Combustion in Air Breathing Aero Engines

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Lecture - 55
Flame Stabilization and Blow off -III

Welcome back. As we have seen that the objective of this part of the course was that we try to understand some combustion phenomena of practical interest in a kind of realistic configurations of an engine in particularly in an afterburner. So, what we have done is that we have described afterburner a little bit and how it works and then we have been going on to discuss laser base diagnostics. So, at length we have discussed about laser induced fluorescence which is one of the most prominent techniques to measure intermediate mass species mole fractions. In a given field and it has especially with that because we want to know more and more about turbulent combustion laser induced fluorescence has really helped in visualizing the flame location and the flame structure as such.

Now, that is that basically goes into quantifying the concentration of intermediates like OH, you can also do laser induced fluorescence of alongside which you can do with formaldehyde you can do NOX, no you can do PLIF of CH and so on and so forth. I can also do PLIF of o atom etcetera. So, PLIF you can really do of many important intermediates, and it has been know very important laser based diagnostic technique that has been used by the combustion of community to basically understand the flame location and understand and resolve the flame structure. Even people have used PLIF to understand how thick is the preheat zone and how does the reaction zone structure looks like of course, you have to do PLIF of different intermediates and so on and so forth; so PLIF is very important, but only PLIF is not enough because PLIF tells you about the concentration of the intermediate.

You need to know how the flow field also looks like. Especially if you are if we are working in a turbulent flow field you variably need to know how the flow field looks like. And the most important non intrusive laser based diagnostic technique that has emerged as the as one of the most important techniques in fluid mechanics for velocity measurements is something called particle image velocimetry.

So, we will go we are going to discuss Particle image velocimetry here.

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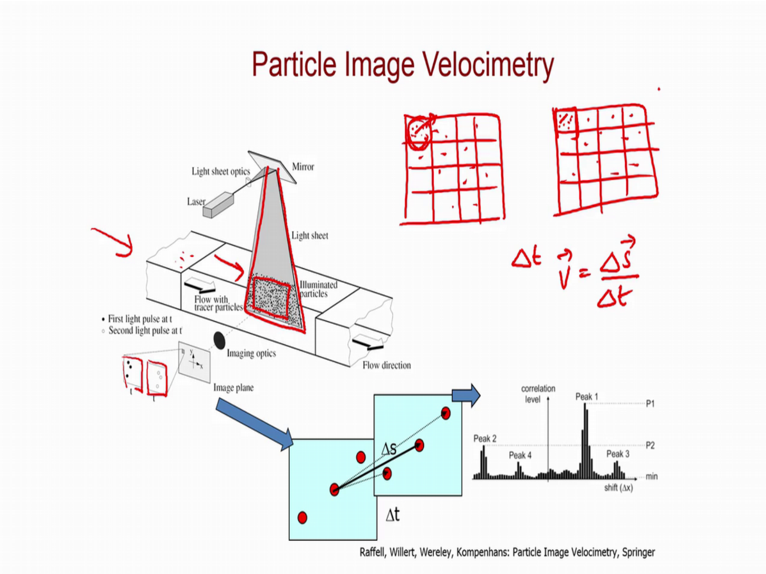

We will not go into as elaborate details as that of PLIF. Another will just give a very short introduction, because this is a this is more than the technique is of course, important, but more than the physics of the technique large part of PIV goes into like data analysis, how you can get meaningful results out of a PIV out of a PIV images or the or the mie scattering images, but I will just give you the very basics here. So, what do you do in PIV? PIV as the name suggests is particle image velocimetry. It involves particles if you look into the fluids surrounding, you cannot visualize you cannot see measure the velocities you cannot visualize the fluid the air is transparent, you cannot see air right.

So, to visualize that you need basically first you need tracer particles. So, first thing you do is that for the flow field that we are going to measure, you put tracer particles in that and you basically shine light on that tracer particles and this tracer particles basically scatter light and you captured that scattered light to know what are the locations of the tracer particles. So, suppose you get you. So, let us consider it like this let us consider this flow field that we have here. This in this set tunnel in this wind tunnel or water tunnel you basically put particles inside like this, but you could not see that because we are not scattering lights.

