis, this is an S-curve analysis. We will tell us under what conditions you can have ignition under what conditions you cannot have ignition like that ok.

So, ultimately this is caused by the system adiabaticity, that is whether if you do not have heat loss then even if you supply a small amount of energy it will automatically the ignition is guaranteed. But then we do not deal with such ideal adiabatic systems, we always deal with systems which are exposed to the surroundings, which are exposed through a which are expose to the surroundings for example, in a in a gas turbine engine you have like a nozzle.

So, the nozzle gives out a spray and this pray atomizes at the, with the spray breaks up then the spray break up basically leads to droplets, and these droplets can break up further to create small and small droplets. And these droplet then essentially mix essentially evaporate and form a gas cloud and mix with the local air. And then you have an igniter somewhere like a spark which actually ignites.

So, now then a small kernel is formed a small ignition kernel is formed, with a higher temperature, but then there is also continuous heat loss to the surrounding cold air, the cold area rather not very cold, because in a gas turbine the compressor at the downstream temperature is quite hot itself, but it is a cold area. So, it is not an adder this kernel that is formed is not an adiabatic system. So, basically if you want to understand fundamentally that what govern So, that this kernel will be able to sustain and ignite or not, forget about all the flow non uniformities etcetera, at least from a fundamental point of view at least for a very simple analysis like, heat generation heat and lost point of view, without considering the flow non uniformities etcetera. If we just want to understand that then what are the considerations.

So, what governs whether in an idealized state if we form a kernel and not, want whether it will ignite or not so that is very important to design your ignition system. And that is a very critical, because if you do not have ignition we do not have essentially power.

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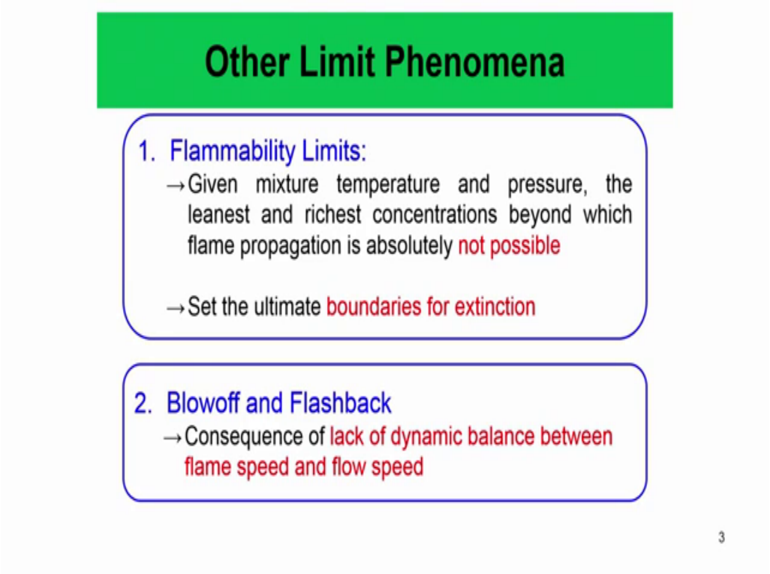

Other Limit Phenomena

1. **Flammability Limits:**
   - → Given mixture temperature and pressure, the leanest and richest concentrations beyond which flame propagation is absolutely not possible
   - → Set the ultimate boundaries for extinction

2. **Blowoff and Flashback**
   - → Consequence of lack of dynamic balance between flame speed and flow speed

So, to have that we need to understand this concept of ignition in an extinction. There can be other limit like flammability limit is that is a given mixture temperature and pressure, what are the leanest and richest concentrations beyond which flame propagation is absolutely not possible. And this set the boundaries of ultimate boundaries for extinction. And then blow off and flashback is a essentially a lack of aerodynamic balance between flame speed and flow speed, but they said there is also some extinction and heat loss whenever can be involved, as we will show that later in a you know when we consider the flame stabilization mechanisms and after one stream scramjets. So, that will come later.

So, in more practical applications and we will not consider a blow off flashback here. So, first is that I will consider the simple consideration of quenching distance and the minimum ignition energy.

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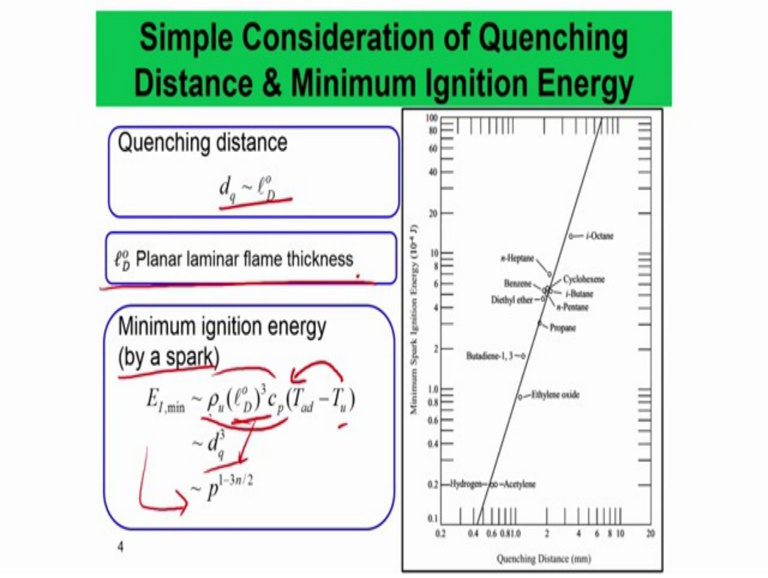

Simple Consideration of Quenching Distance & Minimum Ignition Energy

Quenching distance

$$d_q \sim \ell_D^o$$

ℓ_D^o Planar laminar flame thickness

Minimum ignition energy (by a spark)

$$E_{I,\min} \sim \rho_u (\ell_D^o)^3 c_p (T_{ad} - T_u)$$
$$\sim d_q^3$$
$$\sim p^{1-3n/2}$$

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And So, what is a concept of quenching distance? You see if you suppose have 2 adiabatic parallel plates. So, or not just 2 metal plates which are separated by a small distance.

