Combustion in Air Breathing Aero Engines
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Lecture – 46
Turbulent Premixed Flames V

Welcome back. So, we were talking about turbulent flame speeds and we will go into some experimental configurations. So, just to recap on the concept of turbulent flame speed and what we just did was that we took a now we essentially took if you take a cuboid channel like this.

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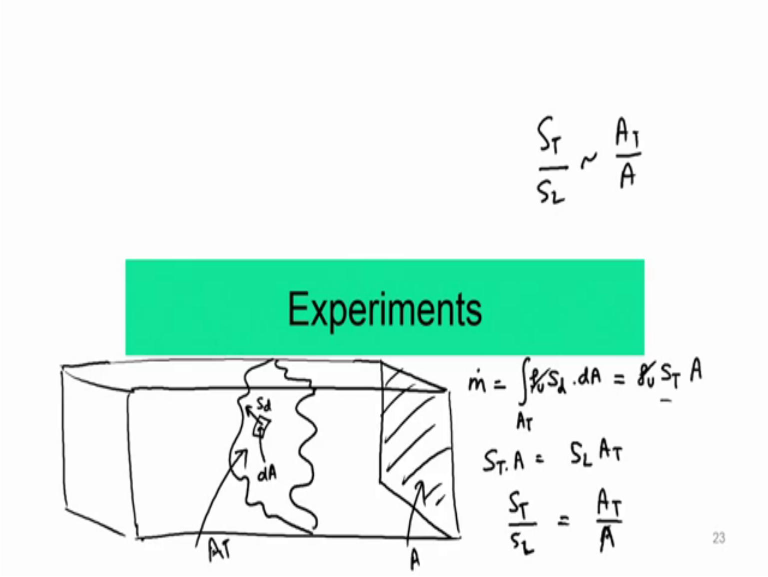

$$\frac{S_T}{S_L} \sim \frac{A_T}{A}$$

Experiments

$$\dot{m} = \int_{A_T} \cancel{\rho_u} S_d \cdot dA = \rho_u \underline{S_T} A$$

$$S_T . A = S_L A_T$$

$$\frac{S_T}{S_L} = \frac{A_T}{A}$$

So, before we going into the experiments we I just want to show you something like this, that is suppose this is this is this is a cuboid in which you want to basically find out the turbulent flame speed, this I am I just stated this little bit in a simplified manner.

But I before we going to the experiments lets discuss this in more details, and here you have the turbulent flame which is stabilized just like the movie you saw. So, this is your turbulent flame. So, now, to give you a more details, now, each of these points essentially say if we say now consider an infinite decimal is small area on the flame when represent this for d A and the relative velocity of this flame surface with respect to the local fluid velocities of course, S d in the normal direction right. So, this is essentially S d dot S d dot n vector times d A vector. So, it gives you S d dot times d A ok.

So, now the local now the total mass flow rate that is entering mass into this whole surface, we can write this as m dot is equal to integral over the entire surface rho times if it is a close to the unburned side then it is of course, rho times we can approximate this as essentially rho u times S d times d A. So, this is the rho u times the local displacement flame speed times the d A, and now that is equal to we can if we now want to represent this whole mass flow rate in to the fuel air mixture by one average velocity of the fuel air mixture, then that is the turbulent flame speed. So, then that is given by rho u times S T and what is the area? Area is of course, this is the area which is this projected area which is given by A. So, this is A and let this of area is be equal to full this thing is equal to AT.

So, then this is rho u times S T times A. So, this is how or we see where the S T come from. So, now, we can simplify this if you assume that S d is equal to S L over the entire flame surface we do not consider any of its stretch. So, then what you get is that to the leading order rho u is this is an iso thermal surface then rho u rho u cancels out. So, rho u cancels out. So, then you get S T times A is essentially S L this is over the entire surface area. So, this is A T. So, then S T is essentially equal to S T by S L is equal to A T by A. So, of course, this comes into the assumption that you have assume that S d is equal to S L over the entire surface which is not true, but still what you seen here is that that what you see here is that even then to the leading order your S T by S L is essentially.

Equal to is close to A T by A and in fact, in reality also your S T by S L is close to A T by A and your S T that is a turbulent flame speed is much much more than the laminar flame speed is simply due to the is due to the fact or the or the overall propagation rate of the flame surface is much much greater than the local propagation rate of the flame surface. This is simply because you have turbulences made has generated a very large flame surface area, due to stretching and wrinkling over a multitude of length and time scales. So, because of this area of the flame is much more it can consume the fuel air mixture at a much faster rate and it can that is why it can essentially propagate on average it can propagate much faster than the planner laminar flame.

So, this is the remarkable property of the turbulent flame which is utilized in different in different engines. So, you that is why saying about gas turbine engines you can have a flames stabilization at high speeds in a gas turbine engine, because your turbulent flame speed is much much higher than the laminar flame speed in a car engine it can run, it can produce lot of power by consuming lot of fuel without producing pollutants is because your turbulent flame speed allows. If you have lot of turbulence inside the engine it allows the propagation the flame to propagate much faster than it can than a laminar flame can propagate ok.

So, the turbulent flames it is a very very important thing and from here you can clearly see that why your S T by S L is much greater than 1 because your A T that is the that is this wrinkled flame surface area is much much greater than the projected area or the area of a planner laminar flame. So, now, in next we will show you how we will determine the turbulent flame it is prevents.

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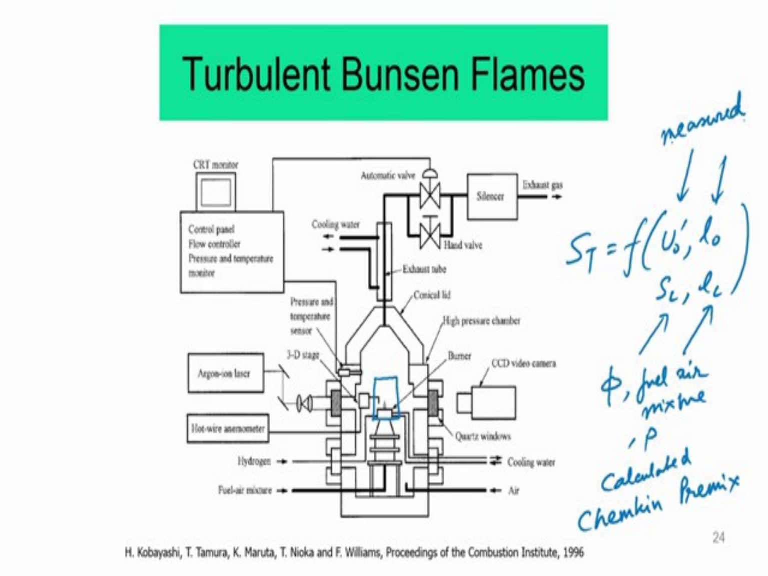

Turbulent Bunsen Flames

measured

$S_T = f(U_0', l_0, S_L, l_c)$

ϕ, fuel air mixture, P

Calculated Chemkin Premix

H. Kobayashi, T. Tamura, K. Maruta, T. Nioka and F. Williams, Proceedings of the Combustion Institute, 1996

So, it is a not a simple experimental set up. So, this is as comes from Kobayashis group and Tohoku university then reported in this proceeding property in 1996. So, here they have a high pressure turbulent Bunsen flame set up. So, this is where your flame is actually. So, you see the flame to be essentially. So, the flame is essentially here.

