Combustion in Air Breathing Aero Engines
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Lecture – 56
Flame Stabilization & Blow off- IV

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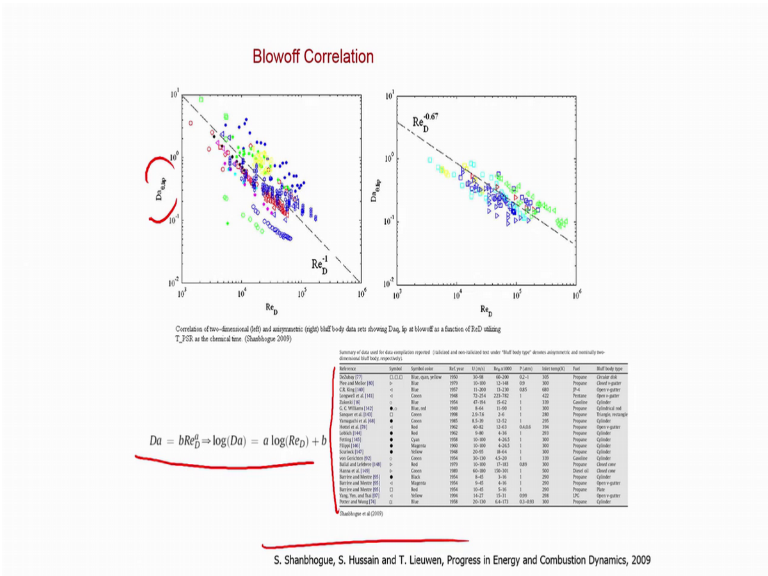

Welcome back. So, we talked about some past works about and the different than the part the researchers of very important contributions by different researchers of very high stature who had different kind of views on blow off. So, there is not a uniform and a consensus view on flame blow off, but anyways we can compile in this paper in this review paper, this author Shanbhogue, Hussain and Lieuwen, they compiled the data from different sources as you see at this Dubey, Plea, Millar, Zhukovskiy, Williams, Hotell, Yamaguchi and all their measurements have been just compiled. And they try to find a fitting correlation between Reynolds number and Damkohler number.

So, Reynolds number is essentially as you have seen that its essentially the ratio of the inertia forces to the viscous forces, but this is a normal diameter based Reynolds number this is not to be confused with the turbulent Reynolds number. And this is also the Damkohler number. So, you see that when you have when you compile all the data it appears though its like a lot of scatter in a log-log plot it appears that they follow kind of this Reynolds number is equal to a times log of Reynolds number plus b. But if I have a scaling have has a kind of a power law scaling of between Reynolds number and Damkohler number. So, this is the data that they that has been compiled.

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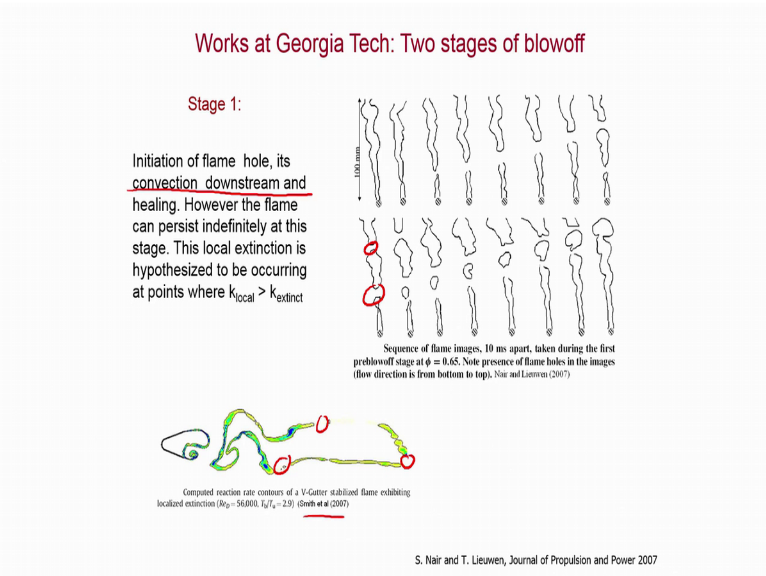

So, recent works I mean in the sense that from about 10 years ago by in the appearing this paper appearing general propulsion and power at Georgia from Georgia tech. They observed that they use this MIE scattering images only that is the put olive oil in the in the olive oil droplets in the flow and the shine laser and allow this olive oil droplets to scatter the lights. And the boundary where this olive oil evaporates can be considered as a flame boundary and obviously, it is a roughly which many consider as a flame boundary and they found using that technique they found out what was the how does the flame structure look or the flame boundaries look when the blow off is approached.

So, they found that as blow off is approach there is an initiation of the flame hole and it is convicting downstream or it can heal also in some cases and that is a flame hole can close. And however, it was they also said that this flame hole that is a formation of an unbound reactant out of formation of a region of this bond product essentially it is a formation of an unbound reactant which is called a flame hole which is surrounded by the flame boundary or the flame front can be can also persist. And the flame hole this say it was created because it is at those at those points there was the local extinction strain rate at those points or the local stretch rates at those points exceeded the corresponding extinction strain rates.

In extinction strain rate is a property that is measured from one or post premixed flame and it can be considered roughly as a property of a pre mixed flame like it is not as rigorous as a property as the laminar flame with that still it is when we consider as a measure for extinction. So, in this reaction also in this simulation also they found that this formation of this, this gaps in the flames of this, this flame holes that is these parts contain this unbound reactants and here these are the flame holes that are being that are being formed.

