Combustion in Air Breathing Aero Engines
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Lecture - 57
Flame Stabilization and Blow off-V

So welcome back, so in the last class we have seen how using this advanced laser based diagnostics and high speed imaging; we can find out how exactly the blowoff happens. So, what causes the final blowoff event that is we found that it is essentially this extinction of the flame along the shear layers which is caused by increased stretch experienced by the flame; because it is now overlapping with the Kelvin Helmholtz vortices due to reduced equivalence ratio. So, this increased stretch is essentially causing the flame to extinguish on the shear layers and once the flame extinguishes along the shear layers this fresh mixture can pass through the shear layers unburned and can come inside the recirculation zone and then due to favorable timescales there, it can ignite and it can cause chemiluminescence.

So, but this was done in a very small setup; it is like an unconfined environment in a small flow rate of about 10 meters per second on a cylindrical disk type flame holder. Of course none of this happens in a real engine; it is only of course, they use a bluff body but this was a very an idealized situation. So, then it was a decided that does this really hold in a prototypical afterburner; so, this elaborate rig.

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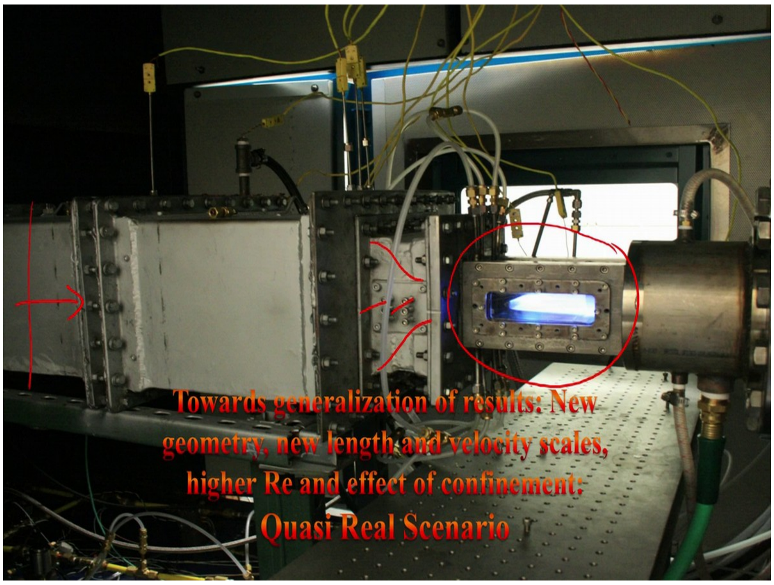

This at University of Connecticut, which essentially simulates the afterburner; this part essentially simulates the afterburner of a gas turbine engine. This was constructed and this is mainly done from projects, from NSF and Pratt and Whitney and it was mainly constructed by my colleague Steven Turtle. So, this part which is not shown here; this previous part essentially just before this is essentially consists of a main burner, which simulates the main burner of the gas turbine engine, but we are not investigating that.

So, what we are doing is that we are allowing the vitiated flow from the main engine to come and we are allowing it to pass through the heat exchanger which simulates this turbine. And then by process with a settling section and then this is essentially a nozzle, inside this is a nozzle and we are through fuel bars essentially on the other side; we are injecting the fuel into this vitiated flow. And we did unvitiated experiments also and then this is our test section, so and here we have the essentially you see this is like a v type of a triangular flame holder and you see this flame.

So, these was very large scale experiment and very large flow rates and large fuel flow rates and this is of the; it is exactly almost simulates one sector of this after burner of a F-22 Raptor. And so then we try to understand whether the blowoff mechanism that we have discovered, whether that holds in this new geometry. Because that was a cylindrical geometry, this is a rectangular geometry; new length and velocity scales much bigger length and velocity scales, much higher Reynolds number and we have effect of confinement and this is almost a Quasi Real Scenario.

This is almost like a; it is almost represents like the sector of a F-22 Raptor; so, does it hold here?

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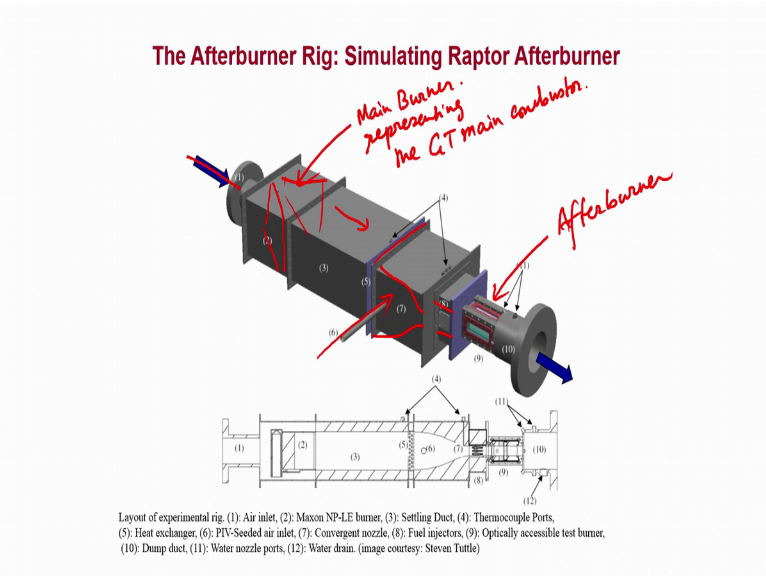

So this is the schematic of that rig at University of Connecticut, so the flow comes in here. Here you have essentially the pre burner; which burns the fuel and it creates officiated flow. Then it passes to the settling section which is insulated, then we have this heat exchanger. And then we here we send in with the PIV the seeds and then this process which is nozzle; sorry this was a nozzle and this is the settling section, where we inject the fuel.

So, this is not the nozzle actually; this was the nozzle and then we have this fuel injectors and we have this the optically accessible; test burner or the afterburner. And then this is essentially the afterburner and this is the main burner or representing the gas turbine main combustor and then we can have the flame and study the flame blowoff mechanism here.