Now, you can easily think that if you have to sustain to say this plate is filled inside of this plate is filled with fuel air mixture. Now if you ignite it is very easy to understand and easy to intuitive that if this plates are not separated by a substantial distance, these flame will immediately extinguish. This is essentially the principle then it will extinguish by the conduction and heat loss. And this is this comes from the concept of this minor safety lamp or the daily safety lamp where you basically this meshes made So fine So that even if there is a surrounding fuel air mixture, the flame inside the lamp really does not cannot get out and ignite the whole mixture.

Because once it tries to get out it just gets quenched to the fine distance between these 2 meshes between this wires. So, that is the concept of the minor safety lamp. And that is the concept of the quenching distance, that for a flame to be for a premixed flame to be not quenched, to be not quenched while passing through 2 a say parallel plates, the distance between them should be greater than the quenching distance, and then what should be the quenching distance depend on? This is very easy to understand that the quenching distance should depend on the flame thickness, because flame thickness is the region over which conduction process is dominant ok.

So, that is why the dq is essentially proportional to l D 0 which is the planar laminar flame thickness. So now, then we can by the same token we can think that, that the minimum ignition energy by a minimum ignition energy by a spark, that is the should be essentially have some bearing of this kind of a relationship, that is the minimum ignition energy by a spark should be that energy by which I should be able to take the temperature of a given mass of gas, and what should be the mass of gas be of course, this is the rho u is on bond density and the volume of gas should be essentially proportional to the volume of the cubic volume of the quenching distance, ok.

So, that is why it is l D cube. So, that it should be at least the in a in a given volume which is the you know which is the characteristic length scale of the which is the quenching distance, and hence the flame thickness of what that volume I should be with the spark energy I should be able to increase the temperature from T u to T u adiabatic. So, that is the criteria and of course, that gives me the fact that then it becomes proportional to the quenching distance and from here it is dependent pressure. And I can using this I can show that this pressure then e min essentially depends on pressure and of course, with a for n greater than or equal to a half, or a 2 thirds you will get a ignition energy decreasing with ignition energy essentially decreasing with pressure, ok.

So, this is the point and here of course, you see that this quenching distance will be plot, and on the yx axis and the minimum spark energy or ignition energy on y axis you still get a law which is essentially proportional nearly close to this 3 behavior, and it says that this relationship is correct in the ballpark, ok.

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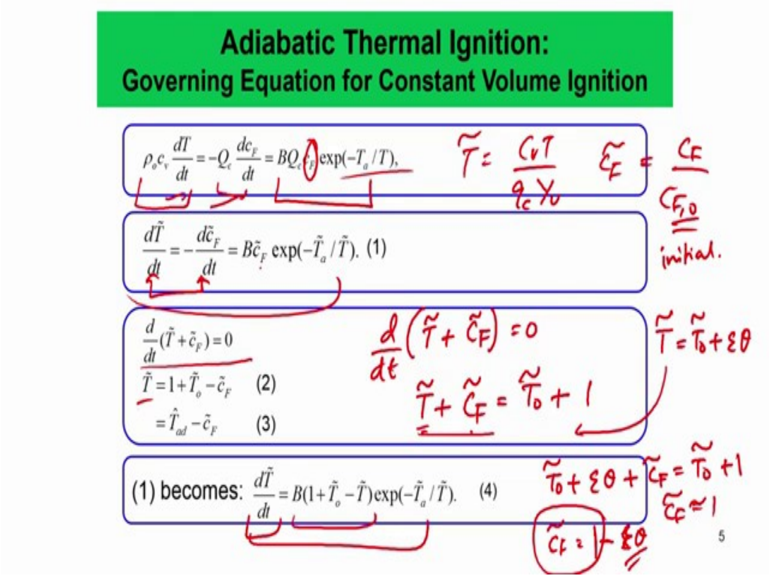

Adiabatic Thermal Ignition:
Governing Equation for Constant Volume Ignition

$$\rho_o c_v \frac{dT}{dt} = -Q_c \frac{dc_F}{dt} = BQ_c c_F \exp(-T_a/T),$$

$$\tilde{T} = \frac{C_v T}{q_c Y_0} \qquad \tilde{c}_F = \frac{c_F}{c_{F,0}}$$

initial.

$$\frac{d\tilde{T}}{dt} = -\frac{d\tilde{c}_F}{dt} = B\tilde{c}_F \exp(-\tilde{T}_a/\tilde{T}). \quad (1)$$

$$\frac{d}{dt}(\tilde{T} + \tilde{c}_F) = 0$$

$$\tilde{T} = 1 + \tilde{T}_o - \tilde{c}_F \quad (2)$$

$$= \hat{T}_{ad} - \tilde{c}_F \quad (3)$$

$$\frac{d}{dt}(\tilde{T} + \tilde{c}_F) = 0$$

$$\tilde{T} + \tilde{c}_F = \tilde{T}_0 + 1$$

$$\tilde{T} = \tilde{T}_0 + \varepsilon\theta$$

(1) becomes: $\frac{d\tilde{T}}{dt} = B(1 + \tilde{T}_o - \tilde{T})\exp(-\tilde{T}_a/\tilde{T}). \quad (4)$

$$\tilde{T}_0 + \varepsilon\theta + \tilde{c}_F = \tilde{T}_0 + 1$$

$$\tilde{c}_F \approx 1$$

$$\boxed{\tilde{c}_F = 1} - \varepsilon\theta$$

Now let us consider this in more details that is suppose we are igniting a gas, by putting an amount of by with the temperature of which is a increasing, and due to heat release So, we have a So, this is the situation that we have a we have, a we have a, we have this condition of this adiabatic thermal ignition, and where we are considering the governing equations for constant volume ignition.