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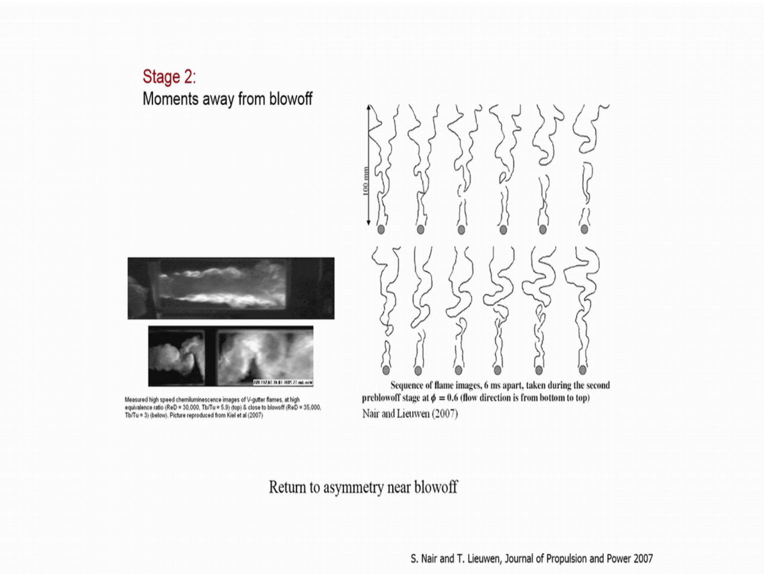

And this was the stage one where this is essentially characterized by initiation of a flame hole. Now, the stage two is that there just before blow off that, but you see even the flame hole is created the flame is still a symmetric in shape. It just not does not has a very large change in like it does not have a change in large scale structures. But they said as that as blow off is approached the and right moments before blow off then the flame essentially loses its symmetry and it takes a more sinus shape which is overall the large scale structure of the flame getting started.

And they said that this is because now the flame blow off is approached, there is a lot of extinction and maybe that is causing the flame of the flow to undergo a transition from this convective instability to like to absolute instability that is from the symmetric vortex shedding as we have seen to their symmetric vortex shading. But of course, we do not know why this is happening, and we do not know the exact mechanism also by which the flames the extinction along the flame structure is happening. So, also this cannot be considered as exact a flame shape or the flame contours because these are only the boundaries where the olive oils are being evaporated.

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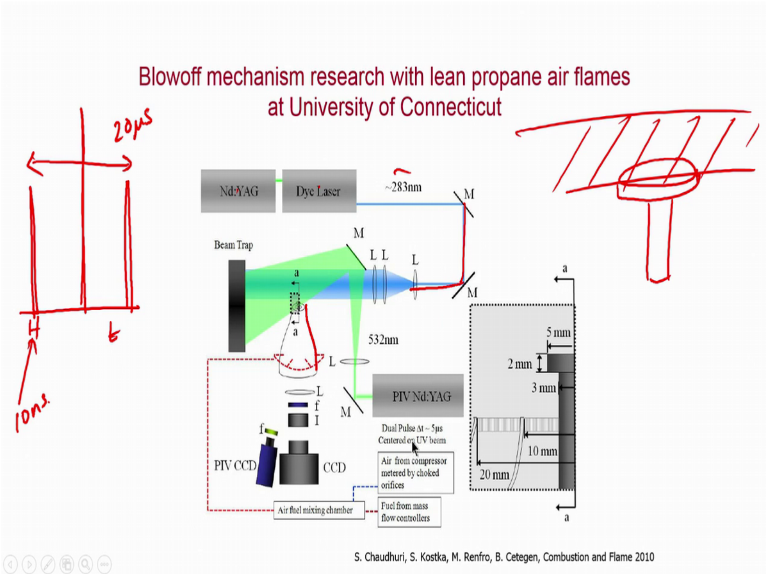

So, if there is a product region high temperature product region, but no flame then also we will see that the olive oils is evaporating and creating a boundary like this. So, it is not exactly representative of flames. So, we need to have better diagnostic techniques like we need to do some laser induced fluorescence. So, with which we can better quantify or better pinpoint that this is the point where my flame is this is the point where there is no flame. So, this is why we did this combined particle image velocimetry and laser induced fluorescence to understand the flame glow off mechanism.

So, this is done in a very small laboratory scale experiment where we essentially have this have this conical nozzle. And at the end of the conical nozzle, you have this bluff body you see this is a cylindrical bluff body which is placed which is in this shape and we have this kind of honeycombs etcetera. And this is essentially the bluff body looks like this. So, of course, it is a fundamental work, but still this kind of fundamental works can be very important to our solving the basic physics that is involved. And then of course, you send pre mixed fuel air mixture into this nozzle after that fuel and air are mixed into a mixing chamber.

And then you basically pass your laser sheet through the mid plane of this of this of this bluff body and you ensure. So, this Nd YAG laser essentially forms this dye laser which mass is and the output of that passes through this doubling crystal to produce this 283 nanometer wavelength and by reflecting into meters and creating a sheet of like one basically gets this laser sheet which forms is this PLIF laser sheet. Now, this PLIF laser sheet is exhilarated exactly in the same location as there are the PIV laser sheet because we want to visualize the PIV and the PLIF or the we want to visualize the flow field and the OH field simultaneously. So, these two are located in the same locations.

And temporarily this laser sheet these lasers typically last for about 10 nanoseconds and this runs at a frequency of about 10 hertz. So, you have to ensure that the PLIF laser sheet temporal is located exactly midway between this PIV laser sheets, these two PIV laser sheets which our at a see at a difference of like 20 microseconds. So, now, if this is the one PIV laser sheet, and this is one PIV laser sheet, so and the difference between them is about say 20 microseconds. So, the PLIF laser sheet is located here it is at it in midway between these two. So, this is in time and each of the width of these things is about 10 nanoseconds.