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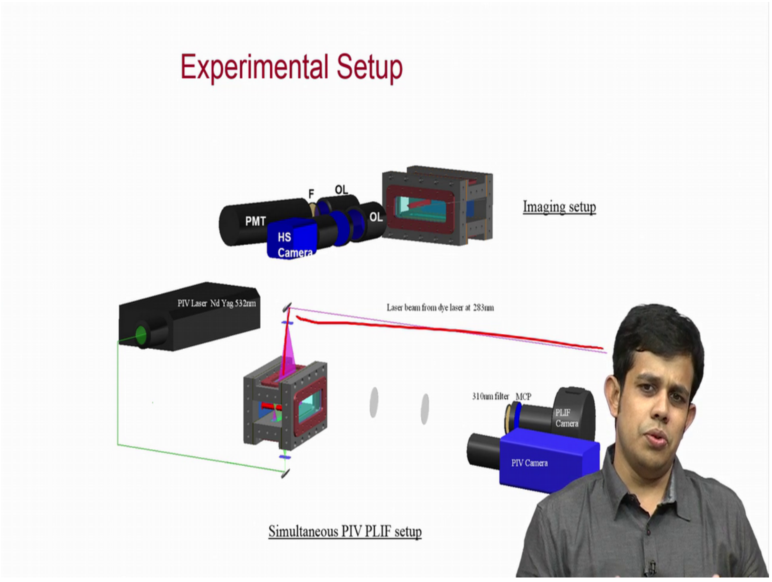

And the experimental setup here also that you see we have a PMT to monitor the overall emission and then we have this high speed camera with an intensifier and focused into this test section. And then we have this test section, where we have this PIV laser beam going in for flow visualization where we have this and we also have this PLIF camera; so that we want to and we have this PLIF laser beam going in at the same place, at the same time almost at the same time. So, this PIV on the PLIF camera are basically visualized in the same region and it is of course, at an angle; so, we do have to do some image correction to take care of this angle between these two things.

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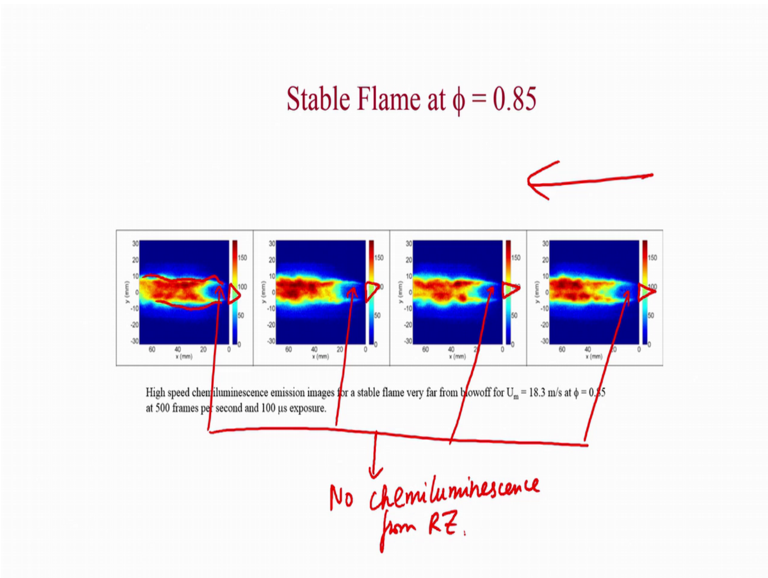

So, how does this stable flame look like; so, the flow force from left to right. So, in stable flame you see that yes this is what it looks like that; you see that this recirculation zone the forces of the bluff body is here and all these images, this flame holder is present here. You see the flame is of course, is emerges from this shear layers and there is no chemiluminescence from the recirculation zone. This is the characteristic of a stable flame, no chemiluminescence from the recirculation zone.

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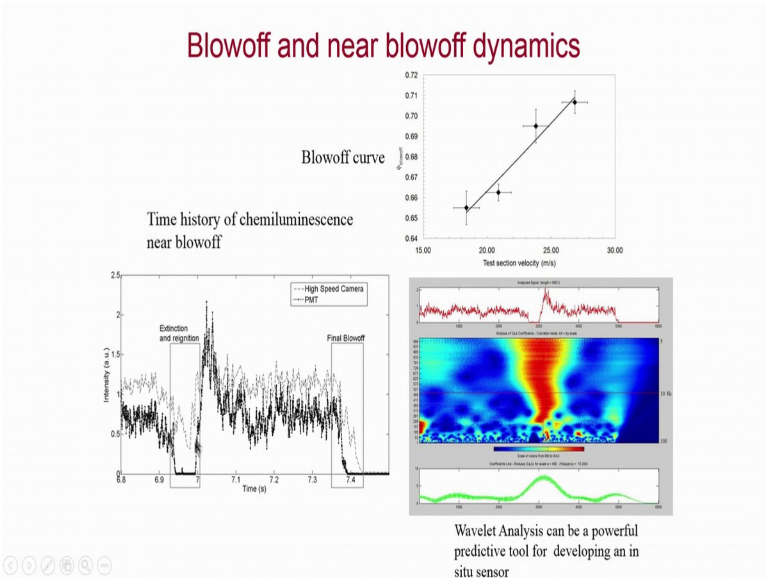

And of course, when you have blowoff dynamics; you see near blowoff, this is a blowoff curve, phi blowoff as a functional state test section velocity and you see that there is a near blowoff fields have this kind of a pattern, that you have this extinction recognition images. So, how does it look?