Suppose for per unit for a per unit volume the temperature rise in a in a given in a given volume will be in which we are not considering any transport. So, homogeneously in the given volume if you supply some energy then the time because of heat reduce, the temperature will rise and the temperature rise is essentially given by this left hand side row C V dt dt that is this rate of change of temperature with respect to time.

So, this is a temporal this is a time varying a transient term. And how much will the temperature rise that is the right hand side of your energy equation which is essentially the heat release times the mass fraction the rate of consumption of this a rate of change of a concentration on the field. Of course, this is to the leading order when you have this fuel in a lean quantity with respect to the oxidizer this is same consideration we had it for the premixed flame. So, then this dc F dt we can write is to be given by this.

So, essentially this rate of change of temperature rate of change of temperature is essentially equal to the rate of heat release of heat. So, it is essentially equal to the rate of heat release is equal to the heat release rate whereas, this is V this is the Q c and then C F which is a concentration and this is system and this is the heat of combustion. And So, we can normalize this of course, by the same manner that is T u tilde is equal to like CvT by Q c Y u and then C F by m a C F a tilde is equal to C F by C F a 0; whereas, C F 0 is the initial concentration, initial concentration of the fuel and then of course, you will get a relationship like this all right.

And then we can a sum these 2 things and create a coupling function. Then this takes on the right hand side and then the dt tilde plus C F tilde equal to 0. And then we can write of course, that at a T u equal to T u 0 at time T u at time T u equal to 0 your temperature is with the T u 0 that is the initial temperature. So, we are trying to find out basically that if we will keep a given volume of a gas at a temperature T u 0 how much time will it take for it to ignite. So, then of course, at a time at a where is a time T u equal to at a later time this a term. So, if dt if we have this equation d dt is equal to T u equal to 0 then T u tilde plus C F tilde is equal to T u 0 tilde plus 1, why 1? Because at C F 0 at T u time T u equal to 0 your C F tilde is equal to C F 0 by C F 0 which is equal to 1 ok.

So, let us this can be anything so, but the final temperature cannot exceed the adiabatic flame this where time T u equal to infinity we have time T u ad this becomes equal to 0 it is equal to T u 0 tilde plus 1. So, we can replace this one plus T u 0 tilde here itself with T u ad and this becomes T u tilde is equal to T u ad tilde minus C F tilde, all right. So, this is the thing. So, then this is then this becomes a dt tilde dt is equal to d times one plus a T u 0 tilde minus T u tilde and we can essentially, what we are doing is that we are essentially substituting here this guy with, with the C F tilde is equal to T u ad tilde minus T u tilde ok.

So, once we do that this dt tilde dt is equal to we can write this in this form. So, once again explicitly what we have done previously also with the premix flames, when we get our when we get this an energy equation the energy equation is always mixed with the temperature term as well as the species concentration term. So, what you can do is that you can by using these coupling functions you can write the species concentration term in term of the temperature term. In terms of temperature and then you can replace this species concentration in this in this energy equation using that coupling function and then you can write it explicitly in the form of temperature. So, that is what you get.

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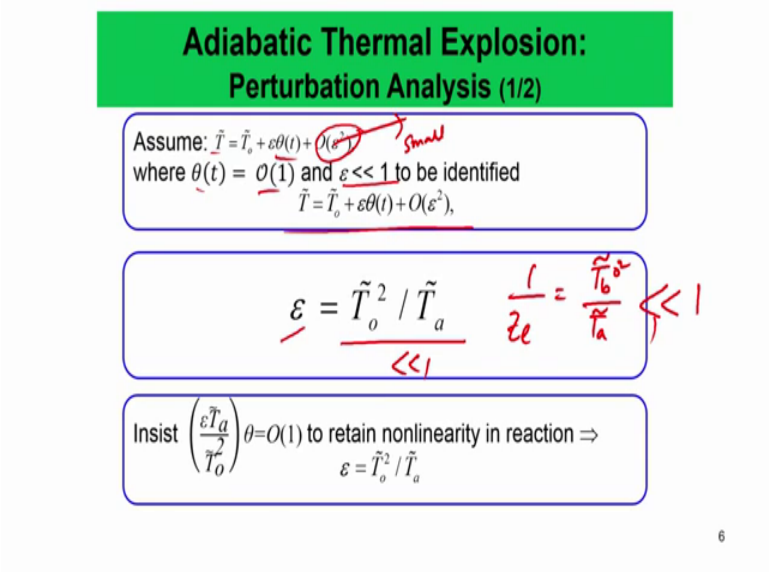

Adiabatic Thermal Explosion: Perturbation Analysis (1/2)

Assume: $\tilde{T} = \tilde{T}_o + \varepsilon\theta(t) + O(\varepsilon^2)$ small

where $\theta(t) = O(1)$ and $\varepsilon << 1$ to be identified

$$\tilde{T} = \tilde{T}_o + \varepsilon\theta(t) + O(\varepsilon^2),$$

$$\varepsilon = \underbrace{\tilde{T}_o^2 / \tilde{T}_a}_{<<1} \qquad \frac{1}{Ze} = \frac{\tilde{T}_{b0}^2}{\tilde{T}_a} << 1$$

Insist $\left(\frac{\varepsilon\tilde{T}_a}{\tilde{T}_o^2}\right)\theta = O(1)$ to retain nonlinearity in reaction $\Rightarrow$

$$\varepsilon = \tilde{T}_o^2 / \tilde{T}_a$$

So, now we can introduce a small perturbation analysis where you say that, that this T u tilde at that is at that is at any time that is a at any time T u greater than 0. Your t less essentially equal to the T u 0 that is the original temperature T u 0 tilde plus epsilon times theta T u which is a function of time plus an order plus higher order terms. Which are proportional to epsilon square and this epsilon is a quantity much greater than 1. So, we do not need to consider this. So, this goes to 0.