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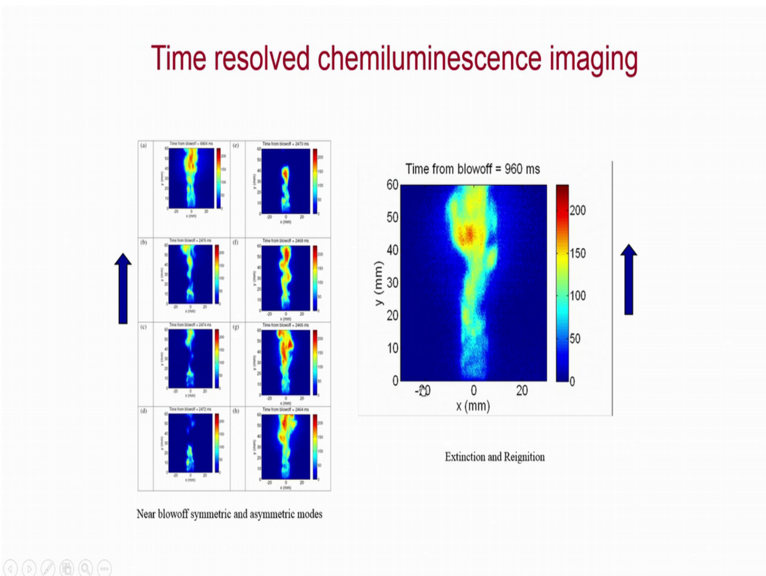

So, this is the thing how it looks like and. So, what does happen before blow off. Now before we do the PIV, PLIF if it is we can do this chemiluminescence imaging also. Now, chemiluminescence is essentially this visual this visible light emission that we see from the flame. Now, one thing you have to know that this chemiluminescence images from radicals which are chemically activated; and as a result of that you cannot these are not in thermal equilibrium and from this chemiluminescence you cannot really measure the radical concentration because there is no equilibrium among them these are chemically activated. So, you really cannot obtain the steady or you cannot really obtain the ground state population of this of the radicals which are emitting this light. So, you cannot do that, but you can do that in the PLIF.

So, from chemiluminescence, what you can get is essentially a qualitative idea of heat release because people have shown that researchers have shown that that if you that the chemiluminescence signal is essentially proportional to the heat release rate for pre mixed flames. So, this quantity qualitative tells us the heat releases. Another problem of chemiluminescence is that it is line of sight integrated. So, PLIF you can get it in one plane, PIV you can get in one plane, whereas chemiluminescence the line of sight integrated, but still you can get a qualitatively organize idea.

So, what you see is that that what do you have near blow off that if you this is a about taken at about 500 hertz this was this work was done in late 2009 early 2010l, so and mid 2009 -2010, so or from 2008 to 2010 something like that. So, you see that here this flame which is about 6.8 seconds before blow off it was stable here, but then it loses, then it then you see that this sort of flame holes forming, large flame holes forming that is this there is no chemiluminescence, there is no heat release. And then you see that the flame becomes essentially sinus in structure. You see this is a sinus mode kind of development here and then it again reestablishes. So, this thing can happen just little bit before blow off. By the way here the flow is going from left to from bottom to up in each of these images and this is the flame holder is something like this. So, this is the flame holder is stabilized here and the flame is stabilized at t shape flame holder or in a cylindrical t essentially and the flame is stabilized just downstream of that. So, here you see that just before blow off we can have this kind of a sequence where you see that large flame holes are forming and then the flame goes into this recirculation zone and then it goes and to blow off again.

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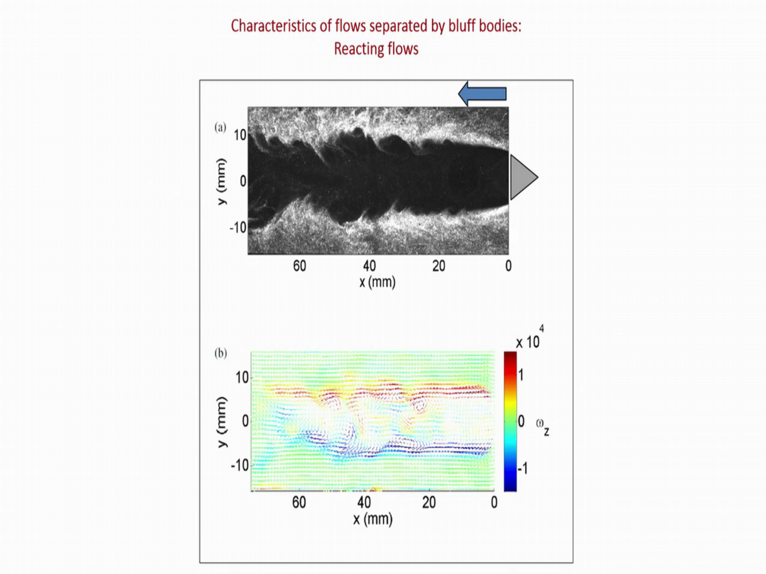

Now, one thing to note is that in that regard that if you just go back to this previous structure of the recirculation zone say in this one, so what happens here in a recirculation zone I mean irrespective of the bluff body. So, the flame is stabilized. So, the this is a this is the you have a flame here right. So, the flame is essentially stabilized let me use a different color, let us use lets use blue for premix flames. So, the flame is essentially stabilized like this.

So, this is fresh mixture which is entraining into this flame. And as soon as it enters into the flame, it recirculates of course, but it becomes bond products. So, outside you have fresh mixtures inside you have bond products. So, as soon as it enters into the flame in this recirculation zone what is recirculating, what is recirculating like this and what is recirculating like this is bond products. So, for a stable flame which is the where there is no extinction along this along the flames along these shear layers as you see the shear layers are formed here which is characterized by a large values of w omega z . So, the flame is stabilized around shear layers and inside the recirculation zone you only get burn products because the flame is continuous, anything that goes through the recirculation zone must be burn products.