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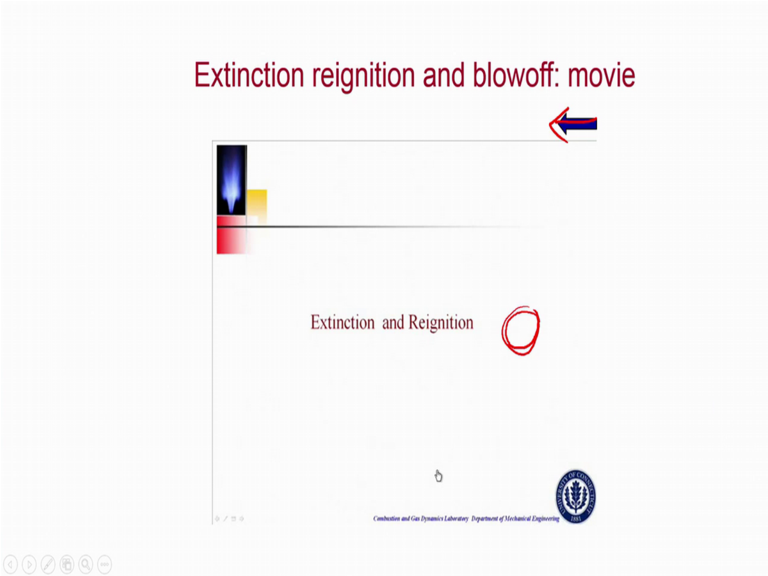

As blowoff happens, the flow is from left to right; from right to left. From this two this direction, you see that again or let me just show it or the flow is from right to left; the main flow goes in this direction, so this is the extinction. So first we will show the extinction and reignition event prior to blowoff and then exactly at blowoff; how this flame goes actually.

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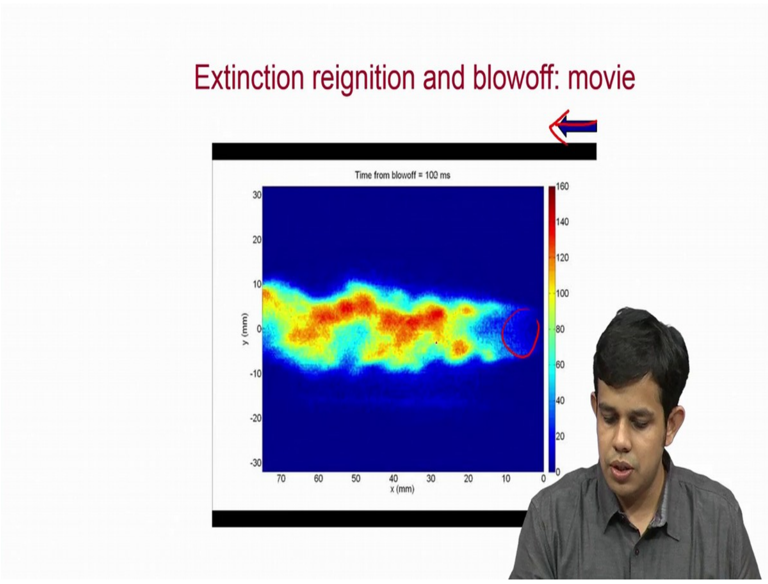

So, you see that this extinction reignition even also this flame essentially gets confined into this recirculation zone. And during the final blowoff event, you see that this before the blowoff event this contains no recirculation zone. But just prior to the blowoff event, you see that this flame essentially gets confined into this recirculation zone and then it goes off.

So, this is a very beautiful the sequence that happens just preceding blowoff and just by looking at the; what I want to show stained is that just by looking into the chemiluminescence images, if you know how the flow structure essentially looks like and how the flame should behave in normal situations, then by understanding the deviation from this normality; from this normal situations you can try to understand figure out a mechanism and then do further detailed testing to; basically try to see whether that hypothesis from this high speed imaging is true or not. So, that is what we have done, so it seems that what we have shown in the small scale set up holds in this large scale setup also. So, the just prior to extinction we have this extinction just prior to the final blowoff even we have this extinction reignition event, where the flame essentially goes into the recirculation zone. But somehow it is able to manage and basically reignite and become like a normal flame for some extent.

Though it is characterized by more unsteadiness than for a normal flame, but eventually it goes off where it circumstance too much of extinction on the shear layers and when the flame essentially would be detracts into the recirculation zone and then it finally, blows off.

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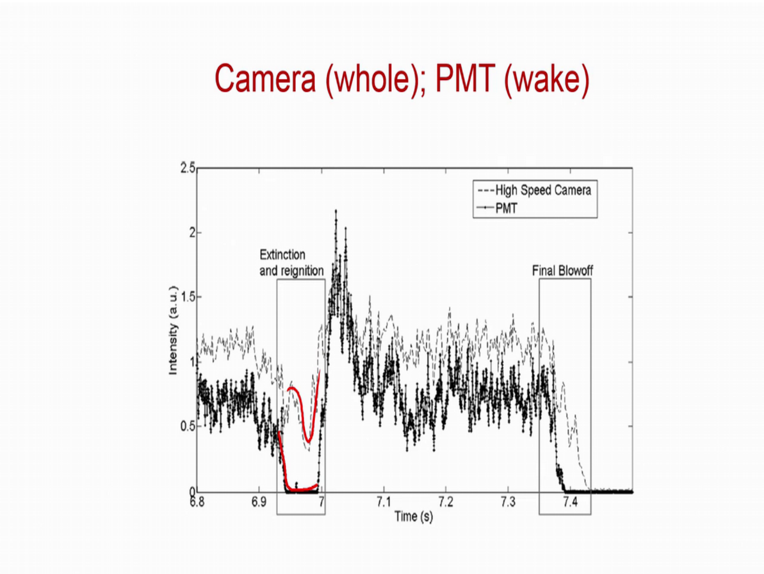

So, this is what it looks like in a time series; where we have the full intensity. You see this when we have this extinction recognition then the essentially this; the PMT almost sees nothing which is focused downstream. But as the camera captures some signal due to this extinction, due to the emission of that is of the chemiluminescence from the recirculation zone.