So, this is essentially small. And So, essentially we write it as a linear a perturbation that is T u tilde is equal to T u 0 plus epsilon theta T u whereas, theta T u is of the order of 1 and epsilon is much greater than 1 and. So, we this is the equation with which we consume substitute. So, of course, and we can find out that we can write this epsilon is equal to T u 0 tilde square by T a tilde, and that actually this if you see that when this is if this was T b essentially comes essentially the one by zelda which number.

So, this is very small and even a zelda which number itself is, if you remember zelda which number itself is or we were let us write one by zelda which number itself is essentially your T b 0 tilde square divided by T a. Tilde and this is of course, still much smaller than 1. So, definitely this quantity if this T b 0 square is by T a tilde is much smaller than 1 then of course, and of course, this is actually T b tilde minus T a tilde, which does not come in which you are not showing the statistical of the order of 1.

So, if this is much smaller than 1 then definitely this is also much smaller than 1, because the to is a to tilde square this is definitely much smaller than T bo tilde squared. So, and then to retain this non-linearity and this is of the order of 1, to retain the nonlinearity and when we substitute this and when we substitute, this we get essentially.

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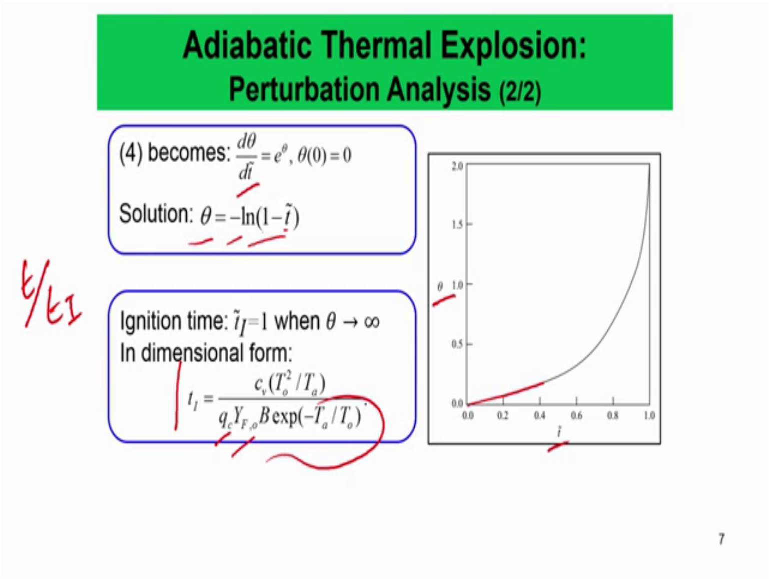

Adiabatic Thermal Explosion:
Perturbation Analysis (2/2)

(4) becomes: $\frac{d\theta}{d\tilde{t}} = e^{\theta}, \theta(0) = 0$

Solution: $\theta = -\ln(1-\tilde{t})$

Ignition time: $\tilde{t}_I = 1$ when $\theta \rightarrow \infty$

In dimensional form:

$$t_I = \frac{c_v(T_o^2/T_a)}{q_c Y_{F,o} B \exp(-T_a/T_o)}$$

t/t_I

What we will get is that we will be get some much simplified thing whereas, d theta dt tilde is essentially is equal to epsilon is given by e to the power of theta and then you can plot theta, with respect to T u tilde and we will get this exponential behavior, let us see you remember theta is nothing, but this quantity we can do this thing analysis and you will find. So, the T u ignition is what this T u is essentially nothing, but T u divided by T I whereas, T I we can solve that we can do estimate this now we can find out the time when it becomes when theta becomes we can essentially find out.

So, this is what the solution is theta is essentially minus logarithm of one minus T u tilde, and that this gives this behavior actually all right. So, now, this we see we can say that that when T u becomes T u tilde becomes equal to 1 then theta becomes infinity. So, over then T u tilde becomes equal to 1 that is T u equal to T I/ then what is T I and you can solve this and then write this in a non dimensional form, and we can find that T I is nothing. But this quantity whereas, T I is equal to C V T u 0 square by T I T u 0 is the initial temperature, anywhere by Q c y of 0 b times e to the power of minus T a by T u 0 ok.

You see that now this strong where the temperature dependence comes from these 2 things that is it has this one and it has this exponential this arrhenius type. So, of course, you can understand that if C V is large your T I will be large, that is it takes more time to heat up the gas. If your Q c is large your heat release is large then of course, T I will be less. If your y of 0 is large your T I will be less and of course, if your exponential this arrhenius times term it is not your T I will be less. So, these are the factors to the first order we can estimate by this analysis that which controls the ignition delay time of a homogeneous mixture in a given volume ok.

Um, but of course, you see here we have not considered any heat loss. So, we can we are considering an adiabatic thermal ignition basically. So, there is the problem once again to reiterate was that we consider a volume which was kept at a temperature T u 0 and we estimated here at the time that is required for it to ignite that is for which this theta becomes essentially fine T u and which guarantees ignition. So, this is the interesting thing. So, one more interesting thing that to look at is that that it can be also shown that the time by doing this time that your. So, that is that is that is it for here and you So, what we can do here is that if you just take this thing and write this equation, that is T u tilde that is T u tilde is equal to T u 0 plus epsilon theta.

That is So, if we substitute this thing here this is the interesting thing to show is that that is this then we write the T u tilde plus epsilon theta plus C F tilde this is equal to T u 0 tilde plus 1. So, C F tilde is equal to 1 minus epsilon theta ok.

