

**Fundamentals of Combustion for Propulsion**  
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**Lecture - 07**

**Premixed and diffusion flames: principal features and differences – Part I**

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**Commonalities and otherwise across various combustion systems**

- General behavior of premixed and diffusion-limited flames
- Turbulence and its role in premixed flames, diffusion flames and in complex flows.
- Droplet combustion physics
- Injection systems - diesel engines and direct injection gasoline engines, monopropellant liquid thrusters, bipropellant liquid engines.
- Role of chemistry in ignition, steady combustion and extinction



What I want to discuss is somewhat I titled here is commonalities and otherwise not so common things of course, various combustion systems. Where you must know some fundamentals at the same because, various combustion systems and we will address them. There is some things which I say which have already been must have been said by Varun. So, some overlap like this will be there, but I will say it to some way, he will say it in some other way and you will understand in the third way. [laughter]

Let us look at what I consider general behavior of premixed and diffusion limited flames, I summarized them; turbulence and its role in premixed flames, diffusion flames and in some of the complex flows. And, there are some questions which have been brought up; we will address them separately, but you kindly listen to this as we go along those which have been posed written down and given will be addressed separately.

We look at some droplet combustion physics briefly again overlap may be there. Injection system - diesel engines direct injection gasoline engines, and monopropellant liquid thrusters, bipropellant liquid engines. I mean combustion chamber, injection strategies and so on. Let us take a role of chemistry in ignition, steady combustion and extinction again a bit of overlap.

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### Behavior of Premixed and Diffusion flames

The diagrams illustrate the structure of premixed and diffusion flames. The premixed flame diagram shows a fuel-air mixture entering from the bottom, with a flame front separating the unburnt mixture from the burnt products. The diffusion flame diagram shows fuel and air entering from the bottom, with a flame surface where they meet. Labels include 'premixed flame', 'diffusion flame', 'post flame radiation', 'premixed flame front', 'fuel + air', 'fuel', 'air', 'No Ox here', 'No fuel here', 'surface of stoichiometric mixture', 'Air/Oxidant Fuel vapor', and 'Burning Liquid drop (0-g, Or 1 g or with forced convection)'.

- Fuel and air/oxidant together
- Therefore air-to-fuel ratio Or equivalence ratio is a key parameter
- It defines the flame temperature.
- Since diffusion is fast, Chemical rate controls the combustion process
- Burning velocity is a reflection of this aspect
- Flame has features like flammability limits, flash back and blow off and quench distance

- Fuel and air are separated by the flame
- Diffusion is slow and when the fuel and oxidizer meet, they react at high rates
- Flame is located where ever the fuel and oxidizer fluxes along a local normal are in stoichiometric proportions.
- For gaseous fuel injection, flame location adjusts itself depending on the flow rate
- For liquid or solid fuels, the air-to-fuel ratio ( $A/F$  or  $O/F$ ) for stoichiometry controls the flame stand-off. Since  $O/F$  is large as is true for most hydrocarbons the flux demand leads to flame stand-off several times the fuel size.
- Flame temperature is adiabatic flame temperature effected mildly by stretch and other effects



The Behavior of Premixed and Diffusion Flames two cases here in a flame jet fuel air mixture coming out and there is a flame here, fuel alone coming here; air is around quiescent shall we

say it could also be flowing, but let us in this case treat it as quiescent. So, air is drawn in and you have flame around. Let look at the features, this is the premixed flame front which have been shown to you earlier as well. This is the post flame oxidation and radiation zone where you get a the look of the flame.

Fuel air oxidant are together, therefore air to fuel ratio or what you call equivalence ratio is a key parameter. It defines the flame temperature look at the flame temperature will depend on the equivalence ratio. Since, diffusion is fast chemical rate controls the combustion process. Burning velocity is a reflection of this aspect, the flame has features like flammability limits, flashback, blow off and quench. These are the features of premixed flames.

As different from this if you look at diffusion flames you see in the, this is the zone where there is no oxidizer, but only fuel. This is a zone where there is no fuel, but only oxidizer. So, they are not coexisted in the larger sense. They exist if at all at near the surface so, called surface, but it is a small thickness discussed as discussed earlier. Situation is not different in the case of liquid drops; you have seen the pictures as well. This feature which you see is valid for 0 g, they have been excellent experiments done by Japanese researchers. Some of them have visited this institute as well taken photographs of this flame, beautifully spherical flames around the droplet.

And, if you take 1 g which is ambient condition which you will get a flame like this which you also have seen. In this case fuel and air are separated by a flame, diffusion is slow and when fuel and oxidizer meet they instantly react nearly right or therefore, high rates. The flame is located wherever now this is the key point I want you to recognize the flame is located wherever the fuel and oxidizer fluxes along a local normal or in stoichiometric proportions.

You must see every word has a significance when you go and look at complex flows, the flame may be wrong very complexly structured, but you will discover that a diffusion flame is located and if you take a local normal and you see fuel on one side, oxidizer on one side. The ratio of the fluxes into the flame will be in stoichiometric proportion.

For a gaseous fuel injection, the flame location adjust itself depending on the flow rate. So, if you put more flow the flame will be longer, the flame will also go. For liquid and solid fuels which is what matter of concern for discussion later. The air to fuel ratios for stoichiometry controls the flame standoff. Since, the oxidizer to fuel ratio is large as is true for most hydrocarbon 15, 16, 17 the flux demand leads to flame standoff several times the fuel size.

If you take here 1 mm drop typically this will be around 10 mm typically. Flame temperature in this case is the adiabatic flame temperature affected mainly by stretched and other effects. Now, what I mean is as distinct from a premixed flame where the flame temperature is a function of oxidizer to fuel ratio or are equivalence to idea equal to equivalence ratio.

Here all equivalence ratio means only stoichiometry equivalence ratio for a diffusion flame is only 1, 1 unity. And, the temperature at the flame is stoichiometric, this is very key to some of the points which we also discussed in the case of gas turbine engines earlier in detail.

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### Role of chemistry in ignition, steady combustion and extinction

- Steady premixed combustion in multi dimensions depends on chemistry much as it does for one-dimensional case.
- In one-dimensional case, burning velocity can be taken as representative of chemistry. When stretch and turbulence effects are accounted, most observations can be understood within this framework.
- Burning velocity justified single step chemistry with activation energy and a frequency factor would be good choice for computations. This is in fact the strategy for modeling solid propellant combustion. It would be adequate for other premixed flame situations as well.
- Unsteady or unstable premixed combustion near limits of flammability can be dealt with using additional features of fluid mechanics as in flame blow off or flash back.
- Diffusive combustion near limits of extinction or ignition need chemistry. This chemistry - whether reasonably substantive (meaning a fair number of species and a large number of steps) is not necessarily identical as what is used for premixed chemistry. There may not be enough demand for clarifying the differences yet.
- Steady diffusion limited combustion can be taken to relatively independent of the details of chemistry
- Auto-ignition and Ignition in practical systems need to account for conduction of heat or diffusion of species and need to treat both diffusion and reaction processes



Let us look at the role of chemistry in ignition, steady combustion and extinction. Steady premixed combustion in multi dimension depends on chemistry as much as it does in the one-dimensional case, there is no distinction there. In the one-dimensional case the burning velocity can be taken as the representative of chemistry. Sometimes if the question was asked earlier; can you measure the reaction rate? Its important to this quickly comes to my mind we talk so much about reaction rate, reaction rate.

What is reaction rate? Reaction rate is the rate at which two of the reactant leads to product. How do you measure the reaction rate? You measure the reaction rate by its effect; you do not measure the reaction you know what are the reaction rate, it occurs at a molecular scale what you see is a result. When reactant changes in its content magnitude something else gets

formed over a period of time in a space mode as well there will be changes. You need to factor all the features involved to get the elements involved in the reaction rate.

To state it simply let us say hydrogen react with the oxygen to get you water vapor and some other products. So, if it is if there is a spatial variation as will happen in every case a droplet or a flow flowing jet or whatever, you need to take into account the convection and diffusion. Suppose you say no, no I will not do it, I will take only let us say take a money per chlorate and I want you to get the decomposition rate, I will put it somewhere in allow it to decompose and measure the composition.

You have to measure the composition, when you measure the composition it will lead you to the decompositions rate. Ultimately the chemical reaction rate expresses itself in changing the composition, you measure the change in a composition with time of space and then the factor it into a expression you will get the reaction rate. Therefore, what is meant is the measurable quantity is the flame speed or the burning velocity in this case.

And, so it is a representative chemistry its just semantics you would you like to treat chemistry as the reaction rate tests if more fundamental or burning velocity is more fundamental. We can keep discussing till any point of time, but what you measure is burning velocity, you know a number. So, you can say that hydrogen oxygen mixture with its flame speed of maybe 2.5 meters per second is more reactive, than methane air mixture at a flame speed of 0.4 meters per second.

You can say that very clearly, keep this in thought in mind in engineering what is more important is what you measure then you can deduce many things consistently. So, there are other features which will influence the premixed flame or diffusion flame something called stretch which will define a little later. And of course, turbulence both of them will influence the burning velocity and therefore, most observations of what you see in reality can be understood within this framework.

Burning velocity justifies single step chemistry which is what I we talked about here that is if you know the burning velocity and you can connect it to a single step chemistry with some

activation energy and a frequency factor and this will be good choice for the computation. This is in fact, strategy for modeling solid propellant combustion which Dr. Varun will speak tomorrow. It will be adequate for other premixed flame situations as well. Unsteady or unstable premixed combustion near limits of flammability can be dealt with by using adding the additional features of fluid mechanics as in flame blow off or flashback.

These are phenomena which occur and is the related to flow rates and so you must factor into it fluid dynamics in some form. And, once you combines them idea of burning velocity with mixture ratio whatever all that will fall into place. Diffusive combustion near limits of extinction or ignition need chemistry. This chemistry whether it should be reasonably substantive you know multi step chemistry, fair number of species and a large number of steps, is not necessarily identical as what is used for premixed chemistry. Pre mixed chemistry has a whole structure, its not clear that it is identical to what happens in diffusion flames.

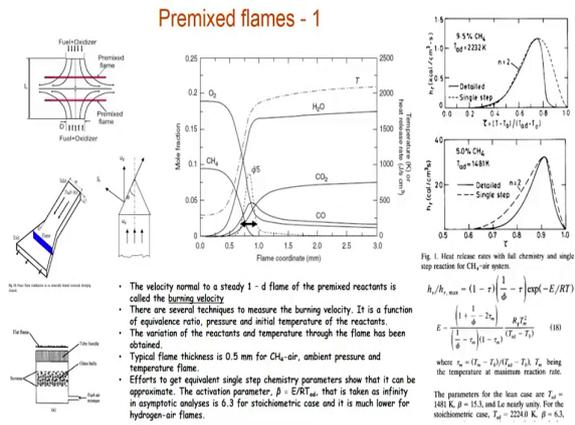
There are differences which we have ourselves observed including Varun, but I think these are still need to be examined. Actually, it is not been examined very much because diffusion flames depend on chemistry not very much, except for emissions. For which case you need to create models for extracting the information and the emissions, that is done specifically for that purpose.

So, the role of chemistry has been used in the literature, but its not obvious everything is hunky dory. Steady diffusion limited combustion can be taken to be relatively independent of details of chemistry, when it comes to burn rate or many such a longer features. There are issues like auto ignition and ignition in practical systems, they need to account for the conduction of heat or diffusion of species and need to treat both diffusion and reaction processes.

Ignition or extinction they depend on chemistry. Steady combustion in diffusion flames is not dependent on chemistry. These simple rules of thumb can be integrated into your mind on a continuous basis ok. Because quite often in some things happen in practice you will be consulted with a situation chemistry must be important something has been. When you do the experiment you will find no difference; oh why is it there is no difference. Difference is not

there because its role in terms of larger heat this heat flux distribution and mass flux distribution is not very much. Emissions yes that is all the point we have to keep in mind.

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Let us look at some examples of premixed flames. Premixed flames in the best definition possible is it just that you have something to make the flow uniform ok. And, then something to make the velocity distribution here uniform. Then you light it you will get a flame here nearly flat, but is very sensitive you know you should be very careful in dealing with it. Small changes in the flow rate and I will blow it off and make it stick to the wall. So, this is one example of so called one-dimensional flame.

But, if you increase the velocity to a fair extent you will get a conical flame. But then the point is that normal to the surface of the flame if you measure the velocity in the cold side it is their velocity differences is the cold and the hot related to a temperature ratio, very simply stated.

The mass flux is the same mass flux is the same across the premixed flame normal premixed plane.

Therefore, if you have  $\rho_U S_U$  here,  $\rho_B S_B$ .  $\rho_B$  is the density on the burned side,  $\rho_U$  is the density in the unburned side. Unburned side typically be 1 kg per meter cube on this point 3.4 kg meter cube. The ratio is related to essentially flame temperature ratios. Therefore, you will discover that the flame speed normal to it will even in a conical flame will be equal to the typical value for k methane air 0.4 meters per second, you will still discover that number. Though the flow rate here is much equivalent velocity is much larger.

In this case you will get identical to flame speed in this case the velocity may be larger maybe even 1 meter per second. But, normal to it will still be 0.4 meters per second ok. Then this is one way of doing that and quite often that many methods, people have tried there is one of our former students with a Professor in IIT Bombay Sudarshan Kumar and he has done lots of extensive pieces of research, on many many techniques. And, one of the techniques he uses is here diverging flame and you could have one-dimensional flame you make measurement of the velocity here it gives you the flame speed.

And, people have also used opposed is called opposite diffusion flame. You use a fuel and oxidizer combination from one end and the other end light it you will get a flame and if the product gas will go out like this. This also gives you a result, but these things are related to the following fact. In this case flame is virtually flat flow rate normal to it. In this case around the top cone you will find the diverging stream lines, same way here you have diverging stream lines. Then you have diverging stream lines you have velocity along the axial direction parallel to the flame.

Now, that gives you stretch, as you keep increasing the velocity this stream velocity you will get stretch effects on this direction. The stretch effects sometimes are positive sometimes are negative and there is the whole theory for that stretch flames. This is one part now, you can measure the composition as it been done by somebody else of oxygen of methane and many

other species. And this is not the results of a compositional measurement, but this result of a calculation, but people have also have measurements for all the many of the major species.

I want you to look at some principle features here. Since, it is the premixed flame you will find both the oxygen and methane keep coming down. And, comes down to low values here, then you will find product going up like this. You see a very interesting feature if the temperature goes to around 1000 800 k or so and keeps on the other 200 220 k takes a long distance for it to reach.

This is something very peculiar about it and you can express it in a another plot where you find the heat release rate plotted as a function of dimensionless temperature which is what the actual temperature minus  $T_{naught}$  that initial temperature divided by the adiabatic flame temperature minus  $T_{naught}$ . If you take this coordinate you will discover that the with a full chemistry if you calculate, the reaction rate drops around 0.8 of this dimensionless number. And, slowly keeps the temperature keeps increasing beyond that point.

This is the feature not only of methane of propane and many other species. And, actually has not really been addressed in the literature or the consequences may be it does not have too much of an effect and therefore, has not been addressed, but it is something very peculiar. It is normally you tend to think it will reach the equilibrium value right away it will not. The actual flame zone thickness you can measure it by looking at the reaction rate plot here.

In this case say very small number about 0.5 millimeter or so. So, let me summarize the facts as you see here the velocity normal to a one-dimensional flame of premixed reactants is called the burning velocity, first stage. There are several techniques to measure the burning velocity; it is a function of equivalence ratio or pressure and initial temperature of the reactants. The variation of the reactant and temperature of the flame has actually been measured consistent of what you see here.

Typical flame thickness for a methane here is 0.5 millimeter and its completely different for others for a hydrogen air it will be much lower than this. Efforts to get equivalent single step chemistry parameters show that it can only be approximate you cannot get a single step

chemistry expression which actually matches with this. But, if you match this you will get an activation something called activation parameter which is the activation energy divided by gas constant times the adiabatic flame temperature.

And, this is taken usually as infinity in the asymptotic analysis and about 6.3 or so; for the stoichiometric case and it actually for methane air case it is much lower for hydrogen air flame for stoichiometry its about 3 or so. But, for a lean limit ranges it will probably much larger about 15. Well, it this tells you how we estimate the parameter of a single step reaction ok. The temperature non-dimensional temperature at which you get the peak reaction rate from that you can extract the equivalent activation energy and so on. There is numbers which are coated here not very important yeah please go ahead hm.

Student: (Refer Time: 19:32) and then I started (Refer Time: 19:38) which is been (Refer Time: 19:40).

No, if the matching of the flame speed is the first thing which will happen.

Student: Ok.

This is say because you have actually one free parameter which is the activation in the frequency factor. The frequency factor is essentially proportional to plane speed. So, there is no difficulty; see there are two things the when you say flame speed it is the integral feature of this particular curve.

Student: Yes.

Therefore, that is no difficulty in terms of expecting it to match. This is the detail of the how the reaction rate varies with temperature and that matching is slightly more involved consistent with the fact that you have flame speed.

Student: Sir, but (Refer Time: 20:32) we have been discussing about temperature as (Refer Time: 20:37) and frequency factor is a (Refer Time: 20:41) frequency between (Refer Time: 20:43) which can lead to reaction and (Refer Time: 20:47) this frequency factor reaction rate in a linear relationship (Refer Time: 20:53). And, the temperature reaction rate it should be more predominant to get a (Refer Time: 20:59) its like a temperature or the frequency factor. Because, both are inter linked and we are looking at different perspective for the same.

No, we are not looking different perspective. Both are involved in calculating the flame behavior in terms of an average you will get the flame speed. Average means integral of this gives you the flame speed. In terms of the variation of the heat release rate or the distribution of heat with temperature, you will find the activation energy plays a role. If you take a full chemistry calculation you have no freedom.

Student: Yes.

You do not have any freedom when you take full chemistry, because each of the steps is a molecular event and for that molecular event people have obtained both the activation energy and the frequency factor. And forward rate, backward rates are all available in literature. (Refer Time: 21:54) gives you all the information and you can use that and compute the full flame structure from that.

So, there is no independence for you to do anything at all. But, in so far the approximation is concerned what is being said is, the flame speed is related to average reaction rate. You saw you know Varun present it in the morning ok. What is the average reaction rate? Average reaction rate is a frequency factor times of a variation of the over the domain of the E to the power of minus A by RT in the rest of the terms.

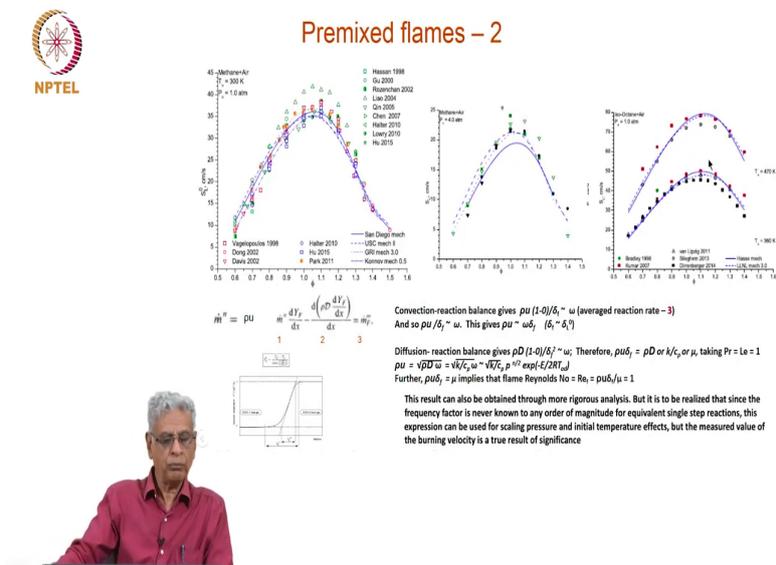
Therefore, that part and the frequency factor are two quantities. The second that second part is dependent on activation energy, the first part is dependent on frequency factor. If you say its proportional to flame speed the frequency factor is a reflection of the flame speed. The variation in temperature of the reaction rate is dependent on the.

Student: Active energy.

Active energy so that is how you should look at it. There is independence on each one of them and there is no conflict.

Student: Ok.

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Yeah. Here is the data from measurement which sent by Sudarshan Kumar you will see for methane air a large amount of data of the burning velocity with equivalence ratio and you can see 36.36 meter per second of the mean number. You have then they have done the experiments for various pressures, initial temperatures and so on so forth.

Even numbers with increase in pressure the burning velocity comes down recognize that. And well with the higher initial temperature the burning velocity increases this is for iso at octane. You see a 360 and 470 Kelvin, the burning velocity is high is its about nearly 78 centimeters per second at 470. And at a 360 Kelvin also it is higher, 45 meters centimeters per second whereas, for methane air it is about 36 centimeters per second.

These numbers or hydrocarbons between 36 centimeter per second or 40 centimeter per second is common for all hydrocarbons. As their function of pressure then liquid comes down, as a function of initial temperature it goes up. These can be stored in your memory no problem actual numbers you will see the results ok.

A little more of a detail discussion we will see very quickly back of the envelope calculation in this manner. Please pay attention to some details, this is the conservation equation for the mixture for the fuel fraction inside the flame  $m \cdot \ddot{Y}_f$  is the single  $p$  mass flux; convection term, diffusion term, reaction term 1 2 and 3.

Now, if the flame is this just shows that the temperature is increasing and going here and it is the flame thickness. Now, if you take convection reaction balance there is 1 and 3 just look at this,  $\rho u \cdot d Y_f$  is 1 minus 0 divided by  $\Delta f$  gives you the average reaction rate some number. So, you will say  $\rho u$  by  $\Delta f$  is the  $\omega$  and gives you  $\rho u$  equal to  $\omega \Delta f$  ok.

I mean by definition there is only other terminology that is all. If you take diffusion reaction balance you say this say this balance is this, then it tells you  $\rho D \cdot \frac{d Y_f}{d x}$  is here  $x$  is also here  $\Delta f$  square gives you  $\omega$ . So, this tells you  $\rho u$  if you couple this with this you will get  $\rho u \Delta f$  is equal to  $\rho D$ ,  $\rho D$  is also the same as  $k$  by  $cp$  or  $\mu$ . If you say Prandtl number is equal to  $\mu$  by  $\mu$   $\mu$  by  $cp$   $k$  whatever and Lewis number  $D \rho cp$   $k$  by  $k$  equal to 1. They are all tell you  $\rho u \Delta f$  is equal to  $\rho D$  or  $k$  by  $cp$ .

So, this gives you  $\rho u$  equal to  $\rho D \omega$  under square root. Why does we gets square root? Because you see here  $\delta f$  square and you can take it to the other side  $\delta f$  is  $\rho u$  by  $\omega$  combine them you will get this result. This is exactly what was discussed in the morning. And if you can express it in explicit form, the mass flux through your premixed flame is proportional to root of  $k$  by  $c_p p$  to the power of  $n$  by 2 and exponential of  $E$  by  $2 RT$  ed.

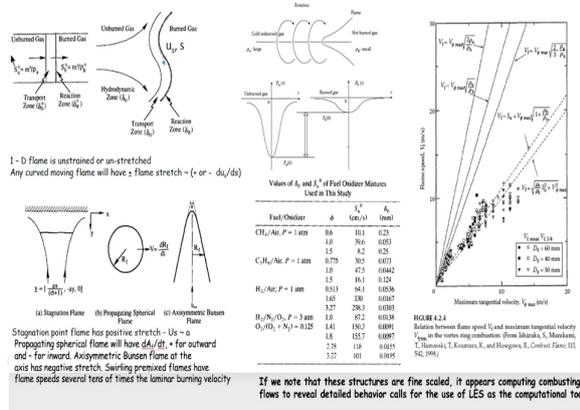
So, all the terms related to chemistry are involved here. And the fact that  $\rho u \delta f$  equal to  $\mu$ , also implies there is something called flame Reynolds number which is essentially  $\rho u l$  del by  $\mu$   $\rho u \delta f$  by  $\mu$  that is equal to just 1. Now the flame Reynolds number is 1 and the fact that the flame speed is proportional to the square root of the reaction rate is explicitly brought out here. By simply a convective diffusive reactive balance more rigorous analysis is possible some of it may be done here itself let us see.

But it is to be realized that since the frequency I mentioned whatever we discussed a little earlier. Since, the frequency factor is never known to any degree of accuracy for an equivalent single step reaction, this expression can be used for scaling pressure and initial temperature effects. But, the measured value the burning velocity is one in only quantity of true significance; a point of view which we were discussing a few minutes ago ok.

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In canonical flames....



There are other aspects of a flames which we were also appreciate. If you take the normal case that we are discussing till now, is a little burn gas coming out with a some speed going out the burning gas with a speed which is the ratio of the densities. But suppose you create a little disturbance under the surface like turbulence that some other means. Then the flame becomes curved and you will find two kinds of curvature conical and convex.

This will have influence and at the one order you can say be the reaction zone it does not change and you can make a calculation of what the role of the curvature also is. So, curvature has an influence on the burning velocity. So, the one dimensional flame is unstrained any curved moving flame will have positive and negative stretch is what I have said here.

What is positive negative stretch? There is a flow velocity which occurs along the flame, which was which is 0 here. And, that variation with stretch is 1 by second which is called

strain rate or stretch as it is classically called. And, this stretch can come from many sources; you can have a flame which expands and because it expands as I mentioned a little earlier. There is a velocity along the axis of the flame and that, changes so you will find variation of that gives you a stretch.

Spherical flame; the spherical flame is always expanding if you spark it to the center and therefore, the area keeps increasing that area imposes a stretch rate. Look at the same flame who is trying to move it to larger and larger diameters and therefore, this is stretch involved in the process. So, also axis symmetric flame near core axis also will have compression here.

These are aspects imposed on the premixed flame I am telling you, it is the additional features. You can also be doing you know swirl you can have a swirling premixed flame if a swirling premixed flame you will discover very peculiar effect which have also been experimentally studied. You see look at the flame here it turns out at the at one zone, we will find that because of the swirl there is a certain variation of pressure with the radius. Because this swirl pressure high is higher here lower here. But when thing is burnt up here that variation will not be as much because the flow expansion.

So, this creates a difference in pressure which actually causes a motion of the fluid into it; so much so that you will discover the flame speed versus the tangential speed to be very significant. You find the flame speed in such situations very large as you can see from experimental data here if you create 10 meters per second of tangential speed. The flame speed itself becomes 10 meters per second varies 0.4 meters per second, varies 10 meter second.

And it is not as though you are creating one experiment where there is a cube and you create a swirl and then you examine what happens, that has been done here. But suppose in a complex flow you have somehow a little swirl created the flame will get burnt up very first locally. This phenomena, which you see is a separate experiment are embedded it in an actual flow it can happen very easily.

You are always have swirl in many situations you know the sometimes the gas in a rocket engine in the central port is introduced with swirl sometimes without swirl you introduce kerosene, which swirl usually in many situations. In the case of gas turbine engines swirling flows are most common. The air is introduced where a swirl to create recirculation zone sometimes liquid is introduces as a film in a swirl mode.

And you will discover this for the swirling flow in a evolving complex flow might have locally structures which I got a swirl and this phenomenon which you see here can occur there as well which of course, is captured by the calculation. But if you must know why certain thing has happened, and the burning velocity here is are the so called the velocity at which the consumption takes place the flame velocity is much larger here, that is something that you should keep in mind.

I here the data simply put together with several mixtures. So, you know this data varies slightly depending on the position you choose for locating where the flame maximum pointing and the minimum pointing. You will see as a consequence of mixture ratio change the flame thickness changes for the stoichiometric flame is very small here and for linear in which it is larger. And for hydrogen and air it is the numbers are small right these are features which you have discussed several times yeah.

Student: (Refer Time: 33:12) structures.

Student: (Refer Time: 33:16).

Student: (Refer Time: 33:18) physical.

Student: (Refer Time: 33:27).

I have shown you the physical interpretation right here. Suppose you take this as a tube cold unburned gas is coming like this, this swirling ok. You put a spark here technically if you had a

tube and in which the gas was present here, coming yet let us say its 0.4 meters per second. If you had simply ignited here the flame will stand there, because.

Student: When it is (Refer Time: 34:01) same.

One dimensional case no yeah if the speed and flow velocities are same.

Student: Flow velocity is same.

So, it will stabilize here.

Student: Yes.

And if you give this velocity a little lower the flame will move into.

Student: (Refer Time: 34:10).

At a different speed.

Student: Yes.

Speed difference between the flows speed and the burning velocity. Suppose 0.4 meter per second is coming here, the flame would stick here. If you give 0.3 meters per second and this is 0.4 meters per second in the flame speed. This flame will move into it at the rate of 0.1 meter per second.

Student: Yes.

And, if this flame this velocity is let say 1 meter per second, this flame will curve into a cone which will not blow off maybe it will blow off if there is no place where it can attach. But if it

can attach you will find a conical flame where the normal velocity will turn out to be 0.4 meters per second.

Student: Yes.

These are classical.

Student: Yes.

I am saying in this tube, suppose you are doing a swirl. I knew it make it at this end, the phenomena which takes place I have shown you here at the normal conditions this unburned gas the pressure will be low at the center; compared to that at the boundary. Because the swirling centrifugal action makes the pressure higher than it is center. If you just swirl the air into a duct you will find suction going in ok.

Now, once it burns up in that zone you see the density has gone down locally when it burns up. Therefore, it cannot accommodate pressure builds up and that difference in pressure between what happens here and what happens and this way, creates a velocity going significantly large. It has been measure experimentally and only point of view I am saying is when you take a complex flow, it will decompose it into the structures which may be responsible for what you see and one of them is this feature.

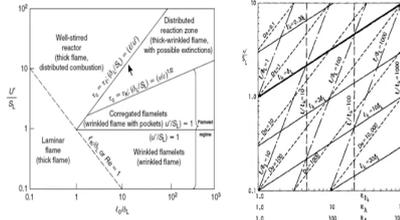
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### Turbulent premixed flame behavior



- When the scale of turbulence  $\lambda$  is large compared to the unstrained flame thickness the flame is wrinkled by turbulence.
- The flame surface area change is taken proportional to turbulent velocity fluctuation,  $u'$
- Because of temperature jump across the flame, viscosity increases and the flow may even become laminar locally.
- Under strong turbulence, the flame structure itself is altered
- Based on these considerations, various correlations are developed.



$$\frac{S_T}{S_L} = \frac{A_f}{A_f^0} \quad A_f/A_f^0 = 1 + u'/S_L \quad S_T = S_L + u' \quad \text{Kolmogorov scale based Re, Taylor scale based Re and inertial scale based Re}$$

$$S_L = \frac{1}{\rho_0} \left( \frac{\lambda_w}{C_p} \right)^{1/2}, \quad S_T = \frac{1}{\rho_0} \left( \frac{k_w}{C_p} \right)^{1/2}, \quad S_T/S_L = (\nu_p/\nu)^{1/2}, \quad R_1^* \approx R_2^* \approx R_1$$

$$\nu_T \sim u' \lambda, \quad S_T/S_L \sim R_1^{1/2}, \quad D_w = S_L \delta_w u'$$



Let us look at turbulent premixed behavior. At once scale you can describe it this is one form, lots of dancing flames at some velocity. And so if you take instantaneous pictures high speed pictures and let us put them on over the other you may get structure like this. So, when the scale of turbulence, turbulence is something which you had characterized it I do not know that I have here discussion.

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### Turbulence, and diffusion limited flows

- There are many perceptions of difference between laminar and turbulent flows.
- It is commonly understood that pipe flows are turbulent beyond a Reynolds number,  $Re (= \rho u d / \mu)$  - typically 2300, where as the correct statement would be that turbulence cannot be sustained below a certain  $Re$ , say 2300.
- Any unsteady flow with fluctuations is not a turbulent flow. It could simply be an unsteady laminar flow.
- A flow with fluctuations like white noise - fluctuations with the same amplitude at all frequencies is not a turbulent flow.
- A flow in which the fluctuations have a power spectrum ( variation of the square of fluctuating velocity with frequency) involving all frequencies (not simply connected to any specific geometrical feature) is turbulent.
- In a turbulent flow, the fluctuating velocity draws energy from the mean field and dissipates it through fluctuations until the final dissipation occurs through viscosity.
- A buoyancy driven flow field (like buoyant jets) can also be turbulent. Here the convective motion gets sustained buoyancy.



Let us look at this and go back to this. This is something which is important for us to discuss. Turbulence and limited diffusion flame, but let us look at turbulence itself. There are many perception of a difference between laminar and turbulent flow. I am sure engineering graduates who come through, who knows (Refer Time: 36:41) things. Then means commonly understood that pipe flows are turbulent beyond a certain Reynolds number, 2300. Is it not correct for me to assume that all of you are familiar with that?

Student: (Refer Time: 36:52).

Yeah. It technically is a wrong statement; correct statement is turbulence cannot be sustained below a Reynolds number 2300.

Student: (Refer Time: 37:02).

What does it mean? It means if you can create in a pipe flow at a lower speed you need any disturbance, it will die. When cross what it simply says, it would cost 2300 it will get sustained. But they are not this particular issue it has got a significance which as some aspects are not still resolved adequately. It is often said that you can get at very high Reynolds number laminar flow in a pipe. Smooth laminar flow you can get very high Reynolds number.

Subject of debate, but leave that as it is, but this much is clear that you cannot sustain turbulence below a Reynolds number of 2300 in a pipe is the statement which we should agree to. Now, any unsteady flow with fluctuation is not a turbulent flow, now I am actually I would like to discuss it in a question answer mode, but let me summarize it. So that embarrassments on both sides will be limited.

Any unsteady flow with fluctuations is not a turbulent flow. Quite often you say fluctuating flow is turbulent flow, it is not true. It could be simply unsteady laminar flow, you have a laminar flow it can be fluctuating the flow speed. It could be acceptable, but it is not turbulent flow. And a flow with fluctuations like white noise, you know you have lots of fluctuations, with this so much similar amplitudes, nearly at all frequencies it is also not a turbulent flow.

A flow in which the fluctuations has a power spectrum, it is the variation of the square of the fluctuating velocity with frequency. Involved in all frequencies, not specific only and not simply connected to any specific geometric feature. You know sometimes you can create an oscillation at specific frequencies. In this case you whether you do it or not, you will find the disturbance if you decompose it into spectrally by using a Fourier, fast Fourier transform you will discover all frequencies.

And they have power spectrum of a certain class when it obeys that the flow is turbulent. What happens what is happening in turbulent flow? The fluctuating speed draws energy from the mean field and dissipates it to fluctuations until the final dissipation occurs through viscosity and that is what we discussed earlier is Kolmogorov's theorem and so on.

And this is true with all fluid flows and a buoyancy driven flow also can be turbulent. And of course, in this case the convective motion get sustained by buoyancy. I said this because you are looking at turbulent premixed flame you must know what is it we are talking as turbulent flames ok. I started by showing you this figure dancing flames. So, when the scale of turbulence, turbulence is characterized by 2 quantities; scale and intensity.

Intensity is the  $U'$  if you say large the  $U'$  is more intense than small  $u'$ . Scale, if you create a disturbance then what this thing does it is it felt. Let us say scale you can measure it by correlation there are other methods Taylor micro scale by some other methods and so on. Nevertheless the extent of spatial influence, the extent of spatial influence of a fluctuation is the length scale.

Whereas, the fluctuation in the intensity: intensity and length scale or parameters which characterize turbulence as we want to use them in here. There are many other features which may be important in flows, but for the discussion here these are relevant and appropriate. So, when the length scale of the turbulence which is the so called the correlation and scalar Taylor Micro Scale and whatever you know we would like to call it. A large compared to the unstrained flame thickness then the flame is incurred.

It's like a you know sheet which is being wrinkled that is all. The flame surface area change is taken proportional to the turbulent velocity fluctuation because, what is creating this disturbance is it a velocity fluctuation. A simple minded approach you say that these are linearly related, this is how Damkohler started his work. And the point of view, that you must know is when you are dealing with a complex problem to begin with unless nature suggests complexity assume it is simple.

Some variation is present; let us see it is linear. If it is not linear let it show we will accept the final result as the nature gives us. But to begin exploration this is what is right thing to do ok. Because the temperature jump across the flame I am making a point here viscosity increases and a flow the flow may become laminar local, can even become laminar locally.

Let me explain this, see you have a flow coming in and other side the high temperature viscosity goes like temperature to the power of 0.7. Did you know this? Gas temperature to the power of 0.7 is a way viscosity increase. So, when the flow comes here and becomes hot it becomes hot viscosity increases. When viscosity increases local Reynolds number goes down.  $\rho u l$  by  $\mu$  when a Reynolds number goes down  $\rho$  tends to become laminarized.

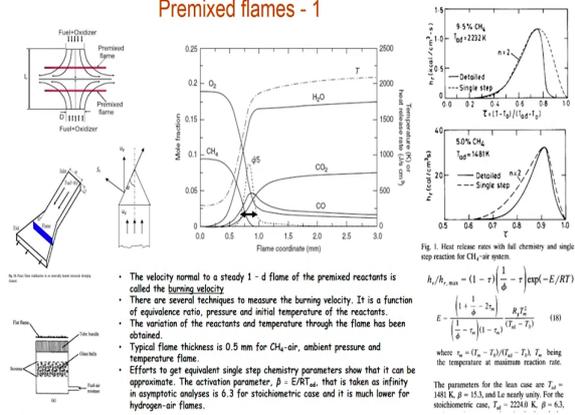
What does it mean? It means any disturbance in that hot flow will die down quicker than what happens in the case of that with lower viscosity. With lower viscosity it means it is able to sustain the oscillation in the in the high viscosity case it dissipates much more, much faster ok.

So, we must keep this variations in our mind. So, what may happen when you discuss effects of turbulence you must keep this in mind? And a strong turbulence the flame structure itself is altered. Now, what is maintains that with the velocity fluctuation and length scales are such that they are comparable to the flame thickness, then you will discover the flame will be structure itself be affected.

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### Premixed flames - 1



What do you mean by flame structure? You saw in this you remember you saw here in 0.5 mm, the whole thing is changing. Now, suppose this length scale of turbulence is 0.2 mm it means it will distort this. So, the distributions which you see here are no longer correct it is far more difficult to analyze this.

But very not so difficult to analyze, the wrinkled flame. Because if you can imagine that or sort of, how to account for the wrinkling effect. So, many people who have put in their effort and time in measuring the flame speeds and analyzing them. This is a very important diagram connected with this, where you see turbulent intensity scaled with the laminar flame speed with the length scale for turbulence divided by the flame thickness. For know unstrained flame thickness which we have been talking about.

There is the line here is  $Re$  equal to 1 and this is a very important length scale below which you will find laminar, beyond which you will find many other behaviors. You will find here the so called wrinkled flame rate, which we discussed that a few moments ago. And you keep increasing the intensity then it becomes corrugated distributed reaction zone and in the final stage when everything is well mixed we will get a well stirred reactor, which we may not have discussed at the moment stirred reactor is more limit of the whole thing. Where, fuel and oxidizer elements are completely mixed with turbulence.

So, we will get at any one length scale if you keep increasing the intensity you approach well stirred reactor ok. You can there many other behaviors which are presented here which you may come back and discuss later. And this length scales are essentially Kolmogorov length scale and Taylor length scale and inertial scale all this again we will come back and address them later.

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### Data On Premixed mixtures

A comparison of turbulent flame speed correlations for hydrocarbon fuels at elevated pressures, 07/2016 – 07/2016 by Burke, G.M., Guther, F., Monaghan, B.F.D.

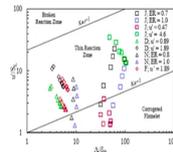


Figure 5 Turbulence and flame conditions for the data displayed in Table 1 plotted on a log-log diagram modified by Peters [1].

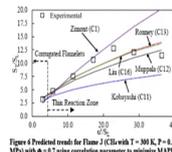


Figure 6 Predicted trends for Flame J (C2H6) with T = 300 K, P = 0.1 MPa with phi = 0.7 using correlation parameter to minimize MAPE for DC1.

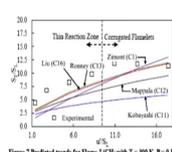


Figure 7 Predicted trends for Flame J (C2H6) with T = 300 K, P = 0.1 MPa with phi = 1.0 using correlation parameter to minimize MAPE for DC1.

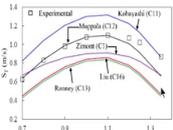


Figure 11 Predicted trends for Flame D (C2H6) with T = 500 K, P = 0.1 MPa with phi = 1.0 using correlation parameter to minimize MAPE.

The conclusion of several authors is that the correlations for turbulent flame speed are not satisfactory. Modeling of the role of turbulence needs improvement.

For complex premixed flows, a simple approach is to use BML model in which the local temperature of an averaged combination of temperatures at unburnt condition and fully burnt condition, the averaging procedure evolved through conservation equations. It is turbulence that controls the averaging process.



And look at the results of on premixed mixtures both laminar and turbulent. Laminar you saw here and you see here the role of turbulence  $U_{rms}$  again from length scale divided by the flame thickness. You will find that the reaction the various zones are shown here the corrugated flamelet, thin reaction zone and the broken reaction zone. And you will find the turbulent flame speed as a ratio of the laminar flame speed; experimental data and a large number I have put their mind into getting correlations.

You see the number of people who put in their correlations is humongous about 25 30 people have put in the correlation, only conclusion we will see in an moment. All experimental and I could fill this whole page with large number of data from various people. They are still broad variations are ok, but predictions are never ok. You will find so much of data in these places

and the conclusion is that of not only one several people is the correlation for turbulent flame speed are not satisfactory.

Modeling of the role of turbulence needs substantial improvement for premixed flames. Well quite often it is said that for complex premixed flows a simple approach is to use (Refer Time: 46:42) mass (Refer Time: 46:43) this is somewhat of a simple model like we discussed the diffusion flame where you have the states which are involved or the progress variable in which you have oxygen fuel going to the oxidizer.

The flame is only at one location is stoichiometric location. Here you say there is flame or no flame, then is the thin zone; on one side is premixed mixture, another side you have essentially burnt products. And, this is a thin flame in premixed flame they go structurally what all you can do is to actually see how the flames moves around in a situation where chemistry is not involved.

You are only looking at zones where there is fuel or actually they are present or burnt products are present. There is the model involved as to how the flow turbulence have to capture it is a substantive study and there is a codes which account for it as well, ok.