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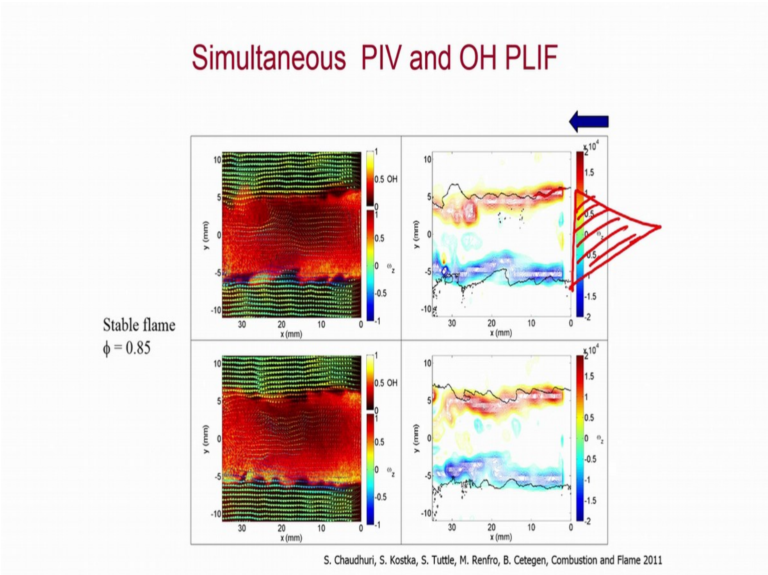

So, what does the PIV PLIF say; so, once again if we do the PIV; PLIF at for a stable flame at equivalence ratio 0.85 far from blowoff, we see that yes once again and if you extract the flame edges; you see this flame edge essentially enveloping this Kelvin Helmholtz vortices; flow is from right to left. And you have the flame holder is essentially like this; downstream of the just upstream of this thing. So, you see that the flame is from right to left alright and we see that the flame edge is essentially enveloping these Kelvin Helmholtz vortices.

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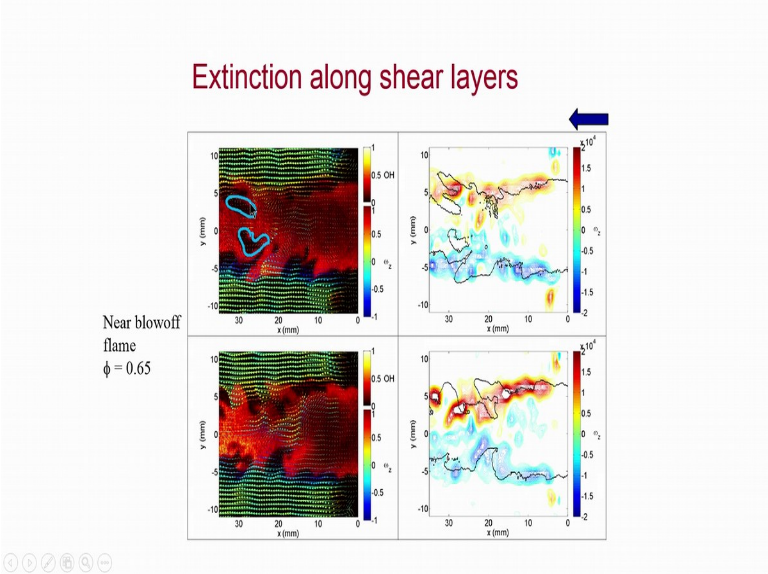

But as is extinction is approaching, you see once again this kind of flame hole is forming. But this may not be exactly (Refer Time: 09:59) because these are 2Ds thing; so it can be like a flame island also, but anyways; this kind of flame gaps in the flame control is forming. And once again you see that now the flame is; it has once again retracted into this shear layers and now it is overlapping with the Kelvin Helmholtz vortices; so, it is possible that it is experiencing strong stretch also.

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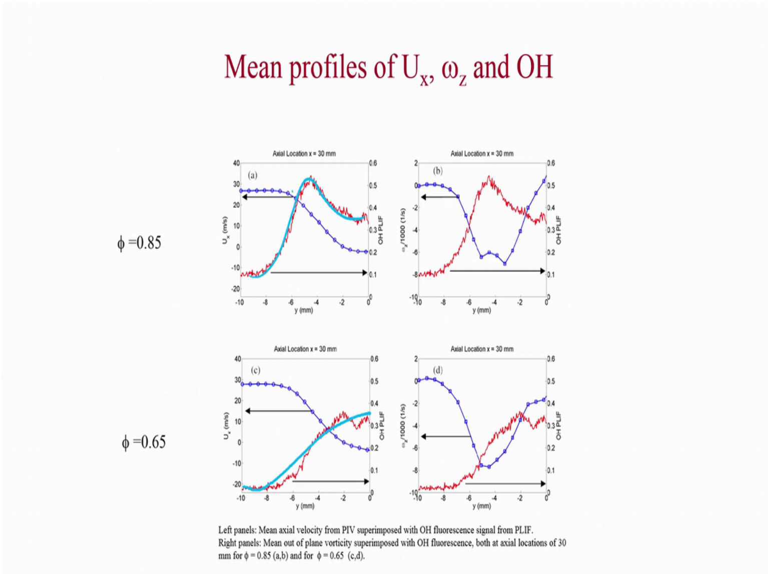

So you see that once again here we see that this is the; if you look into only half, this is the bimodal OH that we are seeing. But once a flame approaches blowoff, it becomes an unimodel OH and it is; so, once the we have this is essentially the shear layer location this what it is is. So, this is essentially the shear layers; this part is the shear layer, so far from blowoff; we see that maximum OH emerges from the shear layer. Near blowoff we see maximum OH emerges from the recirculation zone, far into the shear layers. So, this is the most important thing; so, which means that here the flame is extinguished along the shear layers or it has essentially retracted into the recirculation zone.

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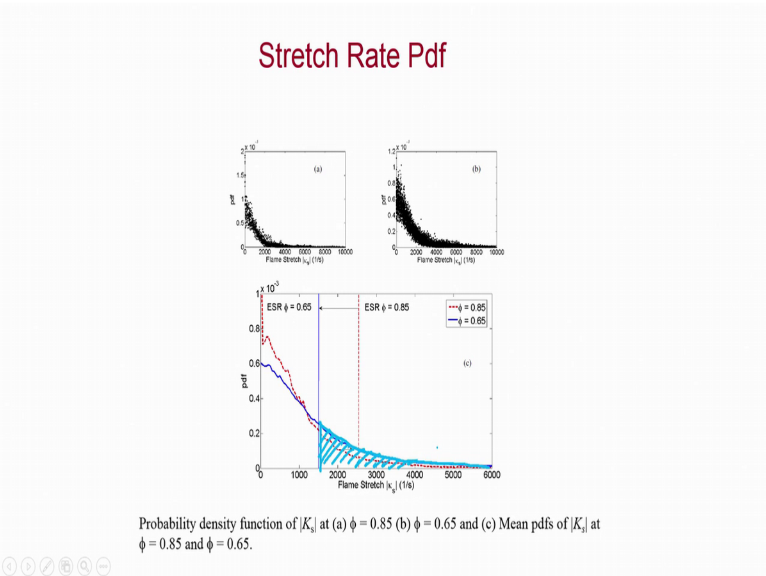

In joint Pdf also say that I will not go into this and if you obtain the stretch rates, so we find that; once again we see that this is the pdf far from blowoff and this is the pdf near blowoff. As blowoff is approached this pdf shift towards right; so, it experiences more and more straining; it experiences more stretching, the flame experiences more stretching actually as blowoff is approached.