So, this is the flame if you can see and then there are like many diagnostics of course, this experiment has to be based in a very high very low thick and pressure thick and walled pressure vessel, and then you need to have optical access. So, that it can of the flame motion of the flame surface can be visualize with a CCD camera using Schlieren techniques, which will give you the density gradients and. So, then it also mon it measures the local flow velocity fluctuation because as we are remember, we want to get the turbulent flame speed as a function of the URMS.

That is of course, one of the important parameters you can get planner laminar flame speed and the and the flame thickness from either by a students or by you cannot get flame thickness by direct experiments and this is a very high and experiments using different provobs (Refer Time: 06:49) Kontron etcetera in a Schlieren, but you can get them easily by using this Chemkin tools, Chemkin premixed tools. So, the planner laminar flame speed and the flame thickness can be obtained easily. So, we wanted to obtain S T as a function of u prime 0, l 0 which are the flow which are the flow parameters. So, these are the flow parameters and S L the planner laminar flame speed and l L.

So, this needs to be measured and whereas, this can be computed, this can be computed. So, this needs to be measured and for a given fee and the given fuel air mixture and for a given pressure your S L and l L can be calculated using Chemkin premix or Cantera. So, these things can be calculated. So, once you have if you can measure the turbulent flame speed if you can measure u prime 0 and if you can measure the l 0 and calculate S L and l L then you can essentially find correlations between turbulent flame speed and this parameter how to measure turbulent flame?

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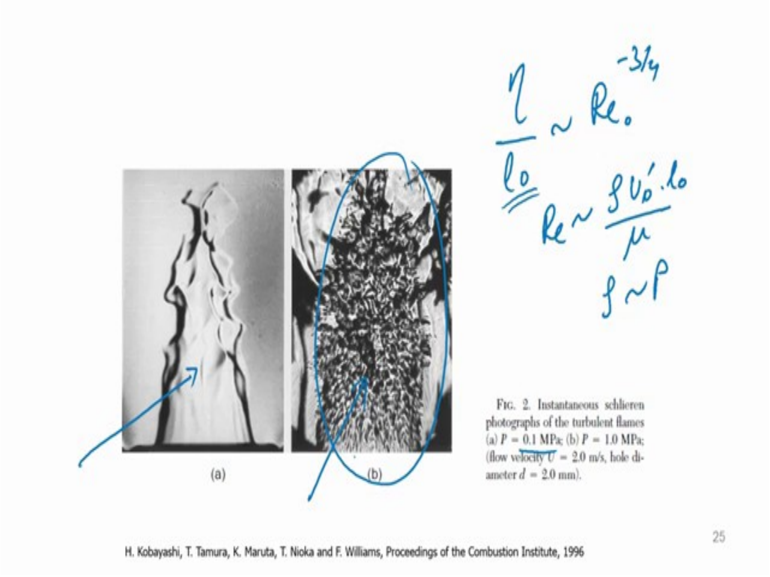

(a) (b)

$$\frac{\eta}{l_0} \sim Re_0^{-3/4}$$

$$Re \sim \frac{\rho U_0' . l_0}{\mu}$$

$$\rho \sim P$$

FIG. 2. Instantaneous schlieren photographs of the turbulent flames (a) $P = 0.1$ MPa; (b) $P = 1.0$ MPa; (flow velocity $U = 2.0$ m/s, hole diameter $d = 2.0$ mm).

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Speed now before you measure lets show you some different structures of turbulent flames.

So, this is you see that at the same flow velocity if the flow velocity is remain same at u average is equal to 2 meters per second and same whole diameter of 2 millimeter. So, this on the left hand side you have the turbulent flame behavior at low pressure, and then at high pressure of course, this is one of the effects if you do the same flow visualization also you will see that high pressure your flow has very very small scale structures in with respect to the flow at low pressure, the reason is that once again if you remember your eta by l 0 is essentially Reynolds number to the power of minus 3 by 4 ok.

So, an Reynolds number you see is essentially rho V d y rho u r m s, u prime 0 times say d by or l 0 by mu. So, if mu does not change much such with pressure. So, u prime 0 and l 0 if that also does not change too much with pressure, but rho is directly rho proportional to pressure right at a given if the temperature is fixed. So, it directly increases with pressure. So, that is why the scale separation the eta for example, given l 0 your Kolmogorov of length scales becomes smaller and smaller with pressure. So, even if you give all the other properties constant, but if you decrease or if you increase the pressure your Kolmogorov of length scale becomes smaller.

And as a result of that any turbulent jet or a flame has smaller and smaller structure because your flow has much small structures. Now it is much more turbulent, that is a same reason why in an engine we have very very small Kolmogorov of length scales at very high pressures. So, this is how a flame one of the turbulent flame will look like at a at a pressure of about 10 bar or 1.0 MP a megapascal whereas, at one bar at that one at positive expression for the what the turbulent flame looks like. So, at different pressure your turbulent flame structure is very very different as you can see from here and of course, this being much more wrinkled it must have a much more flame surface area ok.

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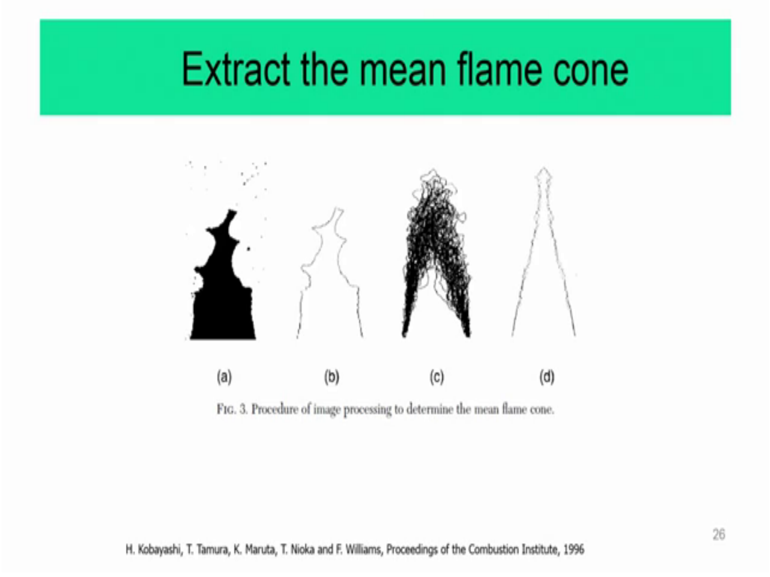

Extract the mean flame cone

FIG. 3. Procedure of image processing to determine the mean flame cone.

