Fundamentals of Combustion (Part 2)
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Lecture - 52
Effects of Chemical and Physical Variables on Burning Velocity (Contd.)

Let us start this lecture with a thought process "Education is not the filling of a pail, but the lighting of a fire".

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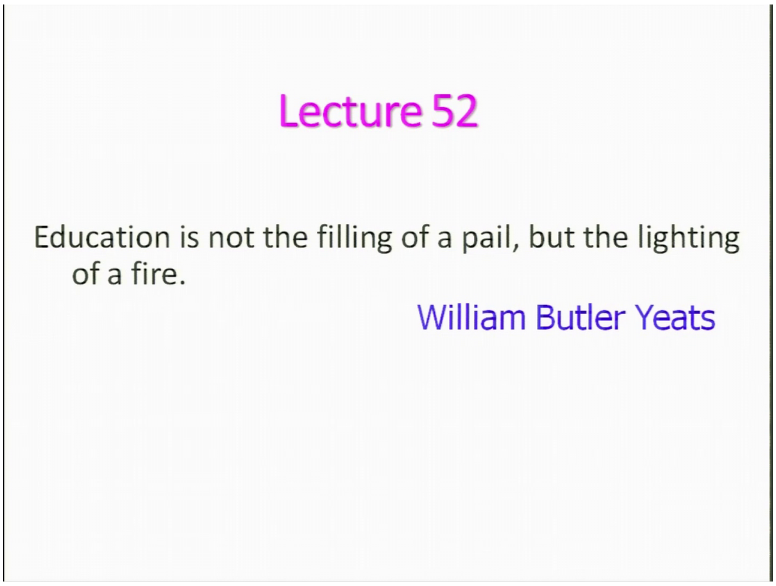

Pail is basically container right or something it is not the content delivery and whatever we are doing, but that is not, but it is lighting up a fire which is lying within a person. So, in the last lecture basically we looked at the effect of the pressure on the laminar burning velocity, right. And of course if you look at, we looked at that depends on the order of reaction, right. The pressure effect will be governed by the order of reactions, however let us look at some of the experimental data which is taken from the literature like.

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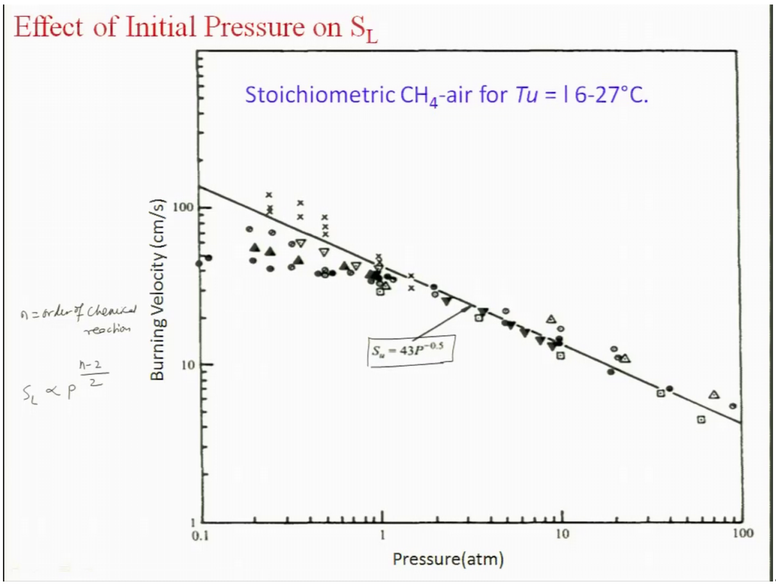

This is plotted here and these are the burning velocity pressure. You can see that most of the data's are you know scattered around and if you take curve, it comes around to be S P minus 0.5. Keep in mind that this is mean for stoichiometric methane air temperature. The unburned temperature varies from 16 to 20 degree Celsius because they will be conducting experiment in various environment. Therefore, it will be changing and this is now in western countries, so is the low temperature. So, this is what it indicates that burning velocity decreases with change in the pressure, right and in some situation you may find that it is remaining constant, right and some situation it may also increase right, but that is not that we are discussing about it. But it can happen depending on the range of burning velocity or rather it will be dependent on the order of the reactions because we have seen that SL.