Once again of course, the extinction stress stretch rates shifts in the opposite direction. So, now you see that this full part is experiencing stretch rates which exceed the corresponding extinction stretch rates and as a result of that, the flame can indeed blowoff in this parts and if we can essentially extinguish and when this extinction local extinction becomes too much then the flame can go inside the recirculation zone and the inside the recirculation zone or of course, it can lose heat into the flame holder and it can blowoff; so, that is the point.

So, once again we see evidence of recirculation zone burn and extinction along shear layers and the recirculation zone burn in this pictures also; in this very beautiful dramatic kind of pictures. You see the flame is now in a very corrugated shape formed like this; of course, these edges are not detected by hand, these are about a obtained using MATLAB can edge detection and so this you see that there is a lot of extinction even forming also.

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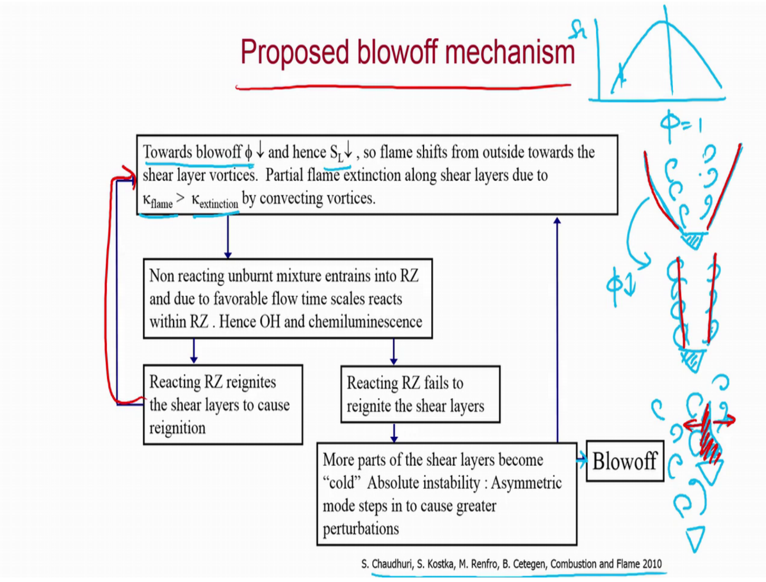

So, here we in this slide we can summarize the proposed blowoff mechanism. So, first thing is that as blowoff is approached of course, blowoff happens when you have little bit of low equivalence ratio in these cases. So, when your equivalence ratio is 0.77; so as blowoff is approached by reducing the equivalence ratio, the flame speed reduces; you remember the flame speed versus phi it was a plot like this.

So, it was kind of maximum at phi equal to 1 and here the flames speed was less. So, as phi is reduced, flame speed is reduced; so, as flame speed is reduced from the flame like this, it becomes a flame like this. So, as phi is reduced it from here to it transmissions to here; so, this is the bluff body. So, as a result the flame shifts from outside towards the into the shear layer vortices and there is partial flame extinction along the shear layers; because now this flame is experiencing stretch, which is exceeding the local extinction stretched why? Because when the phi was large, these are the Kelvin Helmholtz vortices that are formed.

This flame essentially was overlapping these Kelvin elements vortices or was enveloping this Kelvin Helmholtz vrotices. When phi was large, the flame was enveloping these Kelvin Helmholtz vortices like this. But as equivalent ratio reduces and the flame speed reduces and the flame becomes more columnar, it shrinks inside and now the flame is essentially overlapping these Kelvin Helmholtz vortices. Now, as it overlaps Kelvin Helmholtz vortices; the flame, these vortices can induce much more stretch and this stretch can cause the local flame stretch to exceed the low corresponding extinction stretch rate and as a result there can be partial flame extinction on the shear layers; so, this what is quite clear.

As blowoff is approach using equivalence ratio as reducing equivalence ratio of flame speed reduces. Because of this, as flame speed reduces the flame shifts from this shape to this shape. When it is in this shape, it is essentially enveloping these Kelvin Helmholtz vortices, but as it approaches this shape it is essentially overlapping these Kelvin Helmholtz vortices. And now the stretch rate of the flame can exceed the extinction stretcher to the flame and as a result partial flame extinction can happen.

Now, as soon as this flame is now gone; so the flame is like this, so the unburned reactant, so we let this picture be like this. So, as soon as the flame is gone like this; the unburned reactor can enter into the recirculation zone and due to favorable and flow time skills, it can react within the recirculation zone. Hence we absorb OH and chemiluminescence from within the recirculation zone.

Now, the reactant recirculation zone can reignite the shear layers, this can give heat into these things; into the shear layers which is still containing unburned reactants. And as a result the flame can again be formed, on the other hand the other possibility is that the reacting recirculation zone can fail to reignite the shear layers. If it fails to reignite the shear layers then more and more parts of the shear layers become cold, absolute instability now dominates and the asymmetric mode now steps into cause greater perturbations.

So, now if it fails; what happens is that this Kelvin Helmholtz vortices become Von Karman vortices and as a result of this, there is even more stronger perturbations which the flame of course, cannot sustain and this recirculation zone that was formed; this reaction within the recirculation zone also can be disturbed and this can lead to final blowoff event. That is why before blowoff; people have observed this transition from convective to absolute instability or the transition from symmetric vortex shedding to a asymmetric vortex shedding.