So, then you basically take a laser you shine light like this through a mirror. So, that it goes vertically through this plane, and then you can visualize the light the particles immediately because there is no scattering light. And then this suppose this is your interrogation window which is being captured by your camera. And you basically capture this image and you get an image of basically particles, particle positions. Or particles which are scattering light at their particular positions.

So, what you do is that you take in a given after a given interval of time you take another such image. So, in one image suppose you have particles scattered like this, in the next image which is taken after delta t you get particles also scattered, but you see these particles because there is a flow in this direction these particles must have moved in position in the in the corresponding same frame because the flow has advected them in some direction.

So, then what you do is that in PIV you do not calculate the displacement of individual particles. What you do is that you break up this whole grid into several like parts. Each of these boxes may be like 32 cross 32 pixel 64 cross 64 pixels So on and so forth. And then you find out by cross correlation how much does on average how much does this set of particles inside a given box move in a given amount of time. So, for each particular box you get basically a displacement vector, delta S vector say, and since you know how after how much of a amount of time you shine the laser.

So, from delta S by delta t you can get the velocity vector. So, for each box you basically get a velocity vector by combining by finding out the displacement from these 2 images. So, that is what is being elucidated here. So, here you see that you shine the laser and you captured this image here at each time t, and then you this in the second shot this particles have moved and then basically. So, this is say one of this represents one of this box. And you basically then find by cross correlation you find out how much does this set of particles on average move in this box, and that is your velocity vector.

So, the most important thing is that PIV gives you the does not give you the velocity of individual particles it gives you the velocity field it gives you the velocity at these boxes or that these grids individual grids being of a given number of pixels. Some pixel cross some pixel 32 cross 32 pixel is a standard thing that typically do. Of course, now you see that this is basically a statistical process by which you calculate you do not calculate the velocity of a single particle you calculate the velocity of actually say 10 to 12 particles inside a given box, and there are numerous guidelines by how are to your delta t should be. Like your delta your displacement in this amount of time should be greater than point one pixel. And it should be less than like the window size by 4 typically those their different search guidelines and the one has to know the guidelines to get reasonably good vectors.

But the processing in PIV is very important as such the physics is just here the light matter introduction is just scattering. So, you shine light and you get the particle images just like you the way visualize smoke right. So, you shine light you visualize smoke and if you take an image you will get a picture of the smokes of course, you do not get individual smoke particles here the target is to get at least you have to resolve this particles positions at that particular time, because without that without you cannot obtain the velocity vector.

So, it is the physics of light matter interaction is not that complicated here. Like it is more involved in PLIF where it is like real quantum mechanics is involved in laser induced fluorescence there is nothing as such it is much more simple, but the post processing is very, very involved. And you have to have very special post processing algorithms to extract these velocity vectors efficiently and correctly from these 2 sets of images that you get. And of course, both PLIF and PIV can be obtained that high speeds. And nowadays one can also obtain this is in one plane actually as you see this light is light sheet is made. But if it is more thick and a little bit in this light sheet is thick and a little bit one can get the third component of velocity also if you use 2 cameras something called stereo PIV.

And nowadays if you can even do volumetric measurements by using multiple cameras called tomographic PIV. So, flow field measurements are pretty advanced it and laser induced fluorescence I have also been used to understand the species concentration fields as such. And So, you have techniques on one hand to quantify the species in fields you have techniques on one hand to essentially quantify the velocity fields; so both using these 2 we can have a reasonably good understanding of how does the intermediate field looks like in a given flow. So now, we are in a in a good shape. We know how to use how what is laser induced fluorescence little bit. Of course, you see these are more involved techniques it is like it takes years to master them. So, this is just a very brief introduction.

So, you need to you need to read more and we need to understand; we need to have not do practical hands on experiments to really understand have a have a solid control over these in a techniques. So, both of we do in our lab, and essentially both PIV and PLIF we do in our lab and these are broadcast techniques to essentially understand the turbulent flow combust turbulent reacting flow that happens inside the combustor.