We have seen is proportional to P n by 2 divided by 2. N is the order of chemical reactions. Of course, in our analysis we have taken that as single step chemistry, but in the multi steps chemistry where you know which will mimic the actual situation order can depend on this is you know each individual reaction. However, if you look at a global sense, it will be varying from fuel, air systems, weather and also depend on the pressure.

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It is valid only for stoichiometric methane air and also, the range in which it is being done; it would not be valid for all other things, right. So, therefore, this is a very important point. It is known as semi empirical relationship, because this is not generalized, it is not from theory right. It is from experiment and people have also looked at the various data and couch in there some other form which we will be discussing just now.

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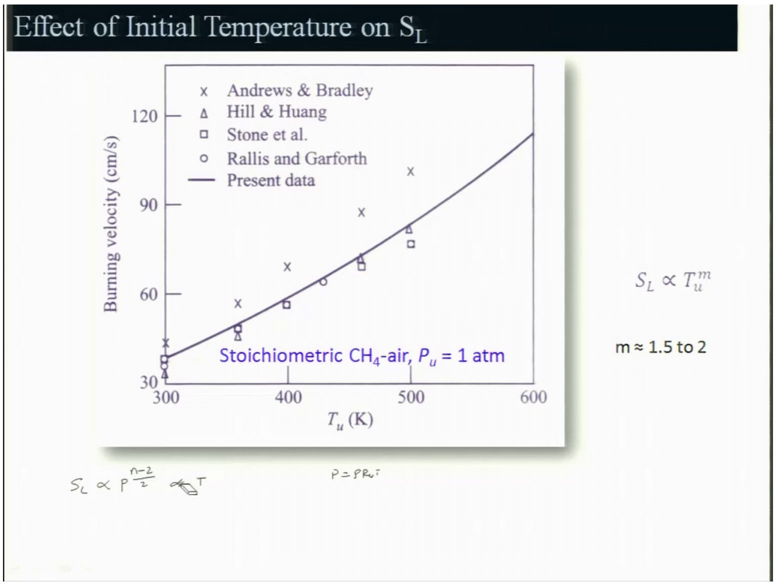

Before that what I am thinking, we look at the effect of initial temperature on the burning velocity. If you look at the burning velocity basically SL is proportional to I have seen P n minus 2 divided by 2, right. And if you look at P is basically you can see that is temperature right is proportional to the temperature P is if I take ideal gas in equation P is equal to rho R U T and of course, then you can think of using basically right, it will be no I think.

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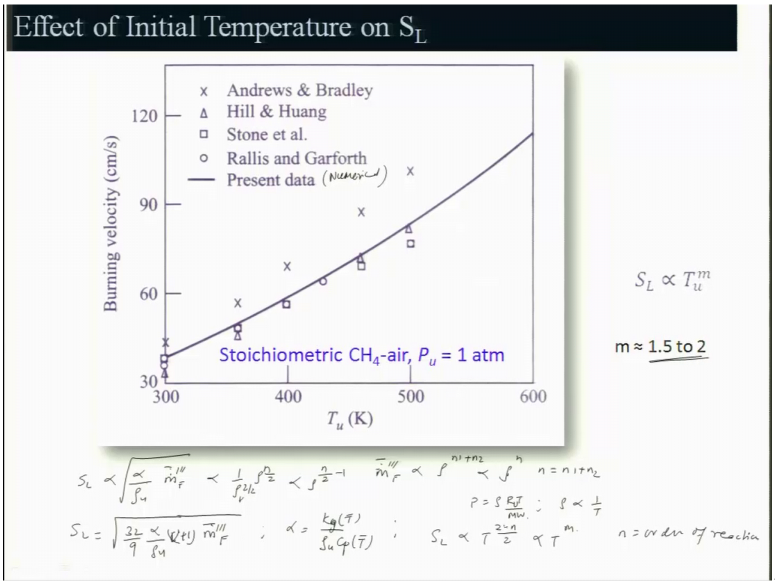