So, of course, now when I mean this because this epsilon is very small, we can say that this C F this is of the essentially of the order of 1. So, C F tilde is essentially equal to 1 for most part at the time. So, it means during ignition there even when the temperature rise is substantial, as long as this is this quantity small your consumption your fuel consumption is very less. And So, C F tilde remains up to one as up to very long terms and up to up to essentially up to your extinction.

So, that is the point and we wanted to show. And that is the fact is comes from the fact that it has this kind of a behavior.

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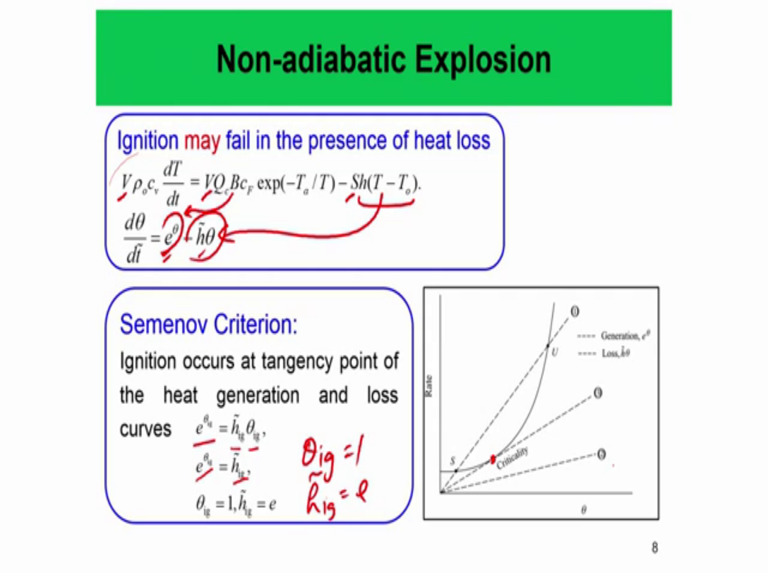

Non-adiabatic Explosion

Ignition may fail in the presence of heat loss

$$V\rho_o c_v \frac{dT}{dt} = VQ_c B c_F \exp(-T_a/T) - Sh(T-T_o).$$

$$\frac{d\theta}{d\tilde{t}} = e^{\theta} - \tilde{h}\theta$$

Semenov Criterion:

Ignition occurs at tangency point of the heat generation and loss curves $e^{\theta_{ig}} = \tilde{h}_{ig}\theta_{ig}$,

$e^{\theta_{ig}} = \tilde{h}_{ig}$,

$\theta_{ig} = 1, \tilde{h}_{ig} = e$

$\theta_{ig} = 1$

$\tilde{h}_{ig} = e$

So, then of course, this gave us a time of a ignition of a volume of a given volume of fuel air mixture when then there is a no heat loss. But of course, in a practical scenario there are heat loss and in that case ignition is not guaranteed. In the previous case ignition was guaranteed because you just keep at you just keep you take a take a volume when make it put it in a basically a chain, but without heat loss. And you put that you put an initial temperature of T u 0 then of course, there is no way other than what this that for that make sure to ignite ok.

So, as a result of that the ignition carried on. Whereas, if you have a heat loss then the ignition is not guaranteed and then we again go to this analysis of like a for that same volume, but here the heat loss text just the surface whereas, the heating up of this mixture and this heat realistic space to the volume. So, you have on the left hand side this is your transient term this is the temperature rise down to volume, for a given mass this is once again volume was this is the surface area and this is the heat loss .

So, this can immediately be going by the previous analysis this can immediately cast into that form, d theta dt tilde is equal to e theta minus h tilde theta. And this now will give you this different things. So, we can plot this things individually this is the heat generation term, essentially this corresponds to this term and this will correspond to and this will essentially corresponds to this term. So, we can plot these 2 terms and the sum on the sum of these 2 terms he e to the power of theta e theta minus and plus of minus of h tilde theta, is essentially equal to the heat loss.

So, this is the heat generation curve this is the e theta curve. And now let us have different possible rates of heat loss. So, see this is above in this case let us go from the case a 2 where definitely your heat loss. This slope is be given by h this heat loss is much weaker than the heat generation this is the curve, which is much larger. So, as a result of that this ignition is guaranteed no problem.

So, for case 2 the ignition is guaranteed whereas, for case one is interesting it helps you see this h this line that is the h tilde theta line intersects with a e theta line at 2 points, s and u what are these things this is a stable point and this is a non stable point . Why because you see at this point this is theta that is increasing this is essentially non dimensionalized it is a part of the temperature. And So, if you temperature is So nomination is actually it is a it is essentially this perturbation this is the product of the it is essentially goes with a perturbation parameter, epsilon it is essentially can be considered as a non dimensionalized temperature.

So, if you increase the temperature slightly to this point. So, the heat loss essentially exceeds the heat generation because this curve is above this curve right. So, if the heat loss exceeds the heat generation, but the temperature drops and then this thing comes back again to this point. On the other hand if you are like at this if you go left then heat generation increases heat loss. So, heat this temperature essentially increases and it comes back to this point.

So, either ways if you go this way or if you go this way you come back to this point. So, that is why it is a stable point. On the other hand if you see this one then if you will go on this way, then your heat generation exceeds the heat loss. So, the temperature further increases and it continues to go in that direction. Here if the if you go on this way then the heat loss exceeds the heat generation and of course, the temperature will drop further and it will go back to the state .

So, this is an unstable point this is a stable point and that is why that is at this point you always go to this point and if you if you are at this point you go back to this point. So, this is the stable state and this is a unstable state. But what is the critical condition; what is the limiting condition for which you can have ignition in this case. The critical condition is given by the point where this generation curve is essentially tangent to the heat loss curve. So, and the definition of tangency is given by these 2 things that is the tendency means that at this point your both your heat generation and heat loss must have same magnitudes, and at the same time the slopes must be same.