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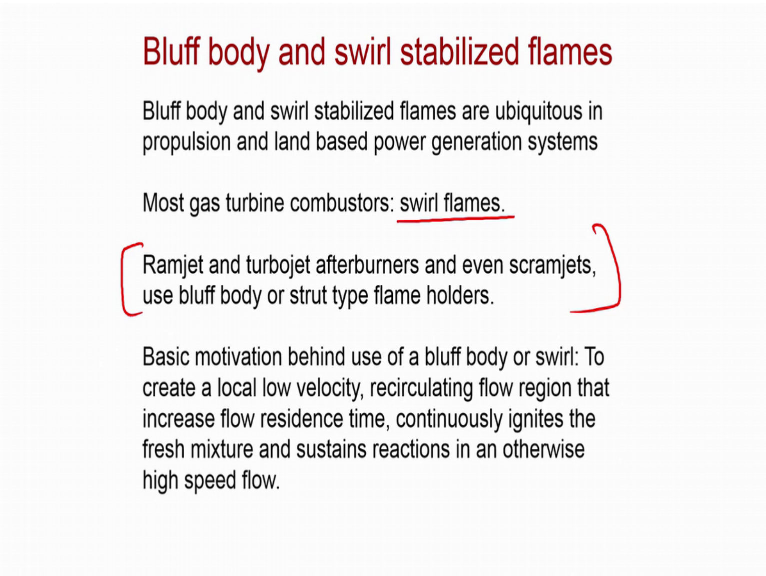

Now, let us go into the actual problem at hand that is the bluff body flame who stabilization mechanism we are interested in. So, the we are interested in bluff body and swirls stabilize flames if we just discuss this a little bit. So, we have already got introduced to swirl stabilize flames. So, you see that both bluff body and swirl stabilized flames are essentially ubiquitous in propulsion and land based power generation systems. We have already seen that in the primary zone of a more of a annular gas turbine combustor, in the main gas turbine combustor they use swirl flames. The reason people use swirl flames is that you see the swirls as they die as they as they create this bubble and the and the whole sprays as the sprays as well as the as the spray cone angle as well as the flame cone angle also diverges, the resultant flames size is little bit compact. Of course, it comes as a at a at a price of a pressure loss, but it is this is a flame is compact.

So, as a result of that the whole gas turbine combustor can be compact. It is important to make it compact because the gas turbine combustor set very high pressure. So, you cannot have a high pressure vessel which is very big in size it is more costly to and more difficult to have a have a have a designer or something like that. So, a gas turbine combustor summate compact and of course, there they are made of very high temperature resistant materials also. So, you cannot really have a very big combustor that is really not realistic.

So, in it is imperative to have a gas turbine combustors compact and for that we use swirl flames. On the other hand that is we need the particular ramjet in turbojet afterburners the ramjet engines. And the afterburners and even scramjets use bluff body or strut type flame holders. So, all these applications you give flame bluff body type flame holders which will come. So, the basic motivation between behind these behind using these either the bluff body or the swirl type flame holder is essentially same. That is either the swirl type the type flame holders or the or the bluff body type flame holders, both of them do the same thing in the sense that, they create a local low velocity recirculating region.

That is they have a list the creator recirculation region. If you have a bluff body, but the physical object itself creates a recirculation region downstream if you have a swirl when the swirl number is pretty large you see there is a vortex bubble breakdown that happens and that itself creates a recirculation region. So, essentially the requirement of both the both the bluff body as well as the swirl of swirlars are essentially the same that they creator local recirculation region and local low velocity region. While you call low velocity region because once again when you have a local low velocity regions, the flow time scales are large. When the flow time scales are large then essentially you can this you can expect that the flow time scales exceed over the corresponding chemical timescales, and you can have complete chemical reactions in a given recirculating flow. That is the Damkohler number is very large. And as you know that you achieve a steady combustion which is not prone to extinction and which can be easily ignited you need to have Damkohlers numbers large.

So, the basic motivation behind both using as a bluff body flame holder or a swirl flame or a swirlar basically is to essentially clear create this local low velocity regions. And which has the increased flow residence time. And also this local low velocity recirculation regions essentially recirculates bond products. So, when you have bond product recirculating you can have this bond products come in contact, but like physically also diffusion. I mean, both through advection or through diffusion come in contact with the fresh reactants and they can act as an ignition source to essentially sustain the reactions in otherwise high speed flow.

So, this is why you need either one some kind of a flame stabilizer to basically sustain reactions in high speed flows. So now, now the thing is that when this does not happen. Even despite the best intentions in a downstream of flame holders. Suppose when the flame is taking a when the when the aircraft is taking a short turn or it is like doing a sharp climb, because of the very fast acceleration of the air inside the combustor you can have flame blowoff ok.

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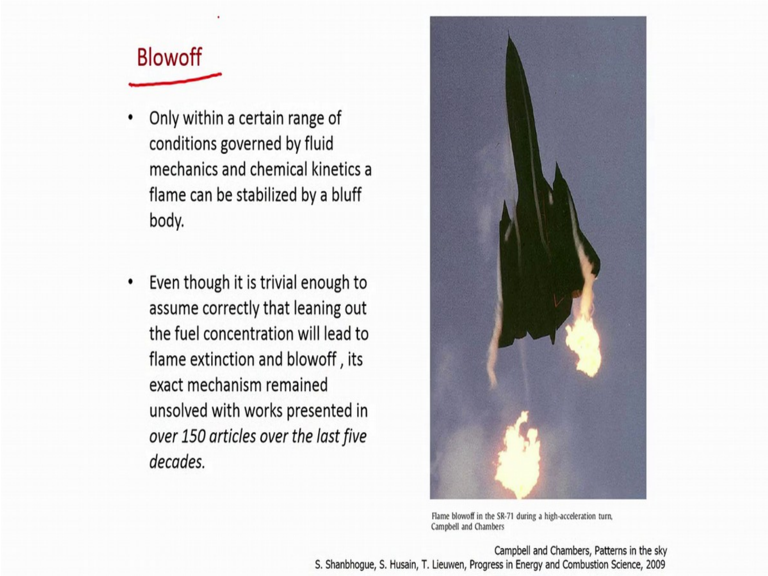

So, like this kind of a situation. So, you see this SR71 aircraft by the way SR71 is one of the best aircrafts manufactured or created in the history of mankind. So, while this SR71 is taking a sharp turn you see this flame has blown off from this engine. And of course, you do not want a situation like this because and of course, you first of all you do not want a flame blowoff like this. And even if the flame blows off you need to have quick ignition, because you do not because if the flame blows out and you cannot have quick ignition then the essentially there is no power inside the engine. There is no chemical to thermal energy conversion and then it can lead to a catastrophic failure of the whole aircraft.

So, blowoff we do not want blowoff at all. So, blowoff must be avoided. So why; so the question is that why does blowoff happen in first place? Now first you need to understand that even if we create a bluff body flame holder, it is only within a certain range of conditions which is governed by interplay of fluid mechanic and kinetics one can stabilize a bluff body one can stabilize a flame by a using a bluff body. So, though it is trivial enough to assume that if you lean out of flame that is as you go reduce to equivalence ratios from say 1 to 0.2, 0.9, 0.8 like that. At some point of time you have extinction the exact mechanism by which extinction happens in bluff body flames, bluff body establish as flames has remained an unsolved works over a long time over 150 articles and over the last 5 decades.

But here what I am going to show you is some progress that has been made we have proposed a hypothesis by which and with a couple with recent works we can have a good solid understanding of this phenomena called flame blowoff . But this is you see this is very exciting right this image this aircraft is taking a sharp turn, is taking a turn like this and this flame has blown off. So, why does this happen? How does this happen? Of course, you see you cannot understand these phenomena inside an engine because you do not have the diagnostics you cannot put a laser up in the sky to do measurements. So, what we need to do is that we need to recreate this engine type of combo conditions in the laboratory ok.

And then we at different scales this first can be a very small setup and then you can have a more bigger like a prototypical combustor to kind of setup. And then you can apply this laser based diagnostics to measure the flow to measure though each. And using these combining these techniques one can try to understand why these sorts of things happen how does the flame blowoff . Because you see the flame you will see the flame blowoff happening for a propane flame at about an equivalence ratio 0.7 0.65. But as a flammability limit is fall lower 0.5.

So, it is not only just the flammability limit not only just the kinetics that control the flame blowoff it is some interaction with the fluid mechanics that cause the flame to blowoff . Of course, kinetics has also a role to play, but in a typical flame that is what I am saying that because it involves the flow structure is So complicated the flame structure is a complicated in a in a given flame one is to understand the holistically turbulence kinetics flame structure transport many things to know how does a make an how does a flame blowoff happens. So, that is what we are going to talk now.

So, how does a bluff body stabilize flame looks like?

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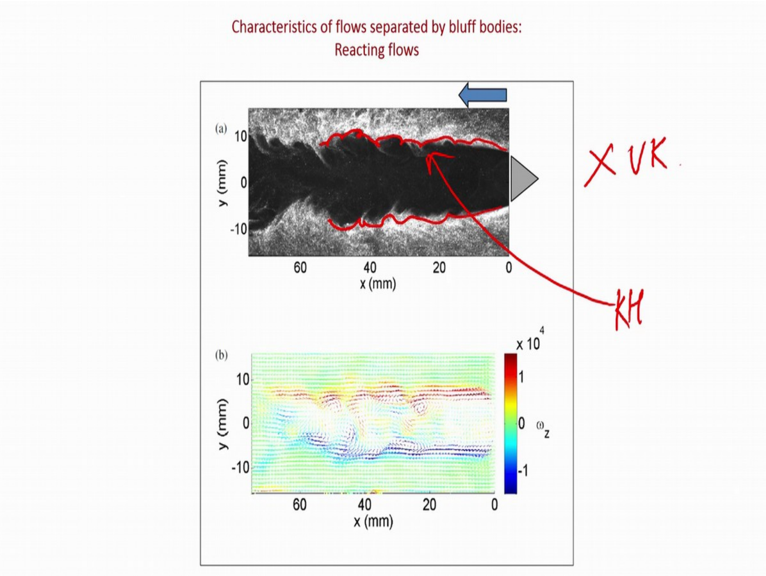

So, of course, we have seen that this is definitely there is a bluff body stabilize flame these, in and you have seen that in this if we go to this afterburner. So, this afterburners you have essentially you have this flame holders are essentially stabilizing this and after burners this bluff bodies will be stabilizing flames.

So, bluff bodies are ubiquitous in after burners in ramjets or in scramjets where we use an aerodynamic shape body which is not exactly a bluff body, but a strut type of flame holder. So, this type of blood is are common, but what happens when a flow approaches this kind of a body? And what does the flame looks like? And how does the flame change the flow so that we can do by using PIV particle image velocimetry in this. So, these are pictures from my thesis actually. So, I see that here we have a triangular flame holder and the flow is coming from right to left. And this is essentially a me scattering image this is that is this is the image of the particle scattering the that is a laser light as scattered from the particles in one plane, in the central in the in the mid plane of this thing. So, this is a you have a you have a basically a cuboid like this and you have a flame hold on like this.

So, this is the typical shape what you have. And then the flow comes from right to left, and then see that just downstream if this flow if this is non reacting flow if this is an isothermal flow at room temperature you see this very beautiful Von Karman Vortex shedding structure, this asymmetric structure. Why is asymmetric? You have a vortex I here, you have I here, you have one core here, another one core here. And then if you do a PIV you will see this beautiful sinusoidal structure where these different recirculations on structures are formed.

So, while it is non reacting, the flow downstream of a bluff body is asymmetric in nature, it is characterized by Von Karman Vortex shedding when the Reynolds number is greater than about 70. And this is this is essentially a manifestation of absolute instability. They are coming 2 types of instabilities absolute and convective. So, this is a manifestation of the absolute instability. Now when you have a flame stabilized along the shear layers, but before that in here what you have is essentially you have in the near field you have this symmetric Kelvin Helmholtz vortex shading. And in that in the in the far field you have this asymmetric Von Karman Vortex shading ok.

So, this is Kelvin Helmholtz and this is Von Karman Vortex shading, all right. Now when you have a flame as in an afterburner which is stabilize bluff body you see that this asymmetric structure is lost and you get a symmetric kind of a vortex shedding structure. So, you see that now this you have the vortex shading along this. This is once again the me scattering images. So, you here you only have Kelvin Helmholtz vortex shading. There is no Von Karman Vortex shading here. So, this is the first thing that when you have combustion the flow of course, will you have combustion the density of the flow changes and that creates even a qualitative difference change in the flow structure.

Now, inter flow structure can be widely different. And the frequencies everything can be very different. So, first of all this is the thing; non-reacting flow asymmetric reacting flow symmetric, when it is downstream of a bluff body. You will see what happens when there are when the transition regime when the reacting flow tends to become non reacting that is when the blowoff is approaching very interesting feature you watch.

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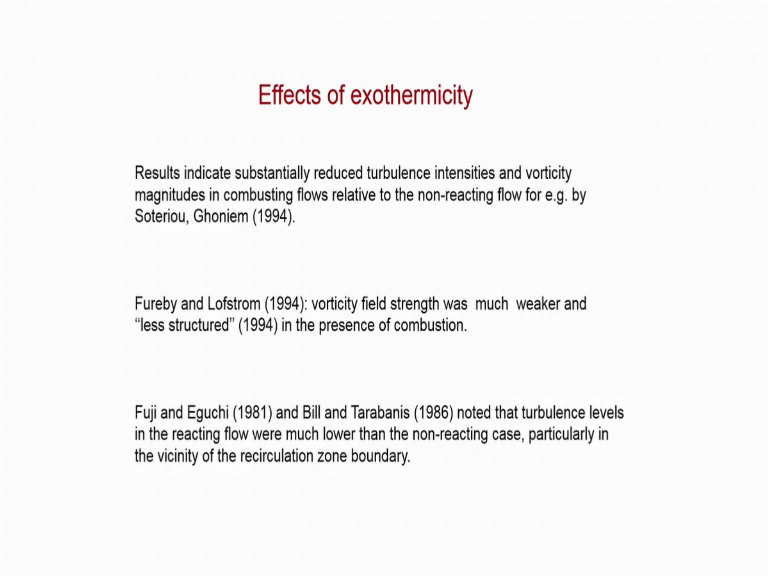

So, the effects of exothermicity that is the effect of heat release on this type of flame on this type of flows downstream of a bluff body is that the results indicate that the turbulence intensities and vorticity magnitudes are substantially reduced. In the combusting flows relative to the non reacting flows and was formed by Soteriou Ghoniem. And these people Fureby and Lofstrom formed that vorticity field strength was much weaker and less structured in the presence of combustion. Fuji and Eguchi and Bill Tarabanis noted that turbulence levels in the reacting flow were much lower than the non reacting cases particularly in the vicinity of recirculation zone boundary, why? You see kinematic viscosity which is essentially the characteristic viscosity here is essentially mu by rho.

So, in combustion when you rho changes your kinematic viscosity essentially goes up. So, this kinematic viscosity results in greater viscous dissipation and as a result of which the vorticity magnitude as well as the turbulence intensities are much reduced, but it is not so simple.

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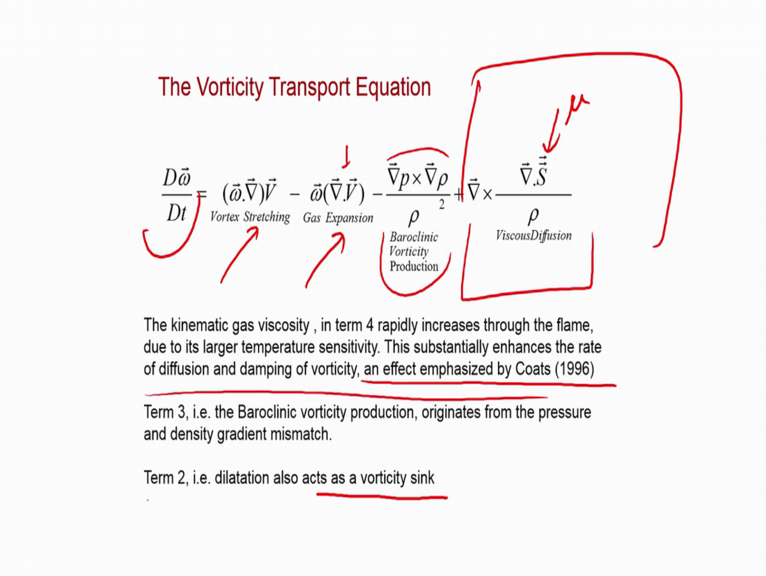

Because if you look into the vorticity transport equation, this equation can be obtained by just taking the curl of the navies stokes equation the density the density varying navies stokes equation. And this is of course, the left hand side the convective the full material derivative of vorticity vector. And the first term we have is a vortex stretching which is essentially the term responsible for turbulence, 3D turbulence and energy gasket. Then you have gas expansion which is a negative term you see that when you have divergence of v not equal to 0 as you can have in a in a combustion then this is a sink for vorticity. Typically and this is very interesting this baroclinic vorticity this is a positive term that when your grad P that is a pressure gradient and density gradient term is aligned, then this misalignment can cause some production of vorticity.

And then this is the viscous diffusion term that that the viscosity essentially goes inside this one and then the rho. And so, when this when you have when you have essentially combustion then this term essentially becomes increasing. So, in kinematic gas viscosity the in term the in term 4 rapidly increases to the flame due to it is large temperature sensitivity. And this substantially enhances the rate of diffusion and damping of vorticity, as has been emphasized by coats. The term 3 is a baroclinic vorticity production which originates from the pressure and density radiant mismatch. And term 2 is a dilatation which also acts like a vorticity sink.

So, this is how the vorticity it is not straight forward exactly how did combustion acts because you can have some vorticity production, and people have think that this can also lead to some kind of an instability because of vorticity production, but anyways we do not go into that, but as such the dominant effect is this one that when you have a combustion, because the this mu nu kinematic viscosity term increases your viscous dissipation vorticity or the or the vorticity is dissipated, because of this viscous diffusion terms.

Now, what happens in the near blowoff dynamics of bluff body stabilized Flames?

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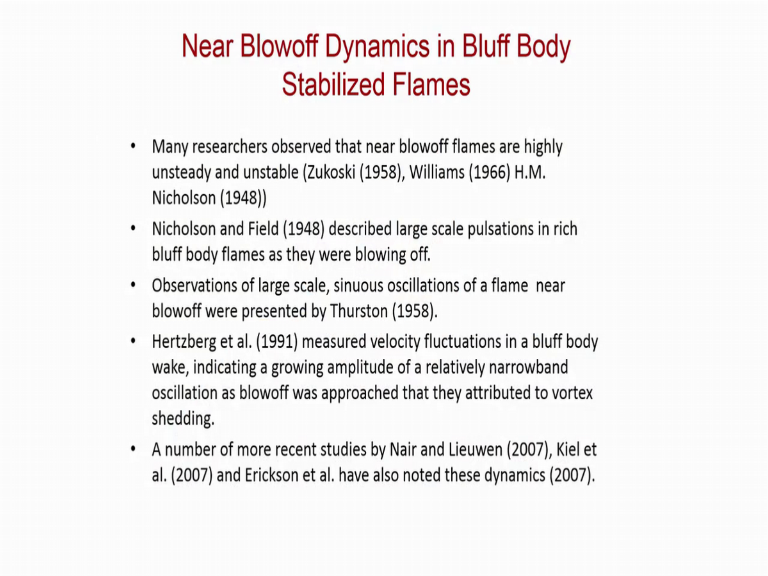

So, many researchers have absorbed that near blowoff flames are highly unstable unsteady and unstable. And this goes rack from the Zukoski. And Williamson Nicholson a Nicholson and field observed that large scale pulsations in rich bluff bodies' flames as they were going off. And Thurston observed these large scale sinuous oscillations of a flame near bluff blowoff . And Hertzberg showed measured the velocity fluctuations in a bluff body wake, and he found that as blowoff is approached this amplitude of this narrowband oscillations increase. And recent number of recent works by Nair and Lieuwen and Kiel et al, have also looked into this dynamics and found that that as no of his approach there is a tendency for the bay flame to become more and more sinus in shape and the vortex addition vortex shedding essentially shifts from this symmetric vortex shedding to this asymmetric vortex shedding.

So, this has been the very brief literature review of what happens near the blowoff dynamics of bluff body stabilize flames.

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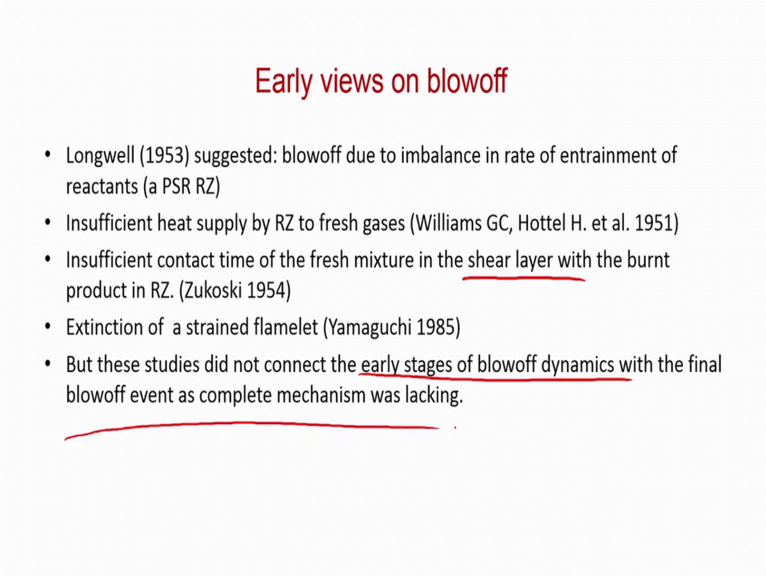

So, what is the view on blowoff ? Why does blowoff happen? So, longwell said that blowoff is essential in imbalance in the rate of entrainment of reactants. That is if you consider this recirculation zone. So, this is if you say that this is the recirculation zone. So, let us define the recirculation zone. So, if the flow here you see that this is the recirculation zone where the flow goes like this and it is recirculates. So, say here this is the typical the recirculation zone of course, in the in the in the flame this is your recirculation zone size increases. So, we say that this is the recirculation zone when we represent it by RZ recirculation zone and here this is the recirculation zone.

So, he found that that he said that they considered the reaction recirculation zone as a perfectly starred reactor. And longwell said that blowoff happens due to imbalance in the rate of entrainment of reactants. And Williams hotel this they said that there is insufficient supply of heat release to the fresh gasses that the fresh gases are not getting enough heat supply. Whereas, the first one said that that the rate of entrainment of reactant. So, the amount of heat released and the amount of heat chemical enthalpy coming in this is somehow balanced and there is a more loss term. So, that is why the flame blows off Zukoski said that that the insufficient contact time.

So, he considered the hot products essentially acts as an ignition source to the fresh mixture and he said that when the flow speed is very high then the contact time between the fresh mixture and the shear layer may not be the contact time between the burnt hot burned gases and the fresh mixture may not be large and along the shear layers and as a result it can flame become blowoff . And Yamaguchi said that it can be considered as an extinction of a strain flame let. But none of this studies connected the different stages of flame blowoff that is they did not connect the early stage of flame blowoff dynamics with the final blowoff may event and as a result the complete mechanism was lacking.

So, we will go on to in the next class we will go on to more contemporary works, which discusses how the blowoff mechanism can be exactly understood.

So, till then thank you.