# Acoustic Instabilities in Aerospace Propulsion

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## Lecture - 32
## Combustion instability due to Equivalence Ratio Fluctuation

In the beginning there we came up with two techniques, one is a frequency domain analysis or the hormonal domain analysis, we went after doing with Eigen values and so on. Afterwards, we did analysis in time domain and we looked at not this normal mode, but whatever problem with having non-orthogonal Eigen modes and that lot of machinery associated with analyzing such problem. But in either approach whether its time domain or frequency domain, we would need to supply a model for heat list. And that depends on how does flame responds to the oscillations, velocity of pressure oscillations around the flame.

And in different combustors this mechanism, that is how the flame or the combustion process responds to the acoustic oscillations is different. For example, in a rocket motor they propellant and they respond heavily to the pressure oscillations. Because, the pressure fluctuation alter the way the flame is standing above the propellant surface and it has a very strong influence on how reaction rate and how the mass flow of activations come out of the paralyze propellant is. Now whereas we looked at pre mixed flame where, the actually the pressure dependence is very week. But it is mainly a velocity fluctuation dependents where, you have velocity fluctuations it affect the flame by some kind of wrinkling.

And we also construct a model by solving econometric model we solve the g equation, we solve for the wrinkles and saw the wrinkles is propagated up. And there was a time lag associate with it, we actually derived expression for the wrinkle and from there we can get the area fluctuation. And then, we said that the area fluctuation translate to heat release rate you also briefly mentioned, spoke about diffusion flames where, in diffusion flames we said that the velocity fluctuations or the acoustic fluctuations affect the mixing between fuel and oxidizer. And that really concludes the, where the fine will set up and that will leads to temperature fluctuations and there is heat release.

In pre-mix flame it was more like the wrinkling, which translate it to area fluctuations which translate it to dye locations. So, it is in each, each case there is a different mechanism and many students pointed out ask me specifically about equivalence ratio fluctuations. So, in the previous analysis we did not have equivalence ratio fluctuations, we can do the same pre-mix analysis with equivalence ratio fluctuations. And what happens to wrinkles and so on, the many preparation the literature which works that out.

Particularly by the groups of ((Refer Time: 02:43)) from Pennsylvania state university and also ((Refer Time: 02:46)) from Georgia. I would not look at that because, it is in some sense a similar kind of analysis, but the same machinery we have to work out. But I will want to introduce the fuel flow modulation, air flow modulation that happens in a, in a more particular combustion, which results in equivalence ratio fluctuations and then, we look at the consequences.

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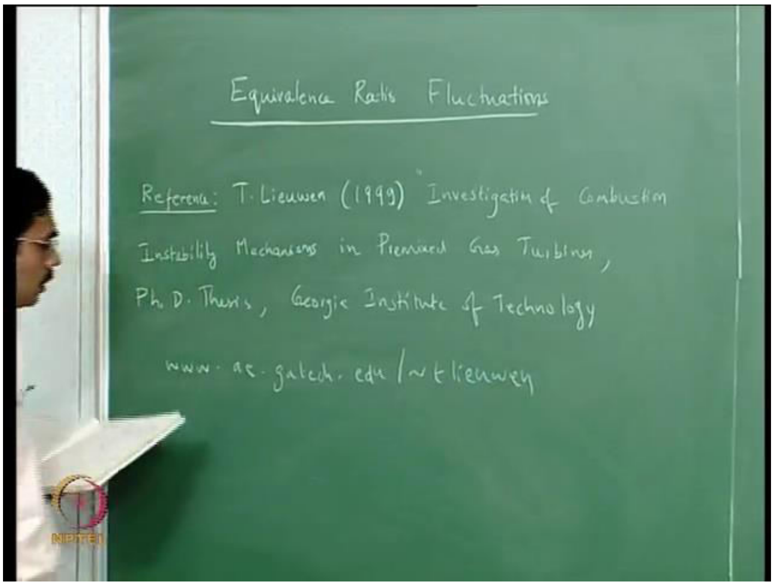


So, let me write down here. Normally we would say that in a combustor you are having the combustion burn exerted equivalence ratio. So, what is meant by equivalence ratio fluctuations here? When you said that fuel floret and air floret you have a certain equivalence ratio. So, what meant by equivalence ratio fluctuations, can you try to imagine.

Student: ((Refer Time: 4:05))

Yeah, why is it, why will say you imagine?