But in such cases you see that for example, now you see this recirculation zone contains some reactions. So, the recirculation zone can contain only reactions can contain reactions, can contain intermediates or it can release heat because it is you are saying chemiluminescence from there. It can be see it only when you have flames extinguish along the shear layers either sideways or downstream when the flame is extinguished along the shear layers only the fresh mixture can entrained through the shear layers and pass through the shear layer sun burnt and go into the recirculation zone. And due to the favorable timescales there can react to produce this heat release and which produces this chemiluminescence.

So, then the question is this is what is happening before blow off that is the flame is extinguished in and along the shear layers. So, then, but of course, chemiluminescence is a qualitative technique, it does not give you the full idea. So, what we need to do is that we need to use this high speed high fidelity techniques like PIV PLIF to basically understand what is going on.

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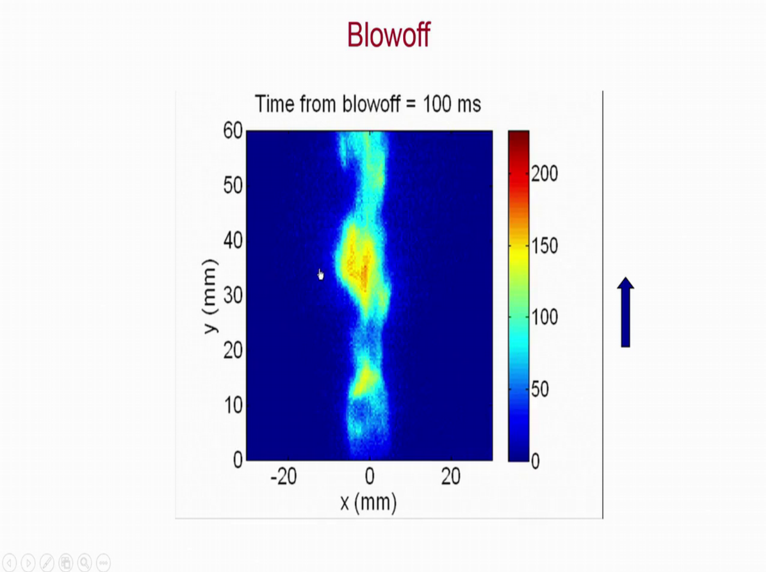

Now, before that we also get this, this is the final blow off event. Do you see recirculation zone burn in the final blow off event also, yes, it is indeed the case. You see that under normal circumstances here you do not see too much of reactions here right because you have had a flame there, but now as soon as the reactions become weak you see the flame is there is no flame here and essentially the product that this goes in it can go in through here. And by the time it enters it can it can burn inside the recirculation zone and that can lead to essentially flame blow off. And this arrow show shape the direction of the blow off from top bottom to top.

So, though you see the flame blow off is characterized with which we observed for the first time that the flame blow off is characterized by this event called recirculation zone burn that is under recirculation zone under normal circumstances contained only hot products. But just before blow off it contains it emits thus chemiluminescence which tells us that the flame must have extinguished along the shear layers and as a result of that it is the fresh mixtures can pass through the shear layers unbound. And by the time it gets into the recirculation zone, it still remains unburnt and but now due to favorable timescales there it is recirculation zone it can burn and it can produce this emission and which can also produce this chemiluminescence which tells us that there is reaction going inside the recirculation zone.

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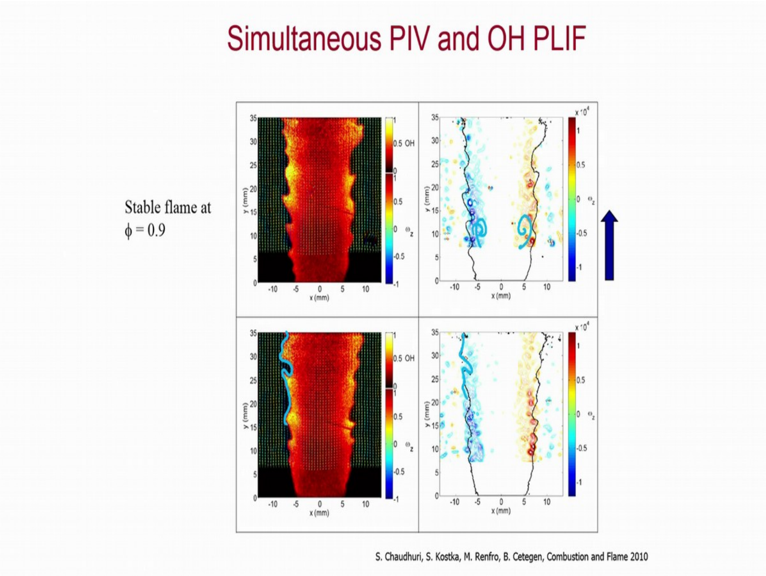

So, is it really the case, and the PLIF, PIV also tells is this. And the second thing is then why does the flame extinguish along the shear layers approach as blow off his approach what causes the flame to extinguish along the shear layers there is a question. So, for that we did PIV and PLIF simultaneously at two cases, one for stable flame which is far from blow off and the other is for the other is for the unstable flame which is more near which is which is more close to blow off. So, what happens for the stable frame you see that yes this flame is there and you see wrinkles because you have Kelvin Helmholtz vortices. These are this Kelvin Helmholtz vortices. This is the positive vortices, negative vorticity because they are in this way it is rolling like this; in this way it is rolling like this. And if we extract the flame edges you see this very sharp flame a boundary is formed and if we extract this flame edges by this large gradients maximum gradient of OH by mathematical by algorithms look like canny edge direction etcetera, we see that the flame edge essentially envelops this Kelvin Helmholtz vortices.

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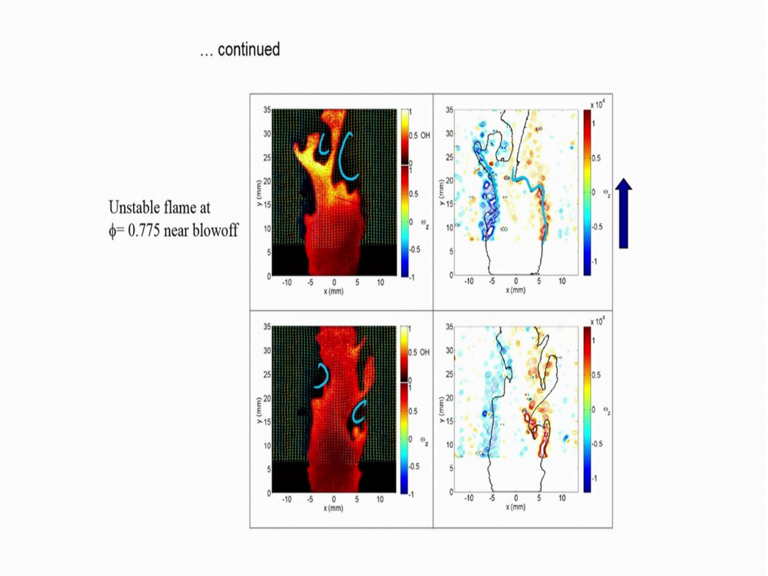

Kelvin Helmholtz vortices are inside the flame edge. Now, what happens as blow off is approached, you see this large regions of flame holes are formed. Flame hole is formed, flame hole is formed.

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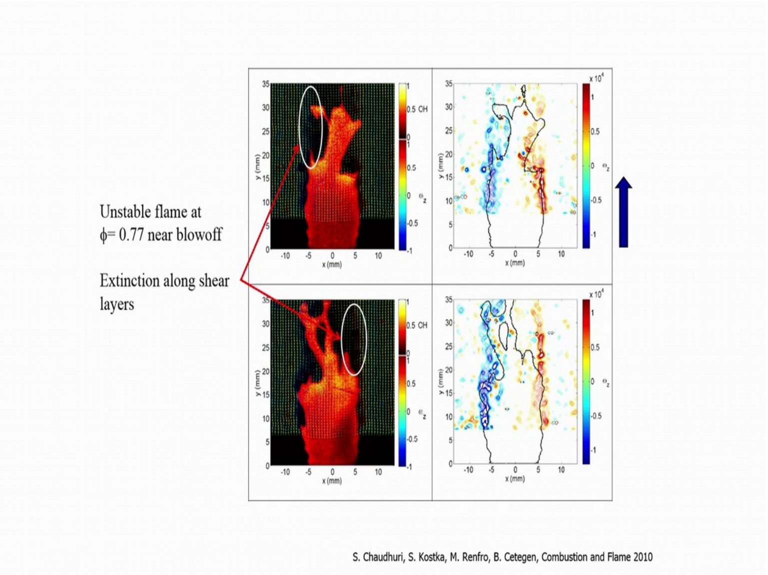

And more interestingly you see that this, now this flame edge is essentially overlapping this Kelvin Helmholtz vortices. Of course, the flame is much more distorted shape, but it is overlapping this Kelvin Helmholtz vortices. And of course, you see this large flame holes being formed and this large regions of extinction being formed and once again you invariably you see this flame edge now overlapping this Kelvin Helmholtz vortices. Now if we look at this these are of course one images you cannot comment on something, but to be are to be a mechanism when you just see one image you have to do get the statistics.

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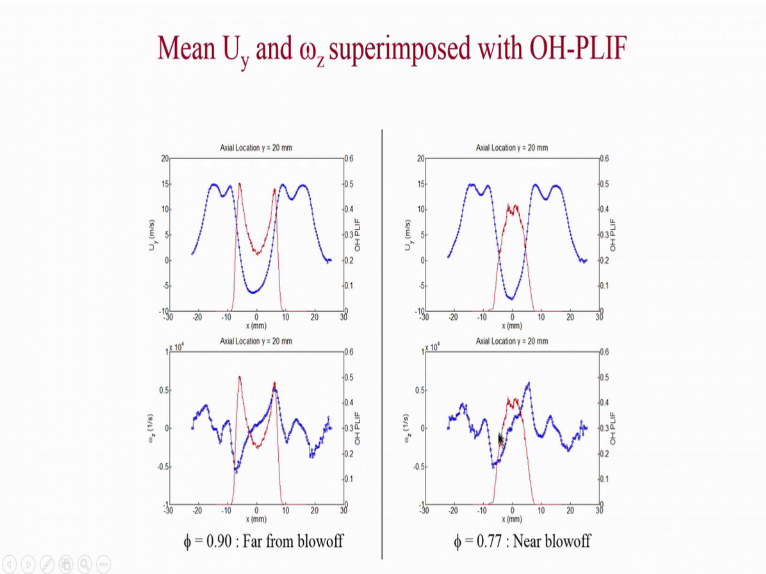

So, if you get the statistics, you see that this is far from blow off, this is near blow off readies for o h on the right hand axis this blue is for velocity and the left hand axis. So, you see that this oh is a kind of a bimodal peak like this you see and this OH peak essentially corresponds to the maximum vorticity that is this says that statistically also the maximum oh is located inside this shear layers. Now as blow off is approached you see this bimodal distribution in spatial distribution of OH it is lost and you get a single like a central distribution. So, this says that you cannot statistically you cannot find maximum OH along the shear layers, you can now statistically you find maximum oh inside the recirculation zone like this.