So, that same magnitude means e to the power of I/ theta ig is equal to h tilde theta ig and then the slopes must be same. So, if you differentiate this thing you get e to the I/ theta ig, but if we differentiate this can we think you can get only h ig. So, if you substitute this. So, it means that the magnitude is same slope is same. So, if you substitute this thing that is, if you substitute e to the power of theta ig is equal to h ig here you get theta ij is equal to 1. And you get similarly h tilde ig equal to epsa e. So, this is the semenov criteria that is a critical condition for which you can have ignition of an in presence of heat loss.

So, what it means that the critical condition your heat generation rate, your heat generation rate is equal to your heat loss rate and also the rate of heat generation rate and the rate of heat loss rate should also be same, by this tangency conditions. So, this is the tangency condition and this is called the semenov criteria. So, next we will consider using these principles we will consider we will consider the extinction enough principle of well stirred reactor.

So, here what we do is that we do not know what transient analysis. So, using that to the previous concepts what we do is that we consider a flow into our well stirred reactor. And we considered the under what states we consider that those steady states which can lead to ignition or which can lead to extinction or whether this. Like a whether that is a steadily burning state whether that is a non-steadily like a mixed state without on a ignition. And under what steady conditions we can get that is we can have ignition and extinction.

So, this is a steady state analysis unlike the unsteady state analysis that we did previously. So, it is a steadily stream. So, it is a steady stream coming into through.

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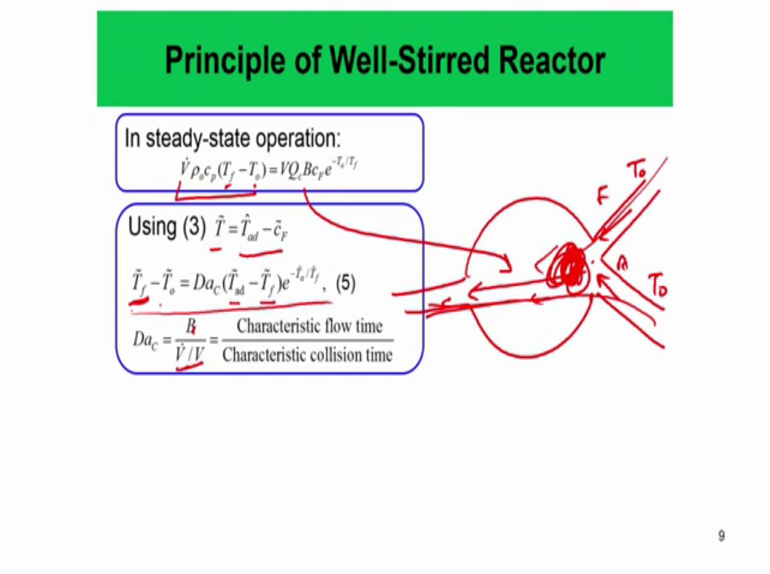

Principle of Well-Stirred Reactor

In steady-state operation:

$$\dot{V}\rho_o c_p(T_f - T_o) = VQ_c B c_F e^{-T_a/T_f}$$

Using (3) $\tilde{T} = \hat{T}_{ad} - \tilde{c}_F$

$$\tilde{T}_f - \tilde{T}_o = Da_C(\tilde{T}_{ad} - \tilde{T}_f)e^{-\tilde{T}_a/\tilde{T}_f}, \quad (5)$$

$$Da_C = \frac{B}{\dot{V}/V} = \frac{\text{Characteristic flow time}}{\text{Characteristic collision time}}$$

And So, we can have a vessel like this, where do you have an inlet, and where you have an outlet . So, this inlet comes in an outlet goes in and say this inlet has 2 has 2 inlet us or through which one fuel comes in one oxygen comes in, and they are immediately next year . So, the mixing is instantaneous.

So, this is fuel and this is air so this mixing is instantaneous and this and then this is also drained out through this. So, there is a continuous flow. So, what we try to understand is that in this thing if you consider the state inside this chamber which is at a particular. So, which is which is always at a particular steady state, that whether these steady states corresponds to a fully burning state whether this consider to a fully, unburned state and under what is limiting state this can transition to ignition under what state it can transition to extinction.

So, this is the steady state analysis unlike a unsteady state unless in the previous cases. So, this is a well stirred reactor thing. So, we have now this rate of a this mass volume flux coming in, or of this volume flow rate V dot times 0 cp because this is a flow operation. And we have the temperature increasing from T u 0 to T F; T F is the flame temperature or the bond gas temperature. And this is of course, this temperature So, this is once again this is say the thing this is if this is the fuel this is the air immediately there is mixing somehow taking place that is mixing taking place and this is the product going out ok.

So, this is. So, this is the T u 0 temperature say the both are at T u 0 temperature coming in and this is the flame temperature where the final temperature that is going out. So, the temperature rise from here to here it is occurring through this heat release rate which is given by this vqc times V times b times C F times e to the minus T m by T F ok.

So, this is the steady state operation that inside this reactor and once again we can use that previous analysis to say that your T u ad this is general of a coupling function. So, it is like true it is we saw the same thing in the in the essentially the premix flame analysis also. It is T u at a tilde minus C F tilde. And So, we can just do the substitution for the same logic, and we can we can find out this T F tilde minus T F 0 is essentially a dumb color number D a c times the difference of the adiabatic flame temperature minus T F. And of course, you see this need not be thus this T F need not be the adiabatic flame temperature, because there is continuous, because the residence time is not infinite. So, it may not reach the equilibrium of flame temperature in this amount of time.