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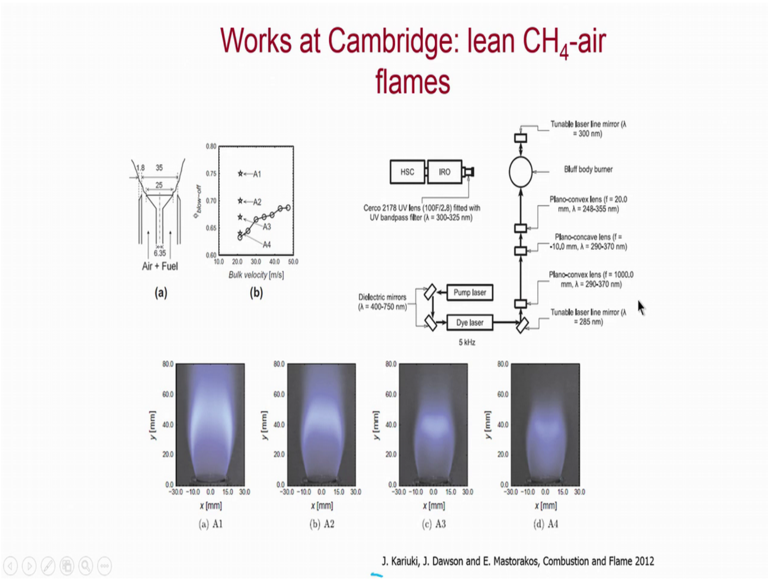

So, this is how the whole thing is coupled; please look into this proposal of mechanism and it can be found in this our 2000 and play flame 10 paper by Chaudhuri Kostka or M. Renfron and Cetegen; so, this is the paper. Now, there has been significant amount of work at Cambridge also from 2011-12 onwards; when where I worked with methane air flames; now methane air flames have reached number less than 1.

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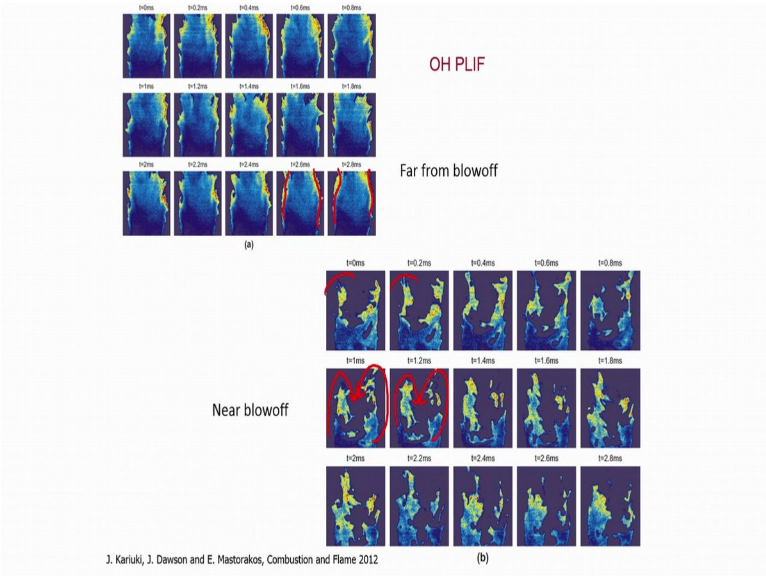

And they also found that as blowoff is approached, essentially you see that this is far from blowoff where we have flames sitting along the shear layers. But you see that as blowoff is approach; this shear layers again extinguished downstream and now once again the fresh mixture can entrain from downstream of this recirculation zone. And this fresh mixture can reignite which can cause reaction within the recirculation zone; or it can fail to even reignite and this cold mixture can even take away heat from the recirculation zone and this can lead to extinction also.

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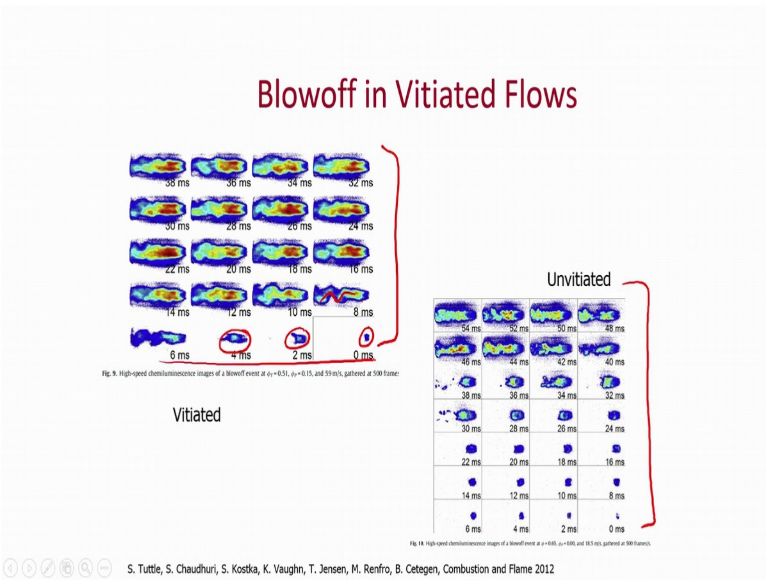

Blowoff in vitiated flows also have something similar; here also we observed that is that we also observe that in the stable flame of course, there is not much recirculation zone burned, but in vitiated flows your temperature ratio or density ratio is much smaller.

So, we see that this kind of an asymmetric vortex shedding even at a before blowoff and you see that this is once again this recirculation zone burned right before blowoff happens . So, the whole thing is that blowoff just not happened at the flame just lifts off from there. It happens to us period sequence where essentially the flame is sucked into the recirculation zone, before it blowsoff. So, it is like and you see that whereas, this is unvitiated case and this is a vitiated case. You see for the vitiated case, the blowoff is much more abrupt; in the sense that with this from 8 milliseconds; within the flame can go off to this small kernel within and can extinguish within this period of 6 milliseconds.

Whereas in this case in the unvitiated case; it really this is takes for a long time of about 40 milliseconds by which this blowoff sequence happens. Because here this is the difference between the vitiated and unvitiated flame blowoff; so, that is the point. So, here also you see that there is a lot of large structures forming in terms of the flame and the flow, when blowoff is approached and you see that this is the kind of; this forms again the flame overlapping. But there is also difference as such because you see that this blowoff is much more abrupt and it does not have a long period of recirculation zone burned unlike what it happens in unvitiated case.