So, if you look at SL SL is proportional to basically alpha, right by rho u and rho u and also, the fractions right average and this is proportional to basically, if you look at 1 over rho u and from the reaction rate because we know the reaction rate is proportional to basically rho n 1 plus n 2 and I can say n is equal to n 1 plus n 2. So, I can say this rho is equal to n, right and this is basically n and by 2, this half it will be rho u square, right. This is half; this is also will be half, right because it is square. If you look at SL is equal to basically 32 by 9 alpha by rho u rho u mu plus 1 M dot triple dash, right. Isn't it? So, therefore if you look at alpha is kg by kg by rho u C p and this is a temperature average and this is temperature average whereas, the cp will be evaluated at average temperature and kg is average temperature. And this I have as I told this is proportional to n and therefore, SL you can say this is proportional to that. Therefore, this will be proportional to n by 2 minus 1, right.

So, you can say that rho P is equal to rho R T, right and of course, this is basically you look at molecular weight universal gas constant molecular weight and I can say that rho is basically inversely proportional to T. So, therefore, I can write down SL is basically inversely proportional to T, sorry proportional to 2 minus n divided by 2 minus basically you will take you know minus of this what you call minus of this. So, that is nothing, but 1 minus n by 2 the 2 n by. So, of course that depends upon order of reaction, however it is you know proportional to T power to the n right. I can say and that is being shown here burning velocity for stoichiometric methane here pressure is 1, atmosphere pressure is remaining constant. So, you can see these are the datas, experimental data and this is of course numerical datas which is matching well except these are I think little higher. You know values which may be not the right one for the experimental that conducted and these on badly. So however, but this thing happens to be quite higher values, right 1.5 to 2 times and which is not matching with the simplified theory what we have looked at because in the order of reaction if you look at order of reaction. Generally it will be maybe 2nd order or the 1st order in between, right kind of thing. So, then it will be very small values, M will be very small, but M is quite big here.

So, that is the limitation of the present model what we are doing, however we will have to go by the experimental data, right which is right one kind of things. So, now what is being done people have looked at experimental datas and arrived at basically a semi empirical relation which will be taking care the effect of the initial temperature and initial pressure on the (Refer Time: 09:42) velocity.

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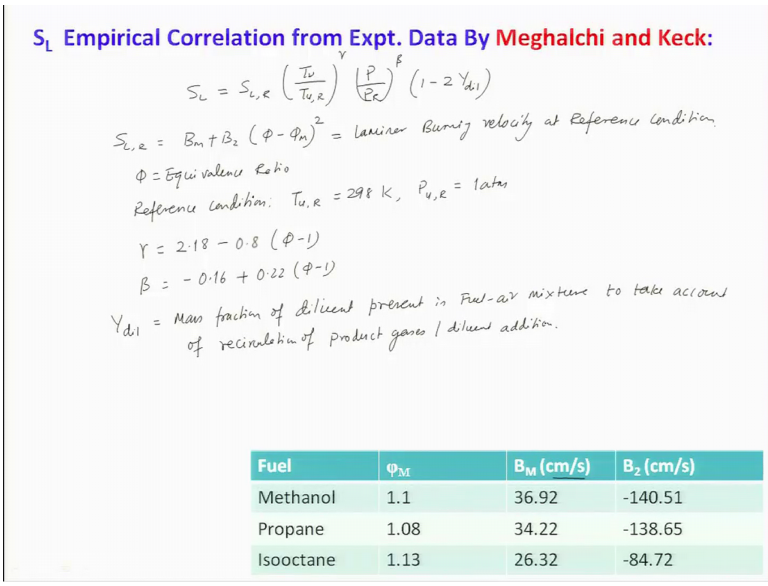

Fuel	φ_M	B_M (cm/s)	B_2 (cm/s)
Methanol	1.1	36.92	-140.51
Propane	1.08	34.22	-138.65
Isooctane	1.13	26.32	-84.72

So, there are several datas which will be available in literature, but we will be looking at very simplified version of burning velocity laminar correlation given by Meghalchi and Keck, right. This is the relationship I am just writing directly which is a semi-empirical relationship. Laminar burning velocity is equal to SLR. This is the reference learning velocities T U divided by T U R power to the gamma and P by P R power to the beta power and of course, there might be some delusion effect, right. Why dilution means in there will be some recirculation of the product gases or nitrogen being diluted and another thing the burning velocity will be affected by that. We will see little later on this effect. So, if you look at this SLR is basically can be given as B m plus B 2 pi by pi m, right square and this B m different values is given here for methanol. This is 36.9 to 1.1 and this B 2 is 140.51 centimetre per second. And this pi is basically equivalence ratio, right and pi m is your this constant, right which is corresponding to the reference kind like you know constant values pi m, right which will be taken from this and this is laminar burning velocity at reference condition.

What is the reference condition? Reference condition is basically if you look at a reference condition in this data, generally it has been taken also, otherwise u R is 298 Kelvin and P uR is taken as 1 atmospheric pressure, right that is being taken. So, if you look at this gamma is also a relationship that is gamma is 2.18 minus 0.8 phi minus 1 and beta is minus 0.16 plus 0.22 pi minus 1, right. This coefficient has to be taken because these are all empirical constant. Keep in mind that you will have to use proper unit. For example B m centimetre per second be 2 centimetre second naturally, what will happen to a SLR? SLR also will be centimetre per second. Similarly, SL also will be centimetre per second. That means, the unit has to be left hand side should be same as the right hand side and these are of course if you look at these are the same unit like you are using Kelvin. So, it will be non-dimensional.

P by PR is atmospheric that also will take care. So, it is non dimensional and Y dil is basically mass fraction of diluent present in fuel-air mixture. Basically to take a count of recirculation of product gases or diluent addition rate; suppose, for example, I am trying to extinguish the flame and look at what is the burning velocity, how it is decreasing. Naturally you will have to look at that way. So, you might be aware that in the gas turbine engines and the other thing, there will be lot of recirculation of product will be taking place. Similarly in the internal combustion engine and recirculation is being used today as a methodology of decreasing the emission level, right particularly in NOX and everything. So, therefore there might be some use in application also. So, this is the thing will what we will be doing now, we will take an example and see how we can calculate using this data.

Student: Sir! what you mean by diluent?

Diluent means suppose for example product gases. Product gases means it will be carbon dioxide, may be if it is unburned little hydrocarbon, right and also the like nitrogen's and other thing. Diluent generally it will dilute the mixtures right and inert gases being used and also, sometimes the combustion product being also recirculated right. There will be advantages of using that one is that heat which is going out can be recirculated. So, the temperature can increase in let some mixture, but it is having also bad effect. The carbon dioxide is there and it will act as a diluents, the cp value will be affecting the temperature, the temperature which will be getting so and as a result if want to reduce the NOX generally the thermal annoys which is predominant. So, reduce annoys, but you will have to pay penalty of reduction the power limit, right and for the example I want to extinguish the flame. What I will do, I will have to add something which will take the heat out. We will be discussing that little later on. So, therefore, these have been used right as diluents. So, we will take an example.

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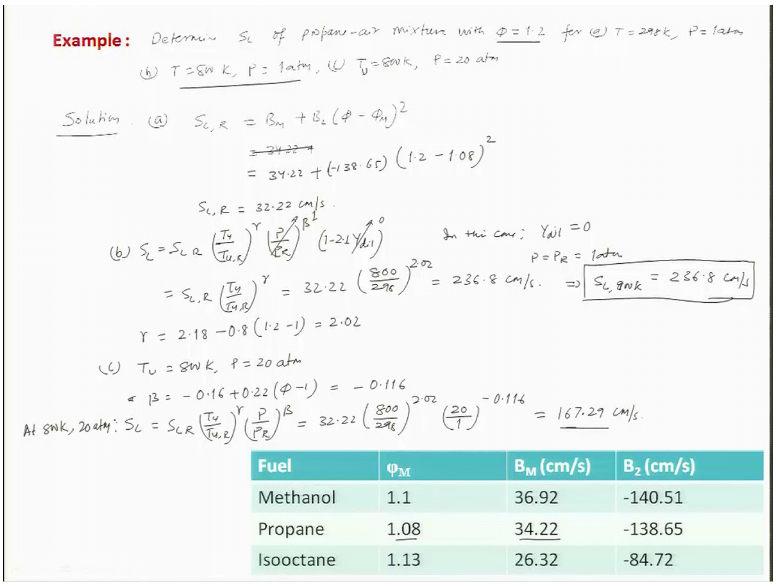