So, what is the temperature reach this T F is may be different for this thing. It is easy to understand that if this comes in at a very high speed fuel and air. So, even if they are mixed because of this small residence times it can go out of the reactor even if the reaction takes place. So, that is what that is this effect is captured through this term called Damkohler number, which is essentially this b which is the characteristic collision time divided by V dot by V which is the, essentially the this is the inverse of the characteristic collision time and this V dot by V is essentially the inverse of the characteristic flow time.

So, the Damkohler number this D a c the collision Damkohler number what we get is essentially this characteristic flow time divided by the characteristic collision time. So, this is the ratio that we get.

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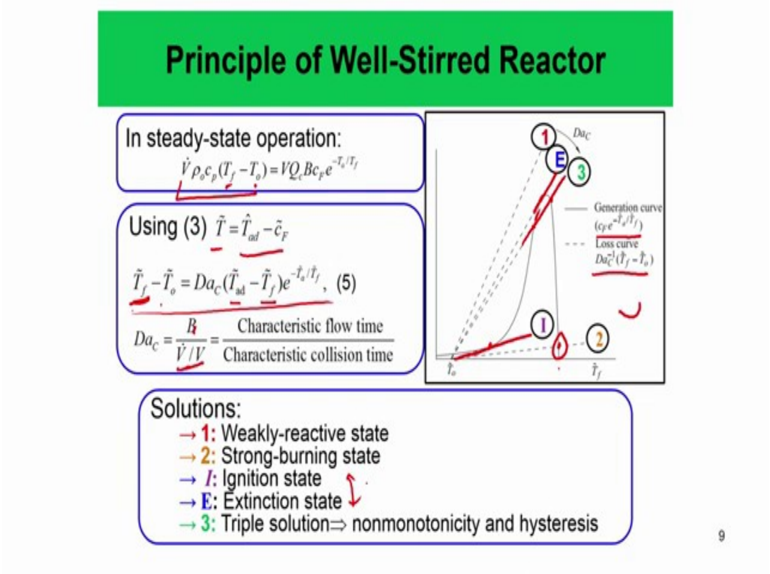

Principle of Well-Stirred Reactor

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Solutions:

- → **1:** Weakly-reactive state
- → **2:** Strong-burning state
- → *I*: Ignition state
- → **E:** Extinction state
- → **3:** Triple solution⇒ nonmonotonicity and hysteresis

So, this is the then we become see that it becomes, the analysis becomes similar to semenov criteria analysis. So, here we also have this sharp e to the power of theta type of behavior going up, but then it comes back because your C F is consumed now ok.

So, in which we did not consider in the previous cases right. So, that is the consumption of C F which we assumed to be essentially constant because of C F was essentially equal to 1, for most part of the time. So, this is the difference. And So, in that case once again we can consider this generation curve, to be given by this right hand side that is a C F times e to the power of minus T a tilde divided by T F tilde. And the last curve which is given by D a c inverse of Damkohler number times T F minus T a 0. And this balance of this we see that this is this e to the power of theta term theta curve for similar to this.

But then you now have a drop because a now C F is consumed which we did not have previously. So now, this one you see that this is the loss is much bigger than this thing. So, this loss is much bigger than then; that means, at the weakly it is a essentially weakly reactive state and this is essentially happens at a Damkohler number of at a small Damkohler number. So, the small Damkohler numbers essentially increase in this direction.

Now, when you increase the Damkohler number; so we would say let us say when you consider this state of 2 , this state intersects this at this temperature at this which you see that this state is correspond to very high temperature. So, essentially this state corresponds to a very strongly burning state. And then you can have this tangency the thing which is essentially the ignition state, and you can have another tangency you here which is the extinction state.

Um and then you can have this thing which is intersects here in the intersects here, which is essentially once again similar to the unstable state because this will lead to runaways, but all other states are stable state this is also a stable this is tangency state. This is a critical this is essentially the critical states where previous to this previous to that to the Semenov’s analysis. And each of this corresponds to the ignition and the extinction states.

Now, here you see that this is similar to the similar to the Semenov’s analysis of the ignition state, but in Semenov’s analysis you did not have the extinction state. Because there was no turning of this curve because of C F consumption C F not equal to 1. So, in that analysis we consider C F tilde is equal to 1 and here we do not have any restriction on the C F tilda.

So, this 3 this is a non monotonicity and hysteresis and it is not a stable state. So, anyways this is the ignition in the extinction states which we analyze and using this that is that is.

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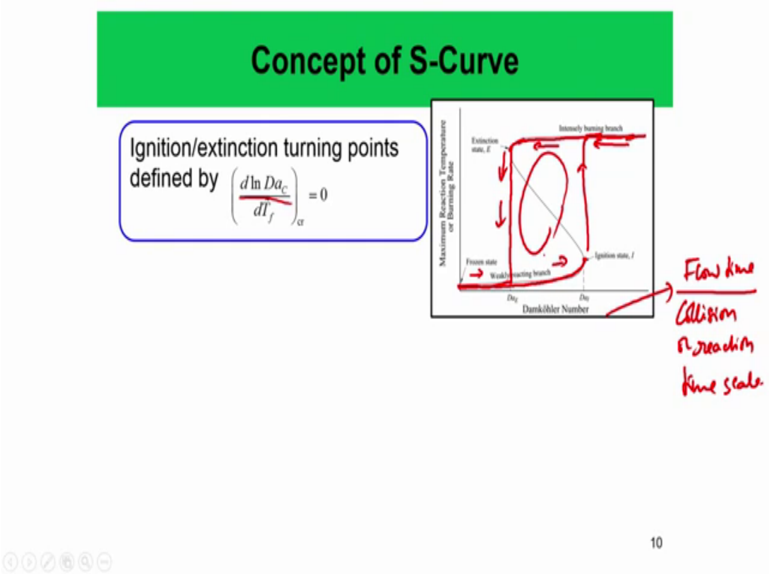
Concept of S-Curve

Ignition/extinction turning points defined by $\left(\frac{d\ln Da_C}{dT_f}\right)_{cr} = 0$

This point that is a can be identified using this d dt of F of lan of D a collision on Damkohler number by d T F temperature equal to 0, and then we can plot this in a more familiar curve which is called the S-curve that is we can plot it as the maximum temperature reaction temperature or burning rate versus the on the on the y axis and Damkohler number on the x axis.