So, you see that the vorticity structure has not changed on average has not changed too much, but the OH structure has changed and there is no OH on average along the shear layers. So, that shows that there is no OH which is a marker of the reactive which is essentially a reactive intermediate and a marker of the most reaction most important to combustion chain most important elementary reaction that is a chain termination chain branching reaction H plus O 2 going to OH plus O. So that reaction is that thing is not happening along the shear layers anymore. So, the flame on statistically is settled inside that is circulation zone and you do not have a flame along the shear layers so that means, there the flame is extinguished along the shear layer or it has gone inside.

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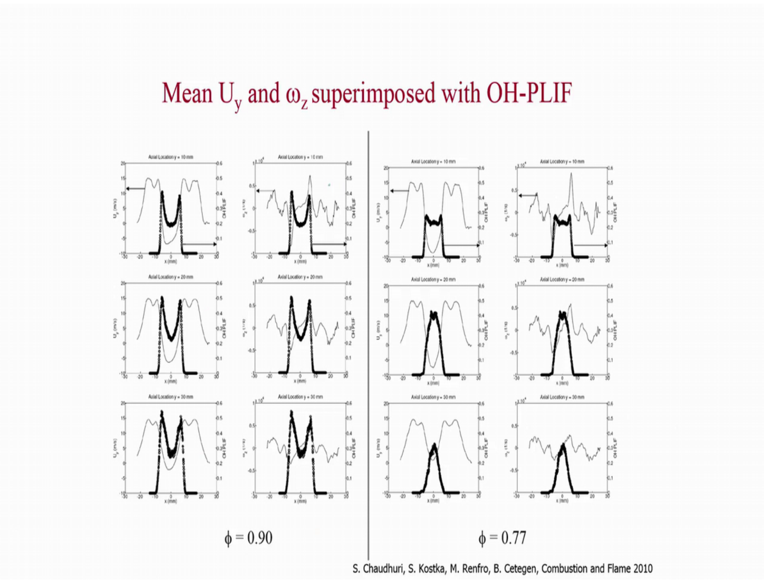

So, you see this consistently here also that at along all locations 10 millimeters, 20 millimeters, 30 millimeters for all these things if you look at this you have by mortal distribution of OH at equivalence ratio 0.9 near blow off. At 0.77 you see this unimodal distribution of OH and this flame has which is the flame is extinguishing along the shear layers. Same thing you can get from conditional PDFs also.

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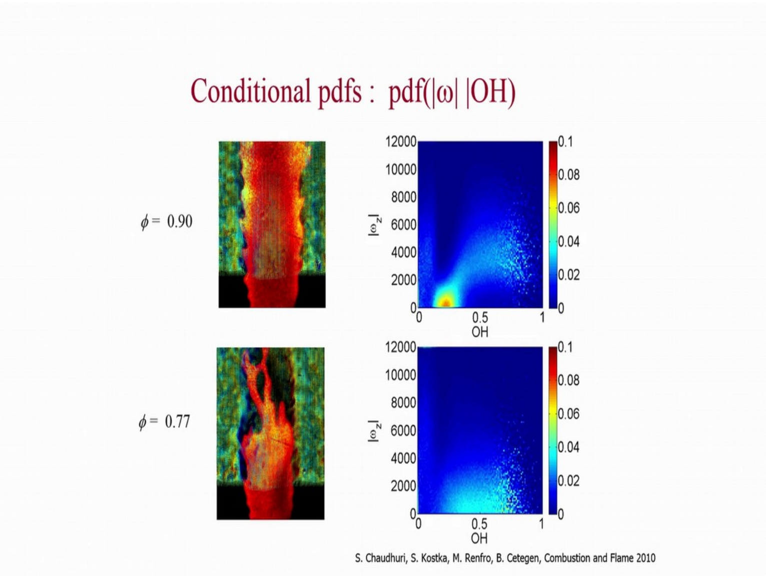

So, then the question is that what causes the flame to extinguish along the shear layers. For that we need to basically go back into the basics of premixed flame extinction by heat loss and by stretch.

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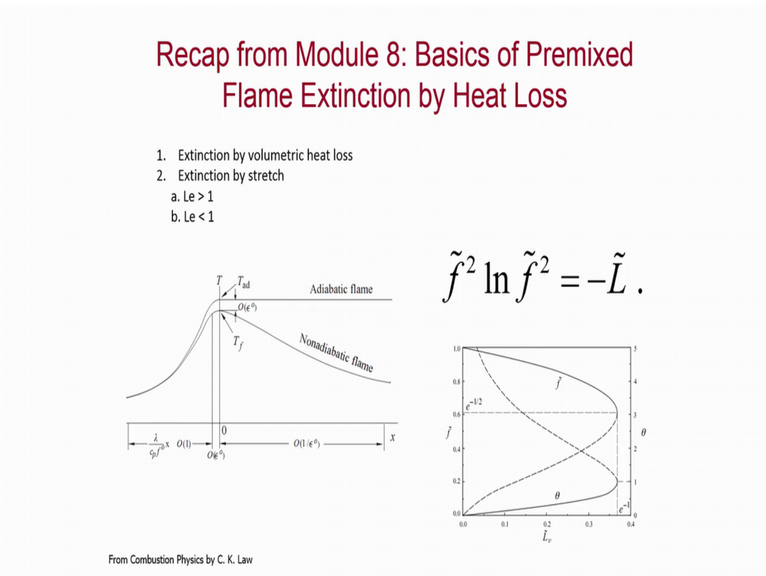

And if you remember that for if you have extinction along the if you have heat loss for a premix flame and this heat loss can be caused by a Lewis number greater than one premix flame when it is under positive stretch. You have this kind of response of course, this is for a 1-D flame it is a 1-D analysis, but you saw that that this was the f f tilde is essentially the your normalized bonding flux. So, when the heat loss is at this point about this about this value inverse then you have a turning point in f which corresponds to extinction.