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So, how do you extract the how do you find out the turbulent flame speed. So, for that first you have to extract the mean flame cone. So, you find out all this flame contours like this, and this is for one realization they are they are coming for another realization like this. So, you will get different kind of realizations and then you can essentially average them ou, and find out the average the for example, the average flame cone for this will look something like this and we do some image processing extract the flame edges and find out the mean flame edge and it look something like this and then basically

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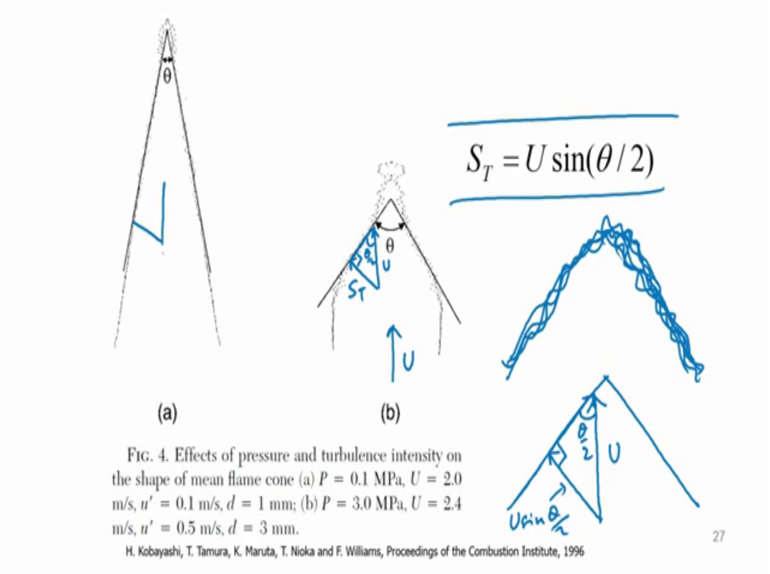

$$S_T = U\sin(\theta/2)$$

FIG. 4. Effects of pressure and turbulence intensity on the shape of mean flame cone (a) $P = 0.1$ MPa, $U = 2.0$ m/s, $u' = 0.1$ m/s, $d = 1$ mm; (b) $P = 3.0$ MPa, $U = 2.4$ m/s, $u' = 0.5$ m/s, $d = 3$ mm.

H. Kobayashi, T. Tamura, K. Maruta, T. Nioka and F. Williams, Proceedings of the Combustion Institute, 1996

You say that your S T is essentially equal to U sin theta by 2, because if this flame cone is like this then my say if my S T is like this. So, then this is how I evaluate it.

So, say this is this one is better. So, this is my u this is not my S T sorry. So, this is my u. So, now, I can resolve this u into the normal and tangential component. So, say this is my u and then this is my theta by 2, this is my normal and this is this is my S T that is the mean flame speed that is the component of u which is perpendicular to the mean flame cone. Now the this is the mean flame means it is essentially statistically stationery because it has been time average. So, because is for it to remain statistically stationery the flow velocity that is perpendicular to it must be equal to the global turbulent flame speed.

So, that is the argument by with which you get this S T. Once again that the idea is that if you have flame surfaces like this and you this is different flame surfaces that you generate extract from the different videos and then you generate basically a mean flame surface by average in over all this surfaces like this, and then this is your say mean fluid velocity which you know from your mass flow readings, and then you basically resolve it into this direction into the normal and the tangential components. So, this is your mean flow velocity. So, we resolve it into normal and tangential components this is your theta by 2 ok.

And. So, then this guy. So, then this now this this mean flame surface for it this mean flame surface to remain statistically stationery it must be fed with the flow velocity which is normal to the mean flame surface and this and this flow velocity normal to the mean flame surface, must be equal to the turbulent flame speed for this given configuration all right. So, then if you can find out what is the mean flame velocity normal to the to this mean flame surface, than that is my S T. So, then that is nothing, but u this velocity is nothing, but U times sin theta by 2. So, then this means that that my S T is essentially U sin theta by 2 ok.

So, if I know my if I can extract this mean flame cone and find out the different the thetas for different configurations, then I can find out what is the mean what is my turbulent flame speed and. So, they did experiments for different configurations that. So, we see that different configuration experiments and when that put this.

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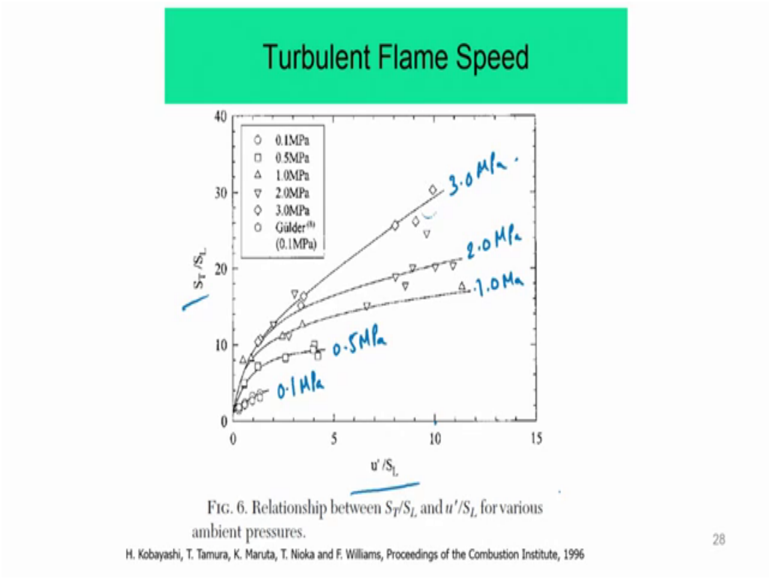

Turbulent Flame Speed

FIG. 6. Relationship between S_T/S_L and u'/S_L for various ambient pressures.

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In a plot we see that this is S T by S L and this is u prime by S L. So, this is you see that this haves a kind of a bending behavior all of this curves. So, like this the bend after increasing and what we see is that that as pressure increases S T by S L increases. So, this is at a pressure of 0.1 MPa in this is at a pressure of 0.5 MPa ok.