So, the Damkohler number once again is essentially the flow timescale divided by the collision or reaction time scale. So, to summarize the previous analysis which you can understand, but this will gives a better picture a clearer picture is that, if you start from here this is the intensely burning branch and if you reduce the Damkohler number that is if you reduce, your flow time scale with respect to the collision time scale that is your flow time scale your flow velocity time scale can be reduced by increasing the velocity or by decreasing the residence time.

Or by decreasing the length by if you increase the velocity then this burned intensive burning branch goes to this point which is an extinction state. And from there it immediately goes down. This is it does not follow this thing. So, this is one thing that is what happens when you from an intensely burning branch if you reduce your Damkohler number will go to a state of extinction ok.

On the other hand if you have your very small Damkohler number to start with. And which is essentially the frozen state because you are say flow times a large is small with respect to your chemical times or collision times. Now you increase the Damkohler number by reducing your flow speed. So, what happens is that it this temperature increases and suddenly at this point you have a ignition state and this point go straight up here and then go to a branching state. So, these are the other 2 points if you have to annotate this it is like this.

So, starting from here you go here, you go here, and from here we go straight to this thing. So, this is the extinguishing extinction happening, and from here you go to this part that is this thing. On the other hand if you go from if you go start from a small Damkohler number and to want to ignite something. So, you start from this state and you go here, or go here and then you add this ignition point at this large Damkohler number you heat it and then you go to the main branch.

So, this is the hysteresis this the loop is the hysteresis loop of ignition and extinction, and the point to be noted here is that the ignition Damkohler number is much larger than your extinction a Damkohler number. So, it is So, even as a given state of a gas it might be burning, but that does not mean that you can at that particular state, if you start from fresh if you start from you can ignite start from fresh mixture and ignite that gas at that state, because it can be that state which is 7 ; however, Damkohler number lower than this state.

So, for ignition it is it is much more difficult to ignite a ignite a fresh a mixture then to then, to essentially extinguish it your, extinction happens at much smaller Damkohler numbers where the ignition happens at much larger Damkohler numbers. And then this other things also can be like this that that there can be a folded S-curve, that is this s shape may not may be lost and that is, when that is the fact of the region is that this critical ignition this critical T F temperature has 2 roots, that is why this basically is the tangency conditions of Damkohler number with temperature.

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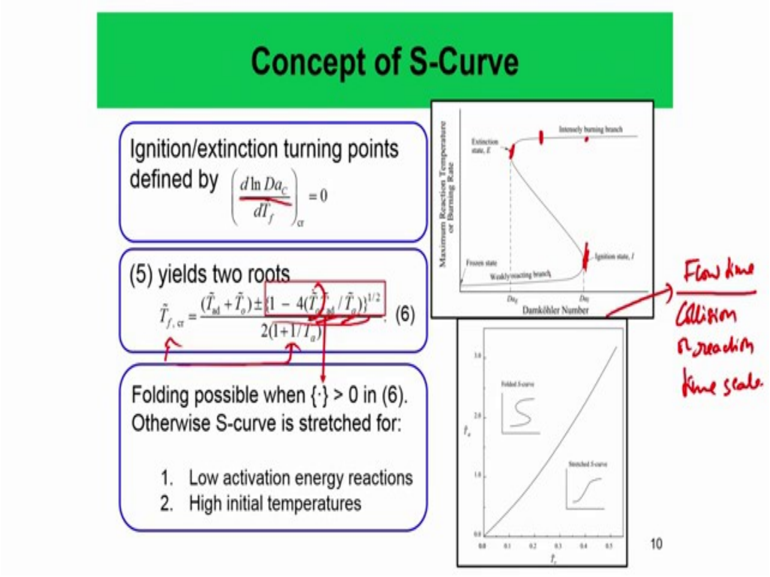

Concept of S-Curve

Ignition/extinction turning points defined by $\left(\frac{d\ln Da_C}{d\tilde{T}_f}\right)_{cr} = 0$

(5) yields two roots

$$\tilde{T}_{f,cr} = \frac{(\tilde{T}_{ad}+\tilde{T}_o) \pm \{1 - 4(\tilde{T}_o\tilde{T}_{ad}/\tilde{T}_a)\}^{1/2}}{2(1+1/\tilde{T}_a)} \quad (6)$$

Folding possible when {·} > 0 in (6). Otherwise S-curve is stretched for:

1. Low activation energy reactions
2. High initial temperatures

Flow time

Collision
reaction
time scale

And these 2 roots, but under the condition where do you may not have root is that is if this is becomes imaginary, then we do not have roots and then it can become imaginary if you have 2 things that is if you are adiabatic flame temperature is very, if you have if you have basically where very low activation energies reactions. And if you have high initial temperatures that is your T u 0 is very large itself.

So, if you start with a mixture which is very high temperature then you may not have this folded this stretched as this folded S-curve, we have a stretched S-curve or that this happens in something like your mile combustion, where your initial temperature is itself very high. So, you get the stretch S-curve and as a result of that there is no direct ignition or extinction behavior. So, it is a it is a continuous a process of a combustion that is happening. And that is that our where low activation energy reactions then you do not have this sudden jump in from the ignition to the extinction states.

With that we will close this class and come back to analyze the extinction processes. So, we have discussed the ignition processes so far.

So, till then thank you very much.