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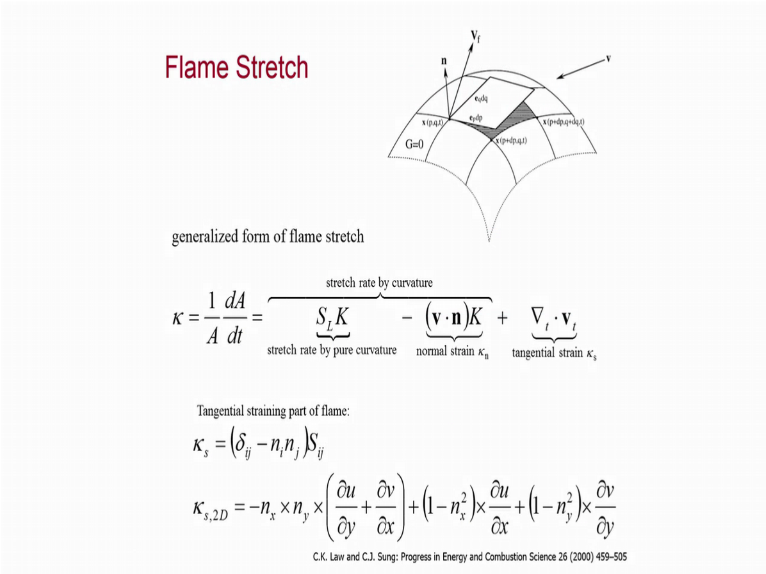

So, the heat loss at this state this you have e to the minus 1 is sufficient to cause the flame extinction. You also discuss the concept of stretch.

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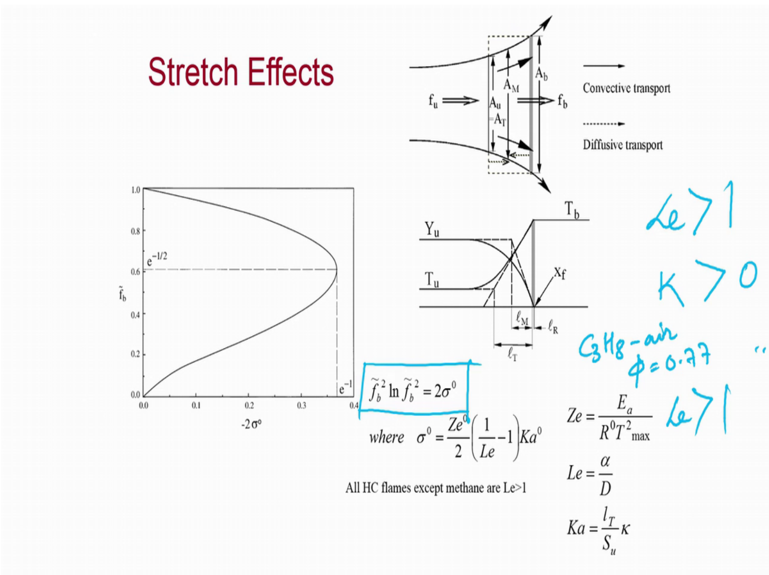

That if you have stretch also the question is that the point is that you have exactly the same analysis same result as you have by heat loss, because what stretch causes for a

Lewis number greater than 1. If this stretch kappa is greater than 0 then you have heat loss and you have this kind of an extinction behavior. And our flame is essentially a propane inner flame at phi equal to 0.77 near blow off and that has Lewis number greater than 1, sorry 0.77 near blow off and that has a Lewis number greater than 1.

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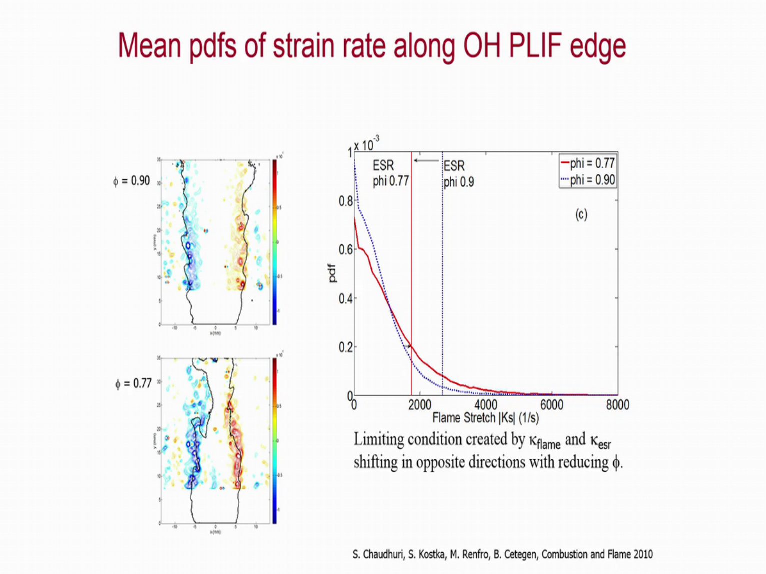

So, if it is undergoing stretch it can if positive stretch it can exceed it can undergo it can be blown off, it can extinguish locally and that can lead to blow off. So, now, we look into the PDFs of strain rate along the OH PLIF edge which can be obtained by this formula that is essentially it is a projection of thus of the strain rates along the flame tangent. If you do that you find that and find the PDF of course, because this is a turbulent flame one you cannot have one value of stretch along the inter flame surface. So, you basically generate a probability distribution for a density function.