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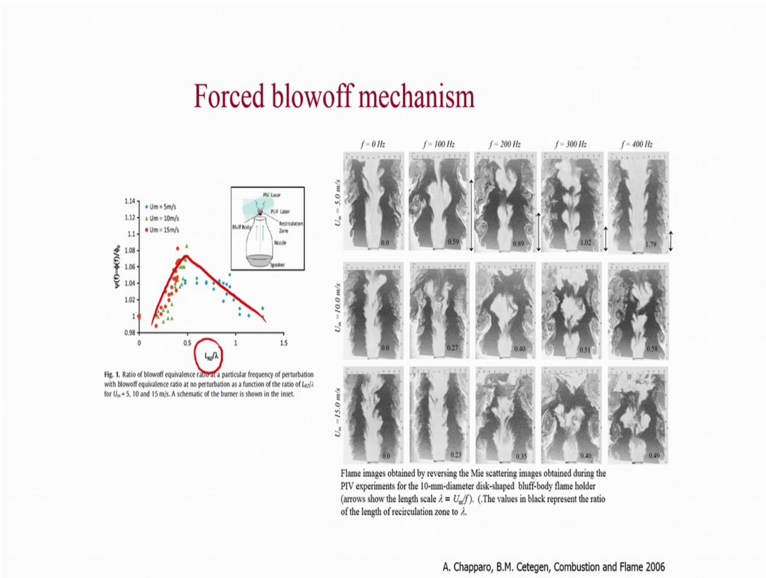

Forced bluff; now it can happen that in the afterburner, which you are interested in this afterburner can have often characterized by instabilities called screech and then the flame can blowoff because of the instabilities also.

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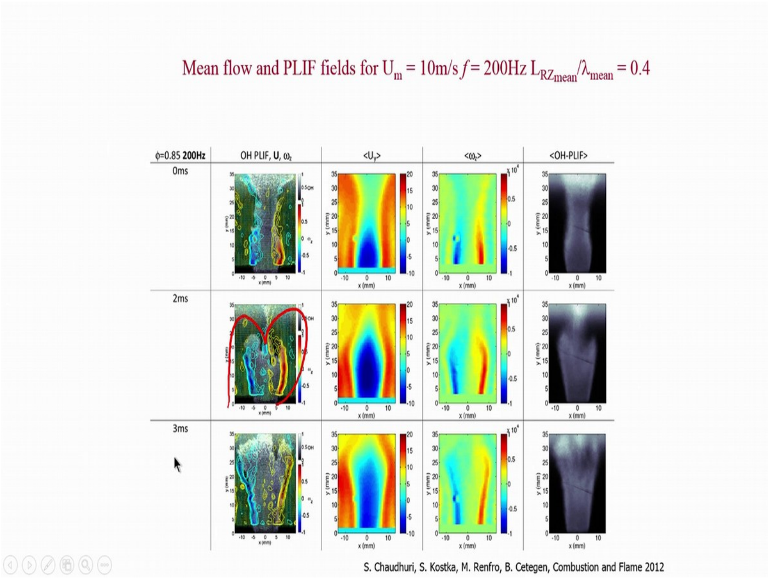

And here we saw that in certain cases where on this; when the length of the recirculation zone is about half of the wavelength of the perturbation, the blowoff equivalence ratio can be large. So, this type of this thing that when the reason being that when the perturbation wavelength is of the order of recirculation zone; there in one perturbation there is can be a lot of cold reactant entrainment into the recirculation zone. Of course, we want the reactant entrainment, but if it is also cold.

So if the enthalpy content of the recirculation zone is not strong enough that it can transport, it can transfer that heat to ignite that reactant. So, then it will essentially lose a lot of heat and energy also and it cannot be able to ignite it. So, as a result the heat loss can be more greater than the heat generated and then it can lead to blowoff.

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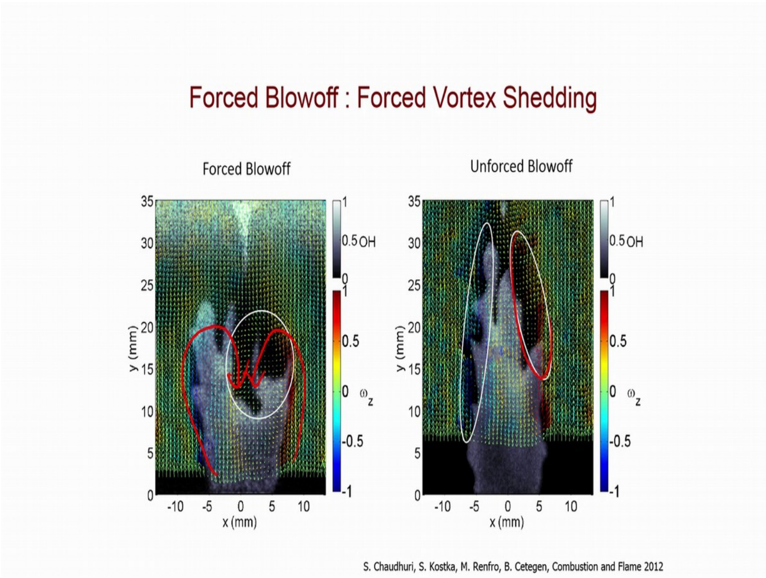

So, that is what is there probably happening here; you see that here we have in the unforced blowoff; you have essentially flame extinction on the shear layers. Whereas, you have essentially flame flow coming in from the top of the recirculation zone and causing this flame to this essentially dumping cold reactants into the recirculation zone and that is causing the forced blowoff. And this essentially we attributed it to the force vortex shedding for this flame blowoff phenomena.

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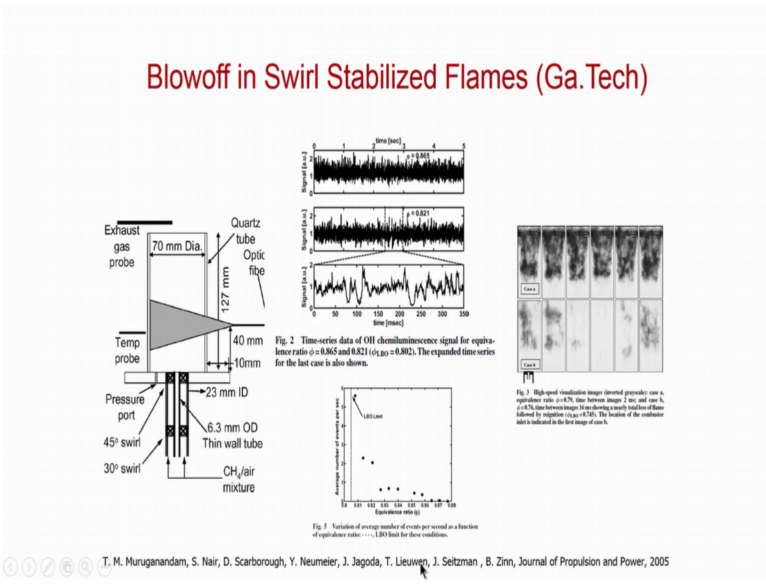

Then blowoff in small stabilize flame has been studied also at Georgia Tech and it has also a unique characteristics.

I will not go too much into this and so essentially this was also studied at DLR, where we found that (Refer Time: 22:21) we found that the essentially the flame tip gets extinguished due to experiencing large strain rates and along the flame edges. So, in the swirling flame blowoff can be summarized with the following that SR; the reaction occurs in the helical regions along the precision at aquatic score. So, you see that in a flame in this swirling flame, so when the swirl number is very large; the 7 larger than what is required for vertex bubble breakdown, then there is something called a prescicing vortex that is formed.

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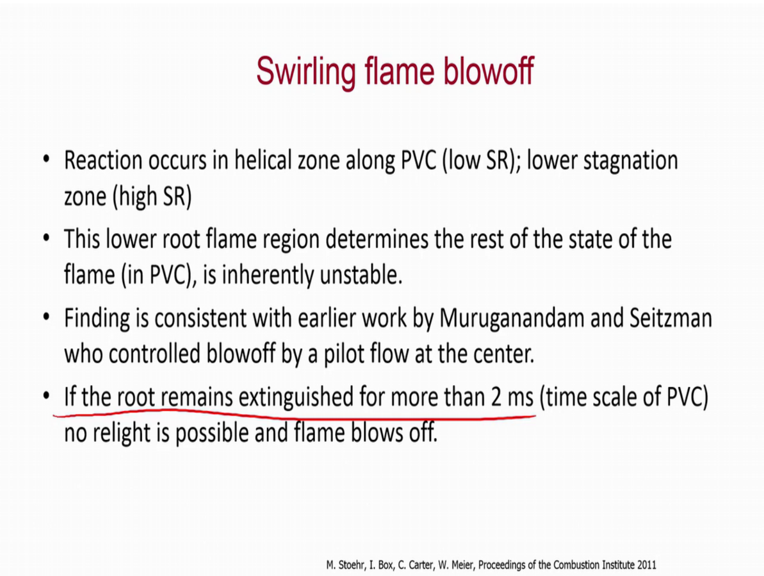

And which is essentially helical region that presides that are given frequency and this lower root region essentially determines and so within the flame lifts up off like this and this is the point which is called the flame root and this floor root of the flame region essentially determines the rest of the state of the flame in inherently unstable and this finding is essentially; that essentially the extinction of that root essentially determines whether the flame will be stabilized or not and acts like a pilot at that point.

And they say that if the root remains extinguished for more than 2 milliseconds time scale of a PVC; then no relight is possible and the flame blows off. So, it is similar to our finding of this recirculation zone burn; where we also found that during the extinction recognition event, if this happens for about a period of 10 milliseconds; so, if this recirculation zone kernel cannot reignite the shear layers within a period of hours of about 10 milliseconds; then it can cool off and it can essentially go into complete blowoff.

So, this is the similar things where essentially reduces to a kernel and then the kernel whether that can sustain the full flame or not depends on the situation where the kernel balance is the thermal energy generated by the chemical reactions due to combustion and the heat loss to the flow to by thermal combustion and by thermal combustion to the metal etcetera.

So, far that is so much for this discussion on the flame blowoff; I will just walk you over through this the flame blowoff mechanism that we found, which is essentially the similar to the other cases also.

So, if we just recap; so, this was the proposed blowoff mechanism. So, we found that as blowoff equivalents ratio reduce, the flame speed reduces. And the flame shifts from the outside into the shear layer vortices and we have partial flame extinction along the shear layers because the stretch rate of the flame exceeds the corresponding extinction stretched by convecting vortices. So, essentially from this state; the flame goes into this state where it now overlaps with this Kelvin Helmholtz vortices. Now, these Kelvin Helmholtz vortices can cause strong stretch on the flame surface and it can exceed the extinction stress rate and the flame can extinguish.

Now, what happens after the flame is extinguished along the shear layers? Now as soon as the flame is extinguished along the shear layers, the non reacting unburned mixture can enter into the recirculation zone due to favorable flow timescales and react within the recirculation zone and we can see OH and chemiluminescent from the recirculation zone which is not possible otherwise.

So, which is a recirculation zone burned is an event which happens only prior to blowoff or when there are other parts of the flame has been extinguished; this is very very important. So, it can be considered as a precursor to go off and it can use for designing sensors for identifying blowoff also. So, the reacting is; so, there can be two possibilities now if the timescale is short, if the recirculation zone reactions are strong enough; it can reignite the shear layers to cause reignition. Or the other possibilities then it can go into this loop again, or the other possibilities that the reacting recirculation zone fails to reignite the shear layers.

Now, if it fails then the more and more parts of the shear layers become cold; absolute instability steps in because now the density ratio is approaching 1. So, now one can on vertex shedding can happen and the asymmetric mode can cause greater perturbation which leads the final blowoff event. So, this is the final essentially the blowoff mechanism for bluff body stabilized flames and similar things can also happen for a small flame blowoff and so what we have shown here is that using laser based diagnostics, we can find out the mechanisms of different type of combustion phenomena that are of practical interest.

So, next class we will look into scramjets and flame stabilization and in scramjet combustors; which is even more challenging because the flow times calls will be lower, but it is of also practical importance.

So till then thank you very much, goodbye.