This at a pressure of 1.0 MPa and this is at a pressure of 2.0 MPa, and this is at pressure of 3.0 MPa. 3.0 MPa has very large pressure this essentially 30 bar and you see that at this high pressure at u prime by S L of about 10, you are u S T by S L is as reached at the value of about 30. So, that is a huge increase over the normal planner laminar fame speed these turbulence flame is reached. So, actually the turbulent flame speed in this cases it can be shown that has not reached increased so much, but if you remember the planner laminar flame speed decreases with pressure. So, whereas, a turbulent flame speed can change slightly with actual turbulence flame speed does not change too much pressure.

But it essentially the decreases of the flame speed with the planner laminar speed that causes this rapid increase with the pressure. So, but anyways that is an important thing because if S T was so, small at high pressure, then it would be very difficult to essentially stabilize flames in a in high pressure gas turbine engines. So, that is good thing next will talk about in.

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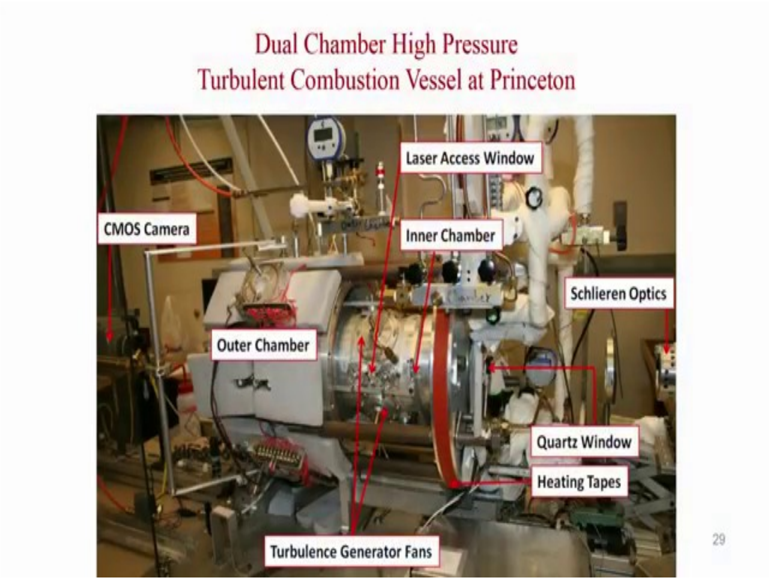

Dual Chamber High Pressure
Turbulent Combustion Vessel at Princeton

Some details about this dual chamber high pressure turbulent combustion vessel at princeton. So, where many of this expand in turbulent flame experiments are done, this were also done at previously at leads university and but this set up is a little bit different from those, the main set up the main purpose is to essentially measured the expand the turbulent flame speed of expanding turbulent flames at high pressure, and at constant pressure. So, to maintain constant pressure there is a nice this set up is used to. So, you see if you have a enclosed vessel and if you increase and if you ignite the flame at the center of that vessel, what happens is that this flame will expand, but immediately the pressure will rise, but as you know that the flame the planner laminar flame speed is a strong function of pressure. So, if you do an experiment where your pressures continuously increasing, then you are essentially changing one of your most important parameter.

So, you cannot do a good experiment by where the most important parameter changes like that, where a where a where a depend independent variable like planner laminar flame speed which is an independent variable in your scaling laws for turbulent flame speed. So, you want to obtain the turbulent flame speed as a function of planner laminar flame speed flame thickness integral length scale URMS etcetera. So, in this scaling laws your S L and l and your flame speed and flame thickness appears as independent variables. So, you cannot do an experiment where an independent variable essentially is changing of course, flame thickness will also change with pressure as you know the flame thickness decreases with pressure, and that is one of the reason also why you see that emergence of different finer and finer scales in the turbulent flame that you saw just for the Bunsen turbulent flame, that you saw.

Now the thing is that. So, in this set up what the people will do is that they we have dual chamber vessel. So, you have an inner chamber and an outer chamber and we ignite the we fill up the inner chamber with the fuel air mixture, and then we ignite that thing with a spark. So, as soon as a spark is ignited this inner chamber and outer chamber has an has some ports which opens up, and this can essentially communicate. So, the pressure that is increasing inside inner chamber due to this gas expansion, due to the flame due to the overall temperature rise inside the inner chamber.

So, that can be observed into the outer chamber as a result the flame essentially propagates in nice Schlieren environment. So, this provides very valuable data for turbulent flame speed.

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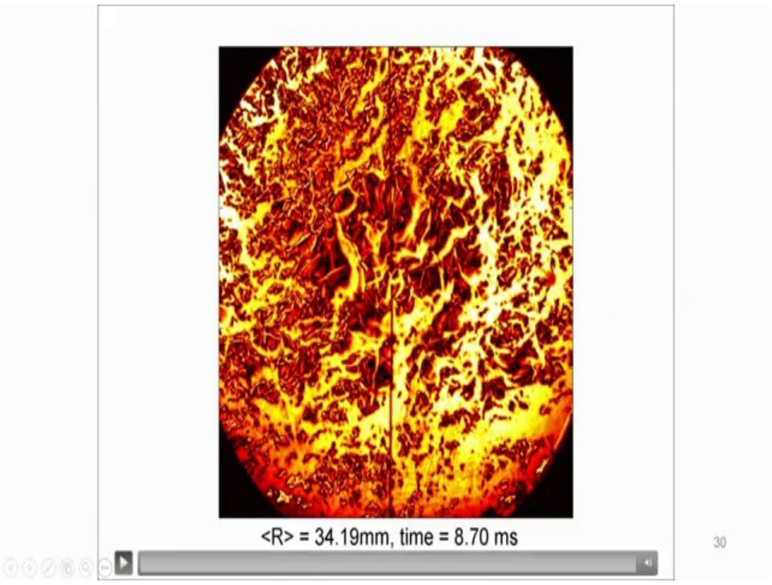

<R> = 34.19mm, time = 8.70 ms

And this is how essentially turbulent fame which is ignited in this dual chamber at a turbulent combustion vessel looks like. So, you see that this is just the this is right after this spark where this kernel is formed, and you see this shock being from right after the spark which immediately goes away. So, this is how. So, you see that this is how this turbulent flame is expanding this is a false Kernel Schlieren imaging of the actual experiment. So, you see that this flame is this is how the turbulent flame is such a look like I will again play this video.

So, you see that it immediately forms this turbulent from several wrinkles at different scales on the flame surface. And essentially the flame propagates very fast at the latest stages and this is a very short time experiment as you see it is of the order of 8.7 milliseconds and the average radius is about 3.5 centimeters. So, these are very important experiments, and this gives you a very clear idea of the how the turbulent flame structure looks like where it is essentially stretched and wrinkled at a multitude of length and time scales.

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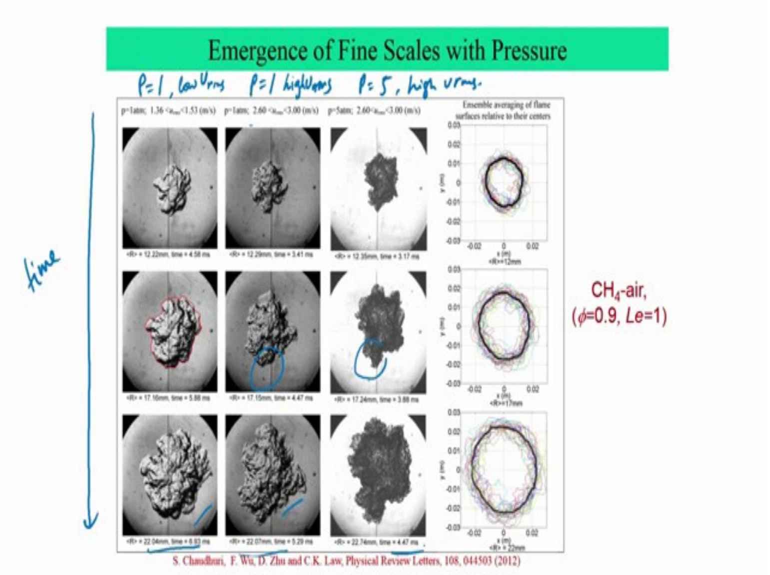

Emergence of Fine Scales with Pressure

S. Chaudhuri, F. Wu, D. Zhu and C.K. Law, Physical Review Letters, 108, 044503 (2012)

So this is how the different Schlieren imaging looks like the and the black and white Schlieren images.

So, you see that at this is at one (Refer Time: 20:02) one atmosphere this is at essentially at one at one atmosphere, but. So, this is on this in this matrix what we have is that, we essentially denote 3 this in this way time increases for a same experiment and in this direction the experimental condition increases. So, in from here this is about P1 slow u URMS low URMS or u prime 0, here we represent URMS by URMS and this is P 1 moderate are [ha/high] high URMS, and this is P equal to 5 and high URMS ok.

So, this is. So, you see that in this one as you see that this is one atmosphere pressure low URMS mild wrinkles are being formed, and the flame is propagating of course, at a given average propagation rate and then here you see as you increase the URMS, this scales become finer and finer. There is small scale structure is being formed and that is clear because once again your now the Kolmogorov of length scale is actually is actually is actually smaller. So, in this case your essentially your turbulence Reynolds number is smaller is larger in this case with respect to this case but.

So, that causes this increase of this finer scale structures and you see that here it has reached 22 millimeter average at 6.93 milliseconds, here it is reach the same radius at about 5.29 milliseconds. As you increase the URMS it is basically the average propagation speed increases all right so on. This case you see that as you increase as you have in gone to 5 atmosphere and URMS of even same URMS as this, but all you have change the pressure this there is this structure the structure of this flame is much smaller than what you have here. So, this flame has structure is even smaller than what you have here ok.

And this has this because you have both your flame thickness, as well as your Kolmogorov of length scale has decreased in this cases. So, that causes this emergence of this fine scale finer scale structures and it has even you see that it is even prorogating at faster rate at about 4.47 milliseconds it has reached the diameter of 22.74 millimeter.

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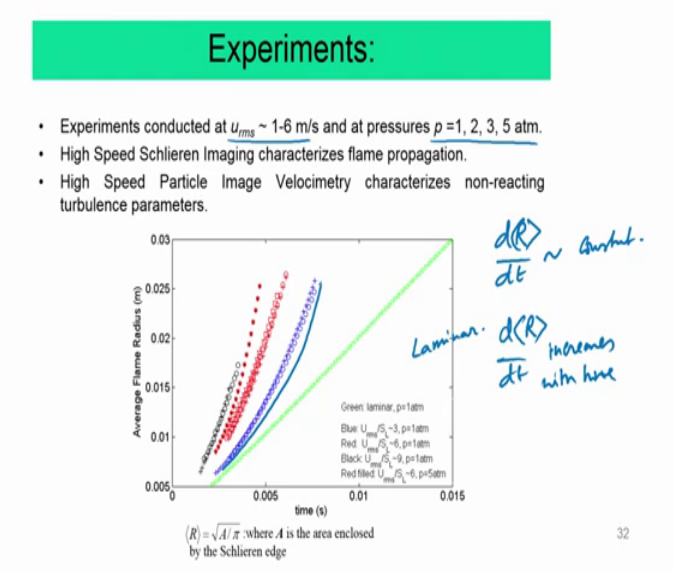

Experiments:

- Experiments conducted at u_{rms} ~ 1-6 m/s and at pressures p =1, 2, 3, 5 atm.
- High Speed Schlieren Imaging characterizes flame propagation.
- High Speed Particle Image Velocimetry characterizes non-reacting turbulence parameters.

$\langle R\rangle = \sqrt{A/\pi}$:where A is the area enclosed by the Schlieren edge

So, then we can the observations of that apart from this emergence of different scales in this experiments. So, in this experiments which are conducted at a URMS at of 1 to 6 milliseconds and 1 to 6 meter per second and pressure of 1 to 5 atmosphere.

And we used high speed Schlieren imaging to characterize a flame propagation and high speed p I v was used for characterizing the non reacting turbulence parameters. If that is an important thing because how do you know what is your URMS, you need to do a high speed PIV or you need to measure the velocity inside by LDV etcetera. But the interesting thing is that if you find out the average radius, how do you find the average radius. So, is this is your you find out the total parameter of the on the total area that is enclosed by the flame surface and you say that is equal to A. So, you define the average radius is essentially is equal to A by pi. So, of course, this is a little bit it is a essentially this average radius this is a characteristic length scale the flame.

So, then this is how you define the average radius. So, if you now plot the average radius by extracting the image from the different from the all the all from the different flames and if you plot the average radius verses time, what you see is that first before going into the turbulent flames if we compare it with the laminar flame. So, this is you see what is the average radius verses time for a laminar flame. So, this is for a laminar flame you see that this is almost linear with time. So, the average radius is almost linear with time so, but the for the turbulent flames, you see that the average radius is not linear because if it was linear it will be something like this.

So, it essentially concave upwards. So, you see average radius verses time being linear means d R d t which S essentially measure of the flame speed is essentially constant whereas, if this is linear. So, then it means d R d t essentially increases with time. So, d R d t essentially increases with time. Now that is a very interesting thing because then it means the essentially the flame is accelerating with time or in the other way as a radius is large the flame speed is large. So, there is a that is a very interesting thing, that is not seen in at in a laminar flame of course, you can see little bit of this effect when you have different Lewis numbers, depending on the Lewis number greater than or less than unity you can have conditions where you have essentially the flame can accelerate.

But it definitely cannot accelerate as much as like a turbulent flame, where you see this strong non-linear A T of this average radius verses time. So, this is very interesting point and this needs to be further probed and then what you can you need to find out.

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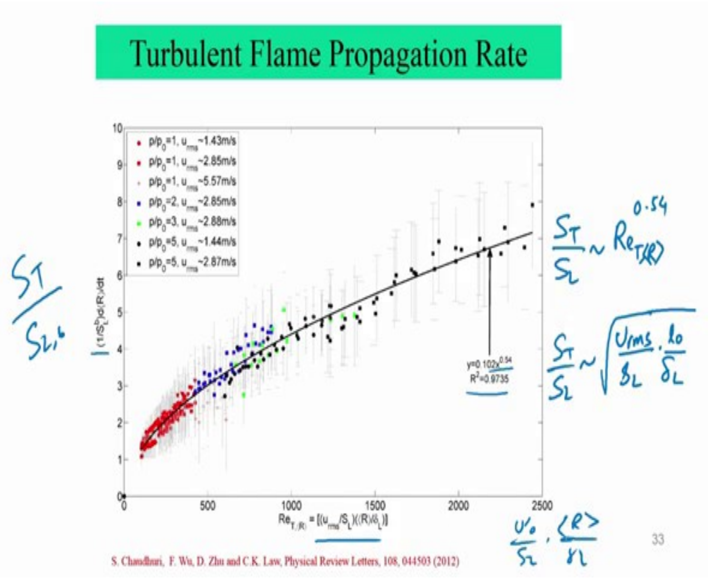

Turbulent Flame Propagation Rate

S. Chaudhuri, F. Wu, D. Zhu and C.K. Law, Physical Review Letters, 108, 044503 (2012)

Utilizing this question was that can be find out the scaling relationship for the turbulent flame. So, if we plot what do you will see is that if we plot y axis as one by S L b that is not normalize with the mean flame speed is essentially can be taken as S T by S L b that is a burn flame speed whereas, d r S d is equal to d r S T and. So, if this if not on the y axis and on the x axis you plot this URMS by S L times average radius by delta l. So, this we plot this thing average radius by delta l, I will come into this y come to this choice.

Whereas see all this experimental data can essentially collapse on this Reynolds number to the power of 0.54 plot. So, we can write in this correlation in this scaling log you see that this law emerges this powerful law emerges, where as we have Reynolds number which is based on a turbulent Reynolds number which is based on average radius, and this scales has to the power of 0.54, which is nearly to the power of 0.5. Now why do we scale with this parameter at all that is need to be understood. First of all the most of the experiments are in essentially the thin reaction zone regime and you saw that by Damkohler and as well as our calculations, analytical work your S T by S L for our planner laminar flame for a statistically planner flame can scale as URMS by S L times l 0 by l L or we are integral length scale by flame thickness.

Which is the symbol that we use here, but that was for a statistically planner flame now for a expanding flame you see the flame is expanding in a cylindrical volume which contains turbulence, but why is the flame accelerating or why is the turbulent flame speed higher than the laminar flame in first place. The reason is that because turbulence has stretched and wrinkled and folded this flame surface at a multitude of length and time scales and that has cause this area surface area to increase ok.

So, for a statistical planner flame all the scales of turbulence that are present right from the integral length scales to the Kolmogorov length scales, can stretch can participate in this stretching wrinkling and folding of the flame surface. But for an expanding flame which are the particular instant is of radius r this statistically spherical flame, which is at a average radius r can only be stretched fold and wrinkled by turbulence of length scales which are equal and smaller than r because the turbulent eddies which are greater than r this will only convict this kernel this will only push this kernel instead of stretching and folding it. So, only those eddies which is equal and smaller than r can participate in this stretching and folding processes, for this statistically spherical flame for this expanding flame. So, at a given radius r if you look at this flame at a given radius r only eddies which is smaller than and smaller than this radius r can stretch and fold it that is the idea. Where as if an if have an eddy which is this it cannot stretch and fold it, it can only push it where as pushing it an convicting it on average does not create any stretching does not create any new area, and hence that should not participate in the turbulent flame speed as such.

So, that is why instead of l 0 the correct instead of l 0 which is of course, in a we can have a l 0 in this configuration also the appropriate choice of length scale in this problem is radius and this was reported in our paper by Chaudhari Wu Zhu and law in the physical review letters, and this choice of average area is very important consideration and other groups are also shown that the when you use average radius, for a expanding flames you can essentially collapse all the data and arrive at this kind of scaling laws. So, that is important thing, but still there is no needs to be understood about what are the different intricate mechanisms about this that are emplaned this from.

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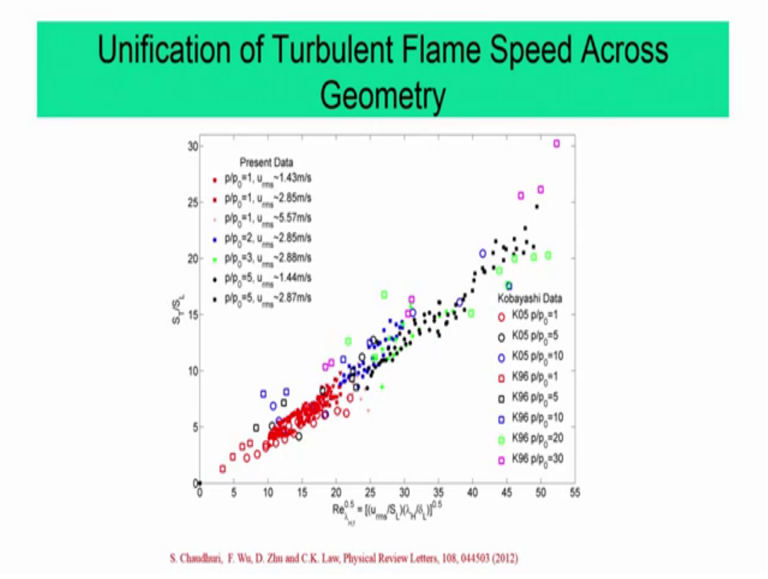

Unification of Turbulent Flame Speed Across Geometry

S. Chaudhuri, F. Wu, D. Zhu and C.K. Law, Physical Review Letters, 108, 044503 (2012)

So, then we show that that if you take Kobayashi data for once on flame and our spherically expanding flame by a appropriate choice of appropriate length scales, we can essentially collapse the different data into one this kind of a uniform plot.

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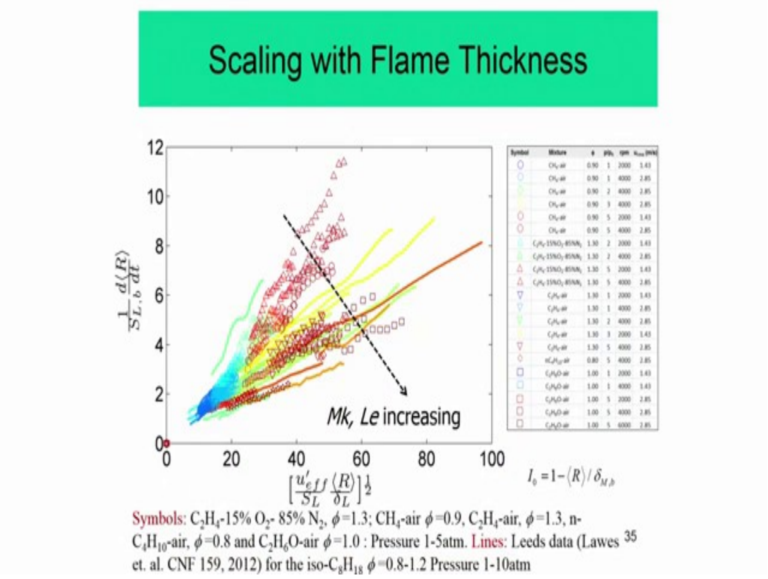

Scaling with Flame Thickness

Symbol	Mixture	ϕ	p/p_0	rpm	u_{rms} (m/s)
○	CH_4-air	0.90	1	2000	1.43
○	CH_4-air	0.90	1	4000	2.85
○	CH_4-air	0.90	2	4000	2.85
○	CH_4-air	0.90	3	4000	2.85
○	CH_4-air	0.90	5	2000	1.43
○	CH_4-air	0.90	5	4000	2.85
△	C_2H_4-15%O_2-85%N_2	1.30	2	2000	1.43
△	C_2H_4-15%O_2-85%N_2	1.30	2	4000	2.85
△	C_2H_4-15%O_2-85%N_2	1.30	5	2000	1.43
△	C_2H_4-15%O_2-85%N_2	1.30	5	4000	2.85
▽	C_2H_4-air	1.30	1	2000	1.43
▽	C_2H_4-air	1.30	1	4000	2.85
▽	C_2H_4-air	1.30	2	4000	2.85
▽	C_2H_4-air	1.30	3	2000	1.43
▽	C_2H_4-air	1.30	5	4000	2.85
◇	nC_4H_{10}-air	0.80	5	4000	2.85
□	C_2H_6O-air	1.00	1	2000	1.43
□	C_2H_6O-air	1.00	1	4000	1.43
□	C_2H_6O-air	1.00	5	2000	2.85
□	C_2H_6O-air	1.00	5	4000	2.85
□	C_2H_6O-air	1.00	5	6000	2.85

$I_0 = 1 - \langle R\rangle / \delta_{M,b}$

Symbols: C_2H_4-15% O_2- 85% N_2, ϕ=1.3; CH_4-air ϕ=0.9, C_2H_4-air, ϕ=1.3, n-C_4H_{10}-air, ϕ=0.8 and C_2H_6O-air ϕ=1.0 : Pressure 1-5atm. Lines: Leeds data (Lawes et. al. CNF 159, 2012) for the iso-C_8H_{18} ϕ=0.8-1.2 Pressure 1-10atm

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So, then we did with different experiments, and we saw that when if we just use the flame thickness, when you use different fuels whose Lewis number and mast in number should different then the only you choice of the flame thickness cannot describe your turbulent flame speed.

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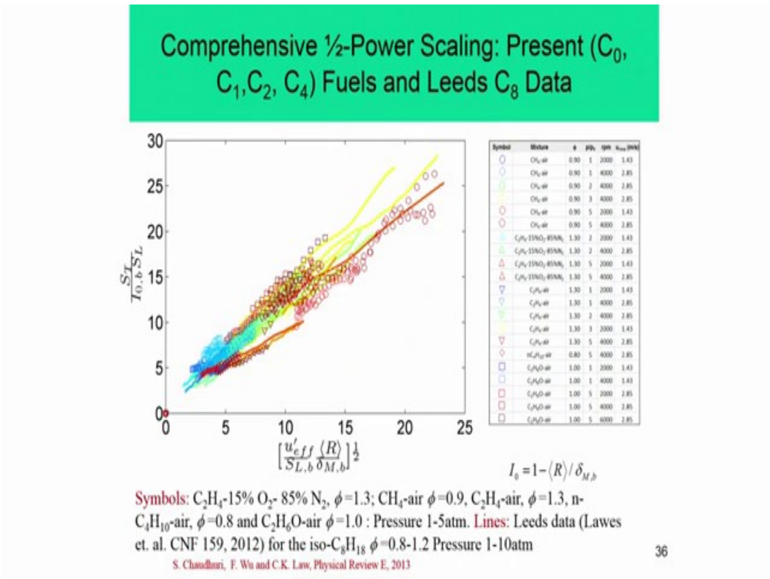

Comprehensive ½-Power Scaling: Present (C_0, C_1, C_2, C_4) Fuels and Leeds C_8 Data

Symbol	Mixture	ϕ	p/p_0	rpm	u_{rms} (m/s)
○	CH_4-air	0.90	1	2000	1.43
○	CH_4-air	0.90	1	4000	2.85
○	CH_4-air	0.90	2	4000	2.85
○	CH_4-air	0.90	3	4000	2.85
○	CH_4-air	0.90	5	2000	1.43
○	CH_4-air	0.90	5	4000	2.85
△	C_2H_4-15%O_2-85%N_2	1.30	2	2000	1.43
△	C_2H_4-15%O_2-85%N_2	1.30	2	4000	2.85
△	C_2H_4-15%O_2-85%N_2	1.30	5	2000	1.43
△	C_2H_4-15%O_2-85%N_2	1.30	5	4000	2.85
▽	C_2H_4-air	1.30	1	2000	1.43
▽	C_2H_4-air	1.30	1	4000	2.85
▽	C_2H_4-air	1.30	2	4000	2.85
▽	C_2H_4-air	1.30	3	2000	1.43
▽	C_2H_4-air	1.30	5	4000	2.85
◇	nC_4H_{10}-air	0.80	5	4000	2.85
□	C_2H_6O-air	1.00	1	2000	1.43
□	C_2H_6O-air	1.00	1	4000	1.43
□	C_2H_6O-air	1.00	5	2000	2.85
□	C_2H_6O-air	1.00	5	4000	2.85
□	C_2H_6O-air	1.00	5	6000	2.85

$I_0 = 1 - \langle R \rangle / \delta_{M,b}$

Symbols: C_2H_4-15% O_2- 85% N_2, ϕ=1.3; CH_4-air ϕ=0.9, C_2H_4-air, ϕ=1.3, n-C_4H_{10}-air, ϕ=0.8 and C_2H_6O-air ϕ=1.0 : Pressure 1-5atm. Lines: Leeds data (Lawes et. al. CNF 159, 2012) for the iso-C_8H_{18} ϕ=0.8-1.2 Pressure 1-10atm

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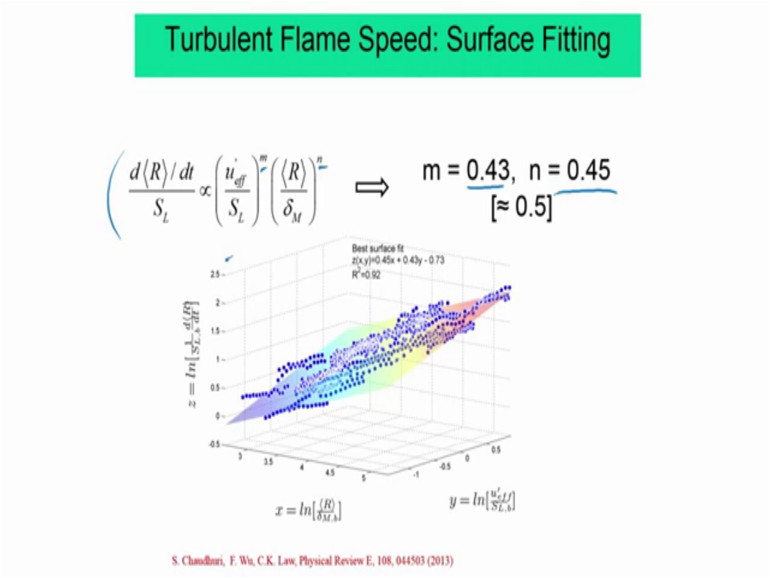
So, then we show that then one has to use this parameter called mast in length derive in an one side for collapsing most of the data on a on a given on an narrow band.

And we show this by using different kinds of fuels engines from methane to ranging from methane to ethane to ethylene to n view 10 to d m e di methyl, ether and also by using data from (Refer Time: 31:34) and data from leeds. So, over this large variation properties over this large URMS as will as different pressure and different fuels we showed that that if you use this kind of a scaling law, and that that also came from this analysis that we use this kind of scaling law, that you can have a you can collapse this turbulent flame speed if you use this kind of a parameter you can collapse turbulent flame speed in narrow band.

(Refer Slide Time: 31:54)



Turbulent Flame Speed: Surface Fitting

$$\frac{d\langle R\rangle/dt}{S_L} \propto \left(\frac{u'_{eff}}{S_L}\right)^m \left(\frac{\langle R\rangle}{\delta_M}\right)^n \Rightarrow \text{m} = 0.43,\ \text{n} = 0.45\ [\approx 0.5]$$

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So, and then the question was that this does this scaling law is does it really hold depend on this 2 individual parameters independently. So, is it just we get this, half just by chance. So, if you just fit this data on the surface using a surface plot.

And if you chose this m and n as independent parameters and you fit, whatever data you get from different experiments in to over the of all the experiments in this plot, then you get a m to be equal to 0.43 and n equal to 45 which is close to 0.5. So, this way you show that this (Refer Time: 32:39) this is in indeed reasonably could scaling law, which holds over a wide range of conditions.

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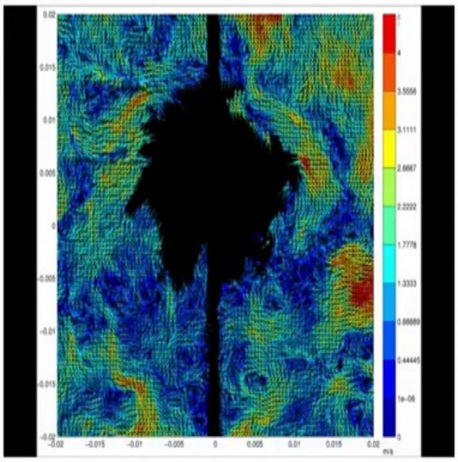
High Speed Mie Images and Vector Fields



And then I will show you how the; we can find out how the different how we can do this miss scattering images are of different experiments and PIV. So, for doing PIV first we have to do high speed Mie scattering and then you see that this is how the flame is expanding.

And then you can find out the vectors and of course, the fuel the flame consume is only at top place which were used for seeding the flow, and you can see that the how the flame expanse in the surrounding turbulence and this is then one we can we can find out.

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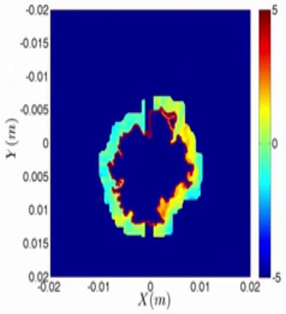
High Speed Mie Images and Vector Fields



- Mie scattering images: Flame edge-locations
- Vector Fields with super imposed flame edge
- Define a zone of influence ahead of flame to calculate statistics
- Evaluate u'_{xy} and mean flow in this zone and then ensemble average over multiple runs

$$u'_{xy} = \overline{\left[\frac{1}{2}\left(\left\langle\left(u_x - \langle u_x\rangle_R\right)^2\right\rangle_R + \left\langle\left(u_y - \langle u_y\rangle_R\right)^2\right\rangle_R\right)\right]^{1/2}}$$

the find out the flame edge and the different things like the tangential flame speed the tangential straining rate as well as the curvature at different points on the flame surface as well as the local flow velocities, which cause this wrinkling. So, then the those things can be evaluated and um and we found out that the URMS does not change too much with and without the presence of the flame, and that was important because all this (Refer Time: 34:02) that represent where obtained with URMS which was obtained in the call flow.

So, question can arise that how much does the URMS actually change in present of the flame, it turned out turns out in this case it did not change too much with the flame, but with the presence of flame, but one is to do other experiments in different other configurations to find out, what is the effect of the flame on the URMS. Because just as the as a turbulence enhances the flame surface area and distort the flame surface, the flame can also can also distort the neighboring flow field by due to the gas expansion.

So, when the turbulent flame is or the laminar flame is expanding its actually pushing the surrounding gases, and that can change the local flow fields. We found out that local average flow field changes, but the local, but the URMS field does not change too much and this was documented in a proceeding of combustion sheet to 2015 paper. So, we will that is how will up to here and in the final thing will take up in this bray moss Libby model and with that will close turbulent flame speed.

Thank you.