So, the PDF say is that that at equivalence ratio point nine you have this is the PDF. You have this is the as this is the PDF. At equivalence ratio 0.77 your stretch PDF is like this that means, as blow off is approached is the stretch PDF or the flame stretch increases for most part of the flame. On the other hand, the extension strain rate that is the maximum strain rate laminar opposes premix flame can sustain which is a measure of the strain holding capacity of a flame before it undergoes extinction that reduces. So, that reduces from this value from greater from near about 2500 to less than 2000. Whereas this actual strains move increase. So, this causes an opposing movement on one hand your strain level of the 0.77 flame is increasing that is it is undergoing more straining, but its strain carrying capacity or its strain holding capacity is reduced because its extension strain it is reduced. As a result what will happen the flame will extinguish.

So, if strain has exceeded its actual strain as exceeded, but its limiting strain has that the threshold strain that it can accept that is reduced, so it extinguishes. So, essentially it is the shear layer of flame extinction along the shear layers that allows this flame to be the flame the shear layers to be free of the flame. And when the flame when the shear layers are free of the flame, the fresh mixture can entrain through the shear layers, and it can go into the recirculation zone unbound. And it can react inside there is a recirculation zone due to favorable timescale and that is why we get high amount of chemiluminescence and large heat released from the recirculation zone just prior to blow off. So, this is the thing.

So, the one question we did not answer is that why does this shifting happen why does the PDF shift into the right direction that is why does the flame get more strained as it approaches blow off there is can be understood from here you see at equivalent ratio point nine this flame was enveloping this Kelvin Helmholtz vortices. So, the flame cone angle like this was large because its average flame speed is large its turbulent flame, so it is also large. But as the flame speed reduces to balance with the local normal velocity the flame angle reduces and you see the flame is much more columnar now.

Now, as the flame from a conical flame becomes a more columnar flame instead of overlapping these Kelvin Helmholtz vortices, now it gets instead of, so this was essentially enveloping the Kelvin Helmholtz vortices. So, while the flame was a conical flame the flame was enveloping the Kelvin Helmholtz vortices, but as the equivalence ratio is reducing from a conical flame the flame becomes a columnar flame. So, that because its flames it has reduced and to balance with the local flow field for the cone angle reduces it can be easily shown you can you should show it actually that how does the flame cone angle reduce and weed becomes more columnar as the flame speed is reduced. But what the fact of the matter is that that as the flame cone angle reduces that the flame becomes more columnar instead of enveloping this Kelvin Helmholtz vortices, the flame now essentially overlaps with this Kelvin Helmholtz vortices.

And this Kelvin Helmholtz vortices can impart strong strain on the flame surface and that essentially caused the PDF of this strain on the stretch rate on the flame surface to increase in the right hand side to increase and to proceed to as the right hand side and of course, the extinction strain is reducing. So, now you see here at 0.9 only, it is very small this percentage this amount of the flame exceeded the extinction stretch rate. So, there is very small extinction, but now you see that whole of this part of the flame is now exceeded the extinctions strain rate. So, as a result of course, it causes the flame to extinguish, and there is the shear layer essentially the flames extinguish along the shear layer because that is what the maximum strain is. And now the fresh mixture can pass through the shear layers and can get into the recirculation zone and can react there due to favorable time scales.

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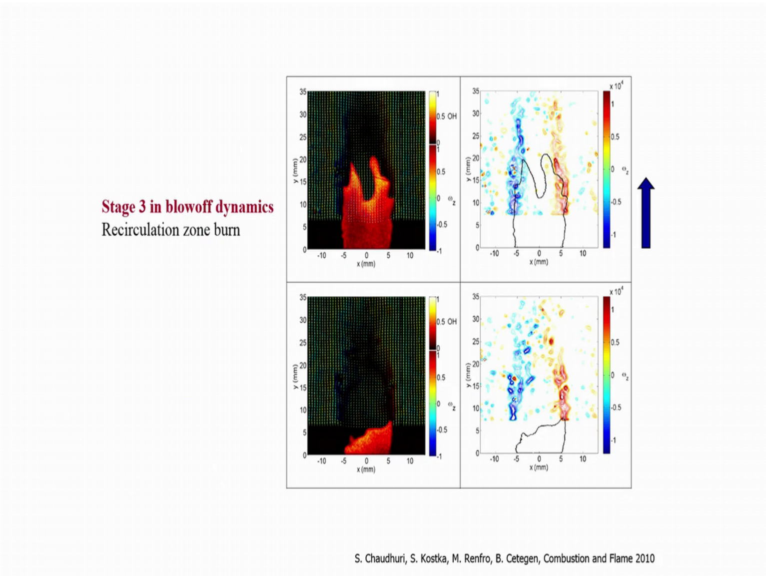

So, we see the stage three in blow off dynamics and which also is characterized with this recirculation zone burn which we clearly see that from the PLIF images also that you see this you know this maximum OH the super equilibrium OH happening along the recirculation zones inside the recirculation zone. And this recirculation zone burn that is the strong PLIF signal from the recirculation zone cannot be obtained in a normal circumstances. So, this is the higher hallmark of this work where we essentially formulated the how the blow off is essentially happens into cause the which connects the initial inception of this flame holes to the final blow off event.

So, in the next class, so this was done in a small laboratory experiment. In the next class, we will see that we will basically do these experiments in a real engine like configuration and we will see if this in a different Reynolds number higher Reynolds number different geometry whether this mechanism still holds or not.

So, till then good bye.