Let us say that determine laminar burning velocity SL of propane air mixture with y is equal to 1.2 for a. We will be doing at T is equal to 298 Kelvin and pressure is equal to 1 atmospheric pressure, right. And b will be looking at T is equal to 800 Kelvin and P is equal to 1 atmospheric pressure. And c we will be looking at T is equal to 800 Kelvin and P is equal to 20 atmospheric pressure, right. So, if we look at 1st one is basically reference state right and 2nd one there is an increase in temperature right, 298 Kelvin to

800 Kelvin and the 3rd, both the temperature and atmospheric pressure is being changed, right.

So, let us look at the solution. We will be using the empirical relation of a Keck and Meghalchi. So, we will be using this empirical relationship and for the 1st case, what we will do? We will have to find out SL, basically reference right that is the reference temperature. So, that will be equal to B m plus B y minus pi m whole square. So, if you look at the data which we have shown in the last slide earlier that B m for propane is 34.22 plus maybe I will do one thing. This is basically if you look at B m for propane is 34.22, right. So, that will get 34.22. Then what is B 2? B 2 is equal to 138.65 that is minus 138.65 and pi in this case it is 1.2 right, 1.2 minus pi m is 1.08. This will be whole square and then, if you look at that is SLR could be 32.22 centimetre per second, right. So, that is coming as 32.22 centimetre per second. Now, we will have to look at 800 Kelvin and what atmospheric pressure is if you are having some doubt.

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So, let us look at this one, because we have seen that SL, we will have to use now for a different pressure and temperature than the reference. So, we will have to use SLR. No no SL is equal to SLR T u by T u R gamma and P by PR beta and 1 minus 2.1

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Y di. Now, in this case what is given? the d l Y d l is 0, right. In this case Yd i l is 0 and that P is equal to PR is equal to 1 atmospheric pressure. So, this will be 0; this will be 1. So, I am getting SLR T u by T uR gamma, right and I need to evaluate the gamma, right. So, we can find out gamma is basically 2.18 minus 0.8 1.2 minus 1 and that is coming around 2.02, right. So, then what I will do is basically SLR we know 32.22 into temperature is T u is under 800 Kelvin and this is 298 Kelvin, right and gamma is 2.02, you will get 236.8 centimetre per second. So, this is my value that is SLR 900 800 Kelvin is basically 236.8 centimetre per second. This is my answer.

So, let us look at c, that is corresponding to T u right,. This is Tu is equal to 800 Kelvin and P is equal to 20 atmospheric pressure. So, we can find out SL. Basically for this we need to find out beta, right. Beta is basically minus 0.16 plus 0.22 pi minus 1. So, that will be if you substitute this pi is equal to 1.2, you will get minus 0.116, right. So the SL, I can find out as SLR Tu by T uR gamma P by PR beta because Y dl is 0. So, therefore I can get this is 32.22 into 800 by 298 gamma is 2.02 and this is 20 by 1 that is beta is minus 0.116 point. So, that happens to be basically 167.29 centimetres per second.

So, you can see that if the pressure is being increased, the SL has been decreased as compared to the temperature, but why? It is because the pressure is having negative effect. That means the burning velocity decreases with increasing pressure. So, that effect is being nullified with the increasing in this example, right. So, that is the point you must appreciate out of this and this is of course, SL at 800 k and pressure of 20 atmospheric pressure. So, that is the thing I want to illustrate, that you can use a semi empirical relationship and then, calculate for your design purposes and other things, but this is limitation. This is limited because of fact that this data has to be used very carefully, right. Wherever it is you know possible, you will have to know or in other words right, you will have to use this data within the range given by you know experimental process, right. So that you will not go beyond the range for which this empirical relationship will be valid.

I think we will stop over here and we will discuss the other thing in the next lecture, ok.

Thank you very much.