Student: ((Refer Time: 4:17))

Yeah, it is good so, it is a very good answer so, when the, this yeah so, in the 80's that is nitric acid rain and sulphuric acid rain and so on where, considered to be a people a woke up factor, it is a big problem. And they want to make combustion which will lower nitric acid rain. Nitric acid rain means you have NO and NOX going up in the atmosphere then it mixes with water vapor in the cloud so on, we have rain and the rain has concentration of nitric acid or any other acid. So, specifically we are worried about nitric acid here so, people looked that mechanisms with which NOH is found and found out or started thinking about, how the mechanisms can be taken advantage of and to result in low and NOX oscillations.

So, what happened is people found that as you would burn under lean conditions, lean is fuelly, I mean that is what it is implied by saying lean be fuelly. We have fuel lean combustions that means, you are there also a, you cannot go as lean as you want, why? There is a limit to which how lean you can burn. Yeah, the below the ability, below some the some limit for a pre-mix flame on burn, you are trying to, suppose you are trying to do pre-mix burners and pre-mix burners have low food production and other can. If you burn the fundament low near the limit we have very low, very low NOX that is what they found out. Now, you can imagine why NOX would be low, if you burn linear, it is one more thing, what happens if you have a ((Refer Time: 6:33)), a low temperature, absolutely.

So, when you are lower temperature so, that is correct, low equivalence ratio low temperature, if you cannot go to, you can also very high equivalence ratio when low temperature, but you are wasting fuel and there will be unburned hydro carbon. So, then we cannot burn rich so, we can burn lean, now so why would why would NOX be low when temperature is low?

Student: ((Refer Time: 6:59))

At low temperature, the NOX production is less so, it is one of the way for producing NOX less. So, people understood that if you lower the temperature of the combustion, you will have less NOX. So wonderful you proclaim that you solved all the problems of the nitric acid and so on, keep all the environment activists and ((Refer Time: 7:21)) happy. And then, you make this combustors and then, some unintended consequence happens, what would that? In stability, so when you go lower and lower the limits the performance of the nocks reduction it is very good. But then the flame speed is starting to be a very strong function of equivalence ratio and in ignition time is getting bigger and bigger.

So, these now make conditions very conducive to form ((Refer Time: 7:54)) instability so, that is what we will talk about. So, troy first give you a reference for this, they are very good PhD theses, download it from. So, this is a PhD theses done on these subjects so, good slow introduction to subjects, but there are also lots of papers on this. And I just have to give you some historical inside behind this. So, the combustion is to be search is very strong in the 60's and the 70's driven by what, do you know? Space program and missile programs and the big rocket programs lot of instabilities and then, the made enough number of motors.

So, try to make out lot of motors, but eventually have certain motors which are working, which they somehow managed to solve the problem or minimize the problem or eliminate the problem. And then, now you can run your program with combination of this number of motors. If you want to double the trust you try to make a big motors if it do not work, put two of the old rockets kind of tie with a rubber band, not quite a rubber band, but and if you want four times of trust. If you incase failed with a big motor, you can put four of the small motors, somehow people found ways to get around it. Because, you know some subject nobody understands so, if you do not understand something you generally would not feel inclined to watching, watching hot movies you do not understand like a sports, which you do not understands.

So, if you, if you do not understand the rules, the program manager has no clue what this thing is. So, they are not interesting in funding because this is always there, but they know somehow, somewhere it can be fixed once it is fixed, use those model. So, what happens to the scientists to work on it, in India like some other curry leaf, I mean after use you through it out. So, it is a kind of way this is a weird subject, that is not like a gas leaks where, you analyze and from that, which you can, but purpose build engine and so on. This is like if something blows up, I can tell or if it blew up I can tell you why it blow up or something like that.

So, we are not doing anything it is like role of a police man or something, first the robber has to rob then you will catch the thief something like that and the police men is not good enough to intimated the robber and not make him robber. So, this I mean so, that the stage is that and then the results when down low and a few peoples still hang around there and trying to do false it in combustion. And they are trying to use acoustic oscillations to increase the productivity and that kind of appeal to the manager because, is it, you know you can the combustion itself happens you are heat and mass transfer momentum increases.

So, can talk into problem in rockets, but they said okay you take a cement plant, you put sound with the first combustion and then make the droplets evaporate faster. Or try to make milk powder evaporate, milk operates faster like milk powder or some ((Refer Time: 12:27)) or burnt waste in the presence of high amplitude sound and waste would which would not burn start burning. Because, intensity mass some sound. So, if you people hang around there, had this subject of this combustion going and so on, almost getting out of business. And then, came this activists who wanted to get rid of nitric acid rain and then suddenly, the combustion scientists is woke up and they were also getting kind of job less with no new things.

So, they propose these things company has bought the idea, made it and banned, instability came and then suddenly all of us got into business. We are almost losing our job because, it is like police men losing job because of no crime and suddenly crime comes and then you are busy. So, suddenly instability comes on and people are busy so, this thing got everybody going in gas turbines, before in the 60's and 70's and 80's people did not worry that much about gas turbines. So, one thing was this knock performances improving, another thing is gas turbines you know once you have engine improve this, improve that and somehow get more and more megawatts out of the engine.

So, the engine it starts giving 100 mega vat in the beginning and then you ((Refer Time: 13:36)) this, it will become 110. So, there will be version 1, version 2, version 3 and then version 3 A B C D E finally, you have version 6 f or something like that. And by then 100 megawatt we are going to want an 800 or 90 megawatt. So, we are really pushing, pushing, pushing it is like I told you the, if you push somebody too much and then they performing very well, but then they can go crazy or like a sportsmen. If you push too hard, you can get injured right before the tournament. So, this is when, what kind of happen in these gas turbines?

They were there, but they not performing to that level of performance in the beginning, but now they are performing at incredibly high levels of efficiency and incredibly high levels of low pollutants and then, instability start. So, then all the guys who are running were closing their shops with rockets and so on, they came back to study instability in this and thankfully problem has not gone away yet so, we are still business. So, that is very important to understand how the technology was also and some day this will stop, I do not know what else comes at that time.

So, here we are I am going to analyze it, but since I am not, I will not explain how to do the acoustic how to do because, I already explain and. So, what I will do is concentrate on how the heat release rate has to be calculated or how the heat release is the effected by the fluctuations. And then I assume that you know, two different methods one is time domino analysis and frequency domino analysis to solve for the acoustic fuel. So, here we concentrate on the participations on the heat release ratio, heat release rate of heat flame, particular emphasis to the role of equalization fluctuations.

So, everything is same we have feedback between acoustic waves and heat release and that is what makes the instability, there is no difference in that. The only difference is all the partavation heat release is coming. So, acoustic partavation of velocity or pressure at the fuel injector in this usually, acoustic pressure at the fuel injector will fluctuate and that will inject model at the fuel concentration and the velocity fluctuations will also kind of modulate the air flow, air flow rate.

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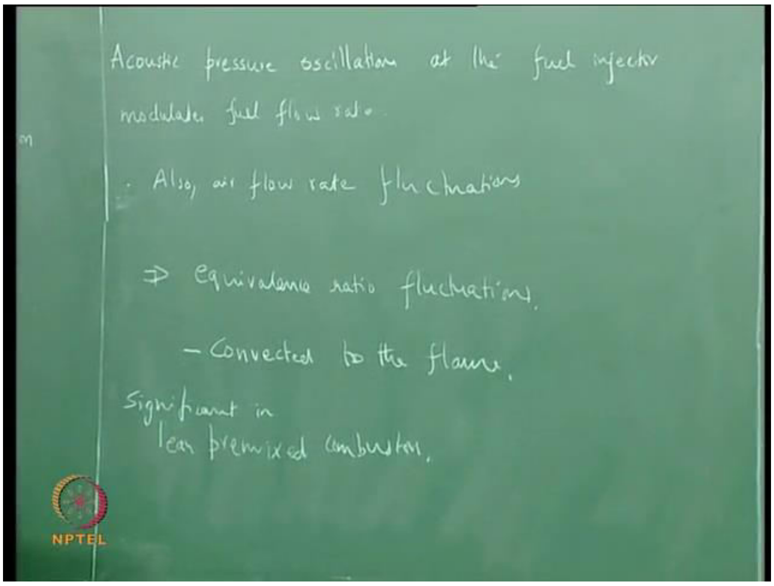


So, similarly acoustic pressure oscillations and velocity oscillation were model at the air flow. So, therefore we will have equivalence flow rate, equivalence ration fluctuations so this will be. So, you have in ((Refer Time: 17:08)) equivalence ratio and they are converted through the fuel air premixing section to the flame front where the model at the heat release of the flame. So, these equivalence ratio fluctuations are converted to the flame and of course, those conversions naturally there will be convective time lags also. So, and we know that, we love time lags, if there is a time lag, you have a chance of under some condition things going unstable.

So, this is very significant and this mechanism is very significant lean premixed premier priced combustion system. And I must emphasize that lean equivalence ratio near the lean blow out limit, the flame speed S L is a very, very strong function of equivalence ratio.

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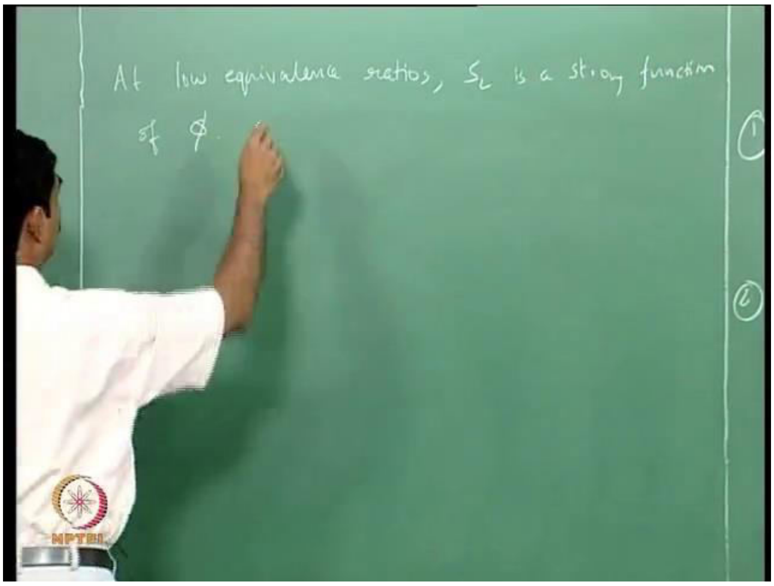


A small disturbance can feel and make actually a large disturbance in S L, which will lead to a large disturbance. I will draw a schematic of this combustor.

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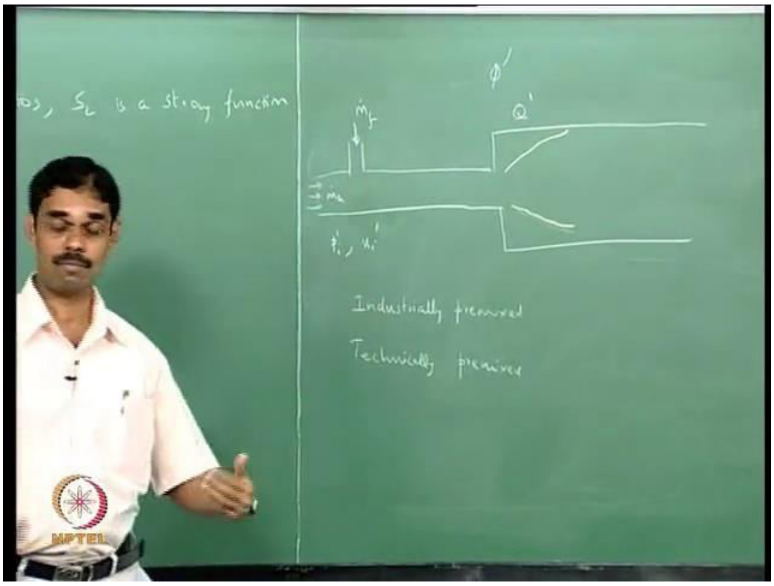


So, we will draw a schematic of a combustor and so you know combustor is you know it is much more complicated than this, but we have. So, this is the heat released so, there will be cube prime here, prime coming here. Now subscript I denote fluctuations at the inlet. So, before I speak any further first I want to ask you a very simple question, you have separate fuel and separate airline and I showed you an example of a combustor where you have a premixed flame and there we had a premixer and then another mixing chamber to damp everything and then you had the ((Refer Time: 20:37)) absolutely premixed. Why are we calling this combustor pre mixed although we have a air flow rate coming here, mass flow rate, I mean fuel flow rate coming, to the separate fuel and air coming and why do call it a?

Student: By the time it reaches the combustion zone it is mixed.

Yeah, why do not you mix it in a big dabba and send later?

Student: This is, this is not only safety in case combustors and all we have air coming in so fuel we have to mix on the way

You can make it a big box or big tank and mix fuel air mixture right, instead of having a fuel cylinders

Student: We can control the equivalence ratio and based on the demand. We can switch off the flame whenever we want, in other case there will be a lot of

You can turn off with a valve, one thing what sir pointed out is important we can locally very fast adjustment of equivalence ratio can be made. If it is in a big tank, it will take quite some time to adjust things.

Student: In graph you cannot have a separate thing.

This in air craft it is not a premixed flame by the way, it is a diffusion flame and what is burning there? Liquid flame so, we are not talking about it, we are talking about gas burners which burnt natural gas or whatever other gasses available and it mostly gas burner or even if it is a liquid fuel. We are talking about, we can actually have injectors here, prevaporize the liquid. So, LPP transfer link premixed prevaporized also so, all you can have natural gas coming one of these things. So, why are we not calling diffusion flame or non-premixed flame and you said it is because we are mixing it in this tube, in this tube.

So, I think safety is the predominant thing I think because it burnt over I mean it is, they burnt a very large amount of I mean several kilograms per second, to even perhaps big ones may burn, I mean 100s of kilograms per second, tons per second. So, it is a lot of mixture and if you have a big cylinder which is I mean you have to pressurize it because, otherwise you cannot store it, it is very huge. And then if you have an explosion, then I mean it is unbelievably, unbelievably damaging or even if you have, you can have protection all that still, I mean this thing is going to go away.

So, this is called industrial premixed combustor or the Germans call it technical, a lot of Germans worked on this German Swiss ((Refer Time: 23:25)) company. So, they call technically pre mixed combustor, let us German English, it is like Germans called technical aerodynamics that means, industrial aerodynamics. So, but that name is there in English now so, it is called industrially premixed or technically premixed so, by the time it comes here it is like premixed, I hope this is clear. So, the fluctuations in equivalence ratio is created by or generated by the acoustic rays, they are here in the combustor they travel upstream and they come here. So, that what I denote by p i u y so, some of the ways come here and then they modulate the fuel and air. So, how does it physically modulate the fuel fluoride ((Refer Time: 24:22)) already answered it, can you repeat the answer again, ((Refer Time: 24:25)). How does the, is it the velocity or the pressure which modulate fuel fluoride? Why does it do it?

Student: Sometimes we get more fuel and sometimes we do not.

When does more fuel come and when does less fuel?

Student: When pressure goes down, it is going to allow more fuel to come.

So, when pressure here is low, you have a higher delta p you are putting here and so there is more fluoride coming and when you have a higher pressure, when the acoustic wave is having a maxima then, you have a large pressure drop. So, then the fluoride will be less so, if you are thinking queasy steady then, the fuel fluoride will oscillate like square route of delta p approximately, when would this mechanism do not work? Why choking will lead to no oscillations?

Student: ((Refer Time: 25:21))

Yeah, it will not go and excite because, fuel is coming so somewhere and this will proceed upstream and therefore the fluoride cannot change.

Student: ((Refer Time: 25:39))

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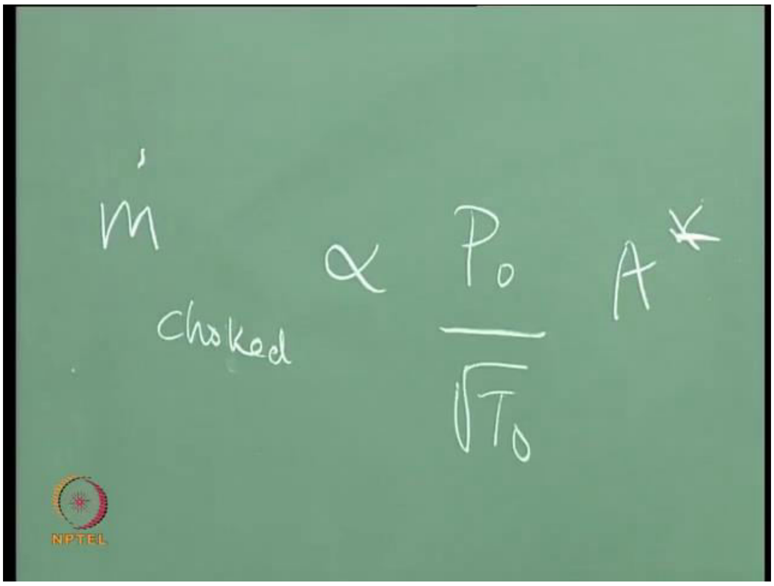


Yeah, what is the formula for so, m dot choking p naught, A star here. So, this actually there are some factors 2 over gamma by 2 over on plus gamma power some gamma plus 1 by gamma minus 1, I do not remember this factor, but do you remember any? But there is a coincidence p naught A star over square root of t naught, t naught. But under incompressible flow situations, this whole thing can be written as square route of goes like square root of delta p effectively. Now when you go to mark one and so on, you have to use this one.

Why would the air flow rate oscillate? We have a very good explanation for fuel flow rate oscillation, why did the fuel flow rate oscillate? Why is the dot A must oscillate?

Student: u prime

u prime, why?

Student: Mass power is proportional to.

Mass power is proportional to u prime, m dot s rho a v, that was the formula you remember and we do not say rho a v is constant you say. If rho a v is, the v is fluctuating then m dot is fluctuating. So, we have both the elastic fluctuations and pressure fluctuations both of them are important, but one cause is elastic causes fluctuation air flow rate and pressure fluctuations cause fluctuation at fuel flow rate.

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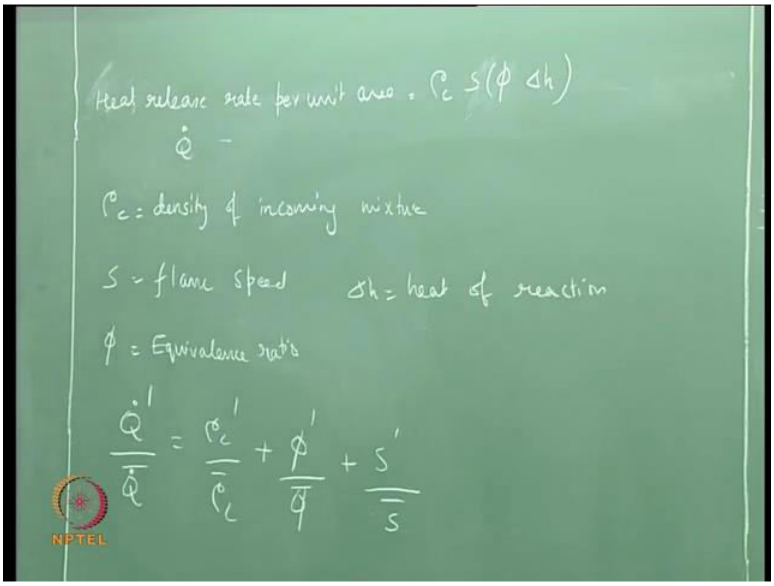


So, write down few things, this is the rho c times s is the fluoride consumed and I mean delta h is the heat to the reaction and your liquid ratio is only few times delta h is released. So, this is the formula for heat release rate per unit area, you call it Q dot so, rho c is the density of incoming mixture, s is flame speed, phi is equivalence of ratio, I could not s l I wrote s so, combustion need not have laminar flame. So, industrial combustions need not have laminar flame so, if you have talking about a linear system.

So, if we are talking about linear system Q dot prime by Q dot bar is rho c prime by rho bar plus phi prime by phi bar plus s prime by s bar. If you are talking about no mark number combustors, aero combustors are the mark number will be somewhat high, 0.2 or 0.15 or 0.25 and so on, but in this domestic burners or industrial power generation, generators fuel will be very low. So, under those conditions this may be negligible, for no mark numbers. So, we will keep this so, we will drop this and we will keep this.

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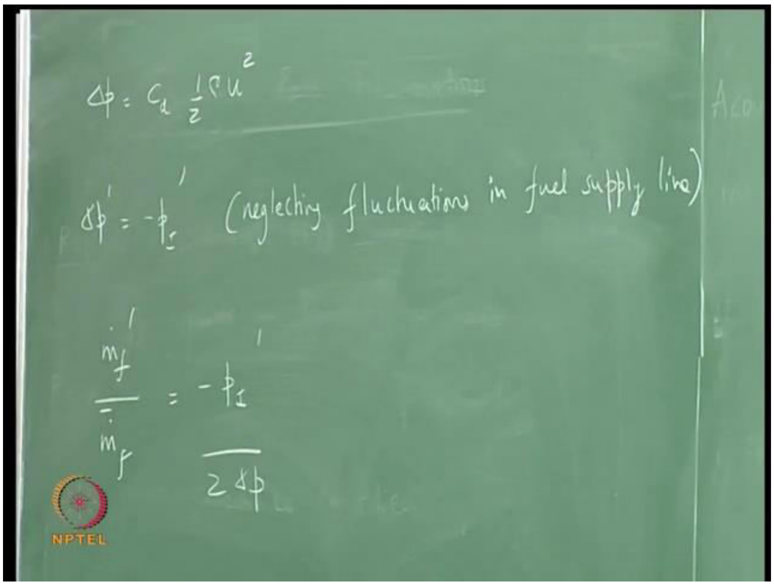


So, we will Cd is the discharge coefficient and you can for low speed flows you can write this formula and. So, delta p prime let minus p i prime assuming that neglecting the fluctuations in the pressure in the fuel line. So, m dot f will be proportional to u so, you can say m dot f prime by m dot f bar equal to minus p i prime by 2 delta p. If you take log and differentiate it, you can get delta p by p goes like 2 delta u over u so, that is where you came to these things.

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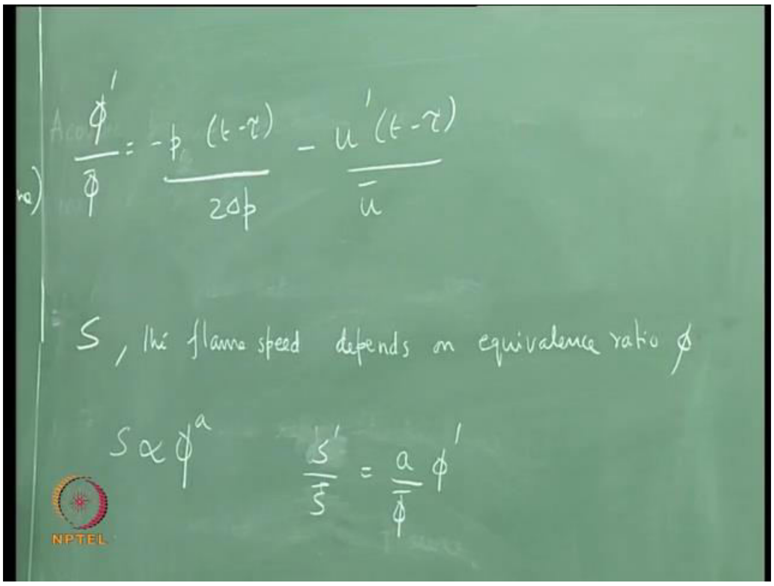


Now we will look at total equivalence ratio. So, I must emphasize that although this is the inlet, but if you think about the pressure at the combustor, then it is actually coming after a delay time of t minus tau, I mean delay time of tau. So, minus u prime of t tau divided by u bar. So, this is a fluctuations in velocity at the injector so, because of the fluctuation velocity sound has both velocity and pressure fluctuations. So, when the velocity fluctuates, velocity is increasing they effort to increase and the velocity is decreasing the air flow will decrease, that is also causes oscillatory air flow rate.

So, together they contribute to equivalence ratio fluctuation so, s the flame speed depends on the equivalence ratio I can say S is in general there are various co-relations, but some other of the form S is proportional to 3 power A. So, d s over s prime over, s bar is equal to we can do some simple differentiation and draw this, I have it here, but you can try this at home. So, you can take log s is a log phi then s prime by s goes like a Q prime by phi bar very simple.

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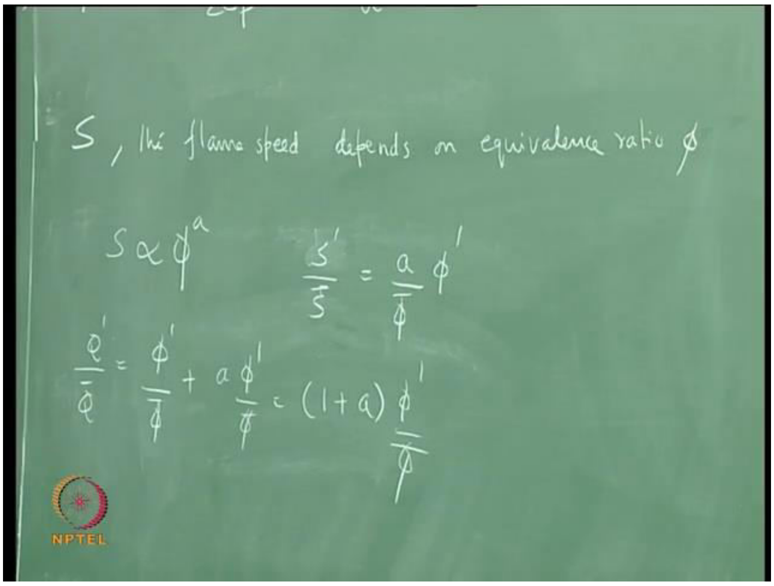


So, Q prime by Q bar is phi prime by phi bar plus S prime by S bar which is a phi prime by phi bar which is 1 plus a into phi prime over phi bar and a can perhaps be somewhat large near the lean limit and therefore, for a given phi prime by phi bar you may get large Q prime by Q bar because, a is larger.

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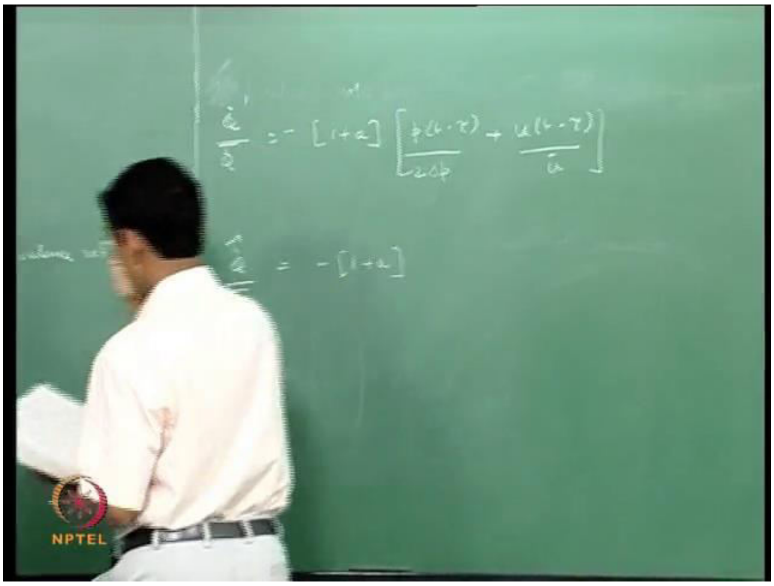

So, we know relationship between dots, heat release fluctuations and equivalence ratio fluctuations and we know how equivalence ratio fluctuations depend on the acoustic fluctuations. We just write the solution so, if you substitute this into this and we have final answer and the. So, this in harmonic domain it will be, sorry I must keep the subscript i here this, sorry I made mistake, not only a mistake.

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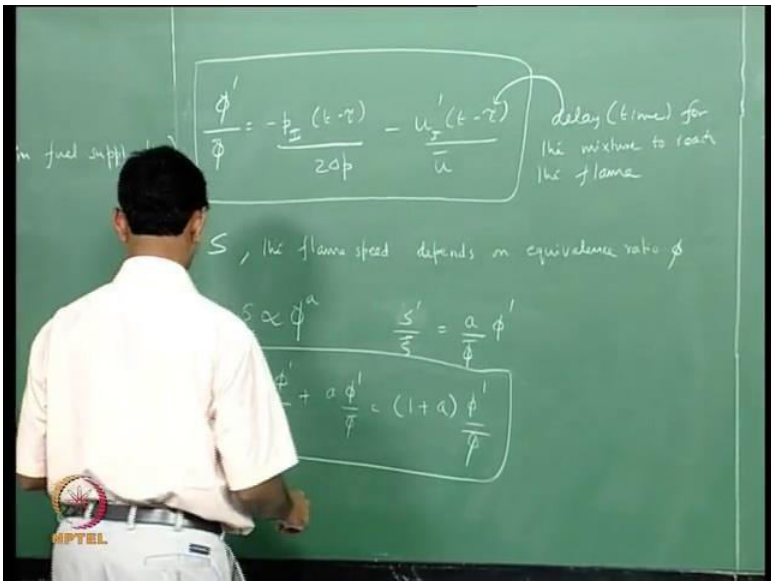


So, the pressure at the inlet effect this then, so you have a equivalence ratio fluctuation, it takes certain time to get convicted here and only after that it burn.

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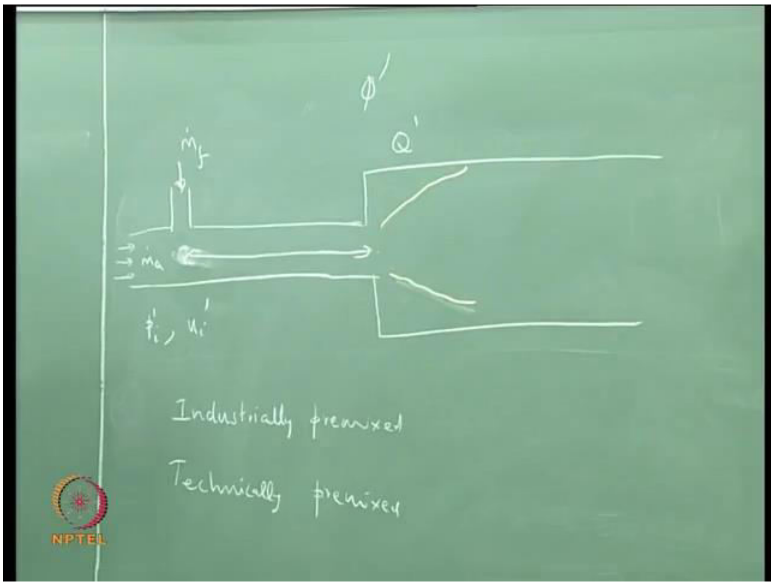


So therefore, you have the fluctuation here and it travels this distance by convective time delay and then it burns. So that is so, the tau comes from the delay or the time for the mixture to reach the flame.

Student: Here order of tau will be velocity

Yeah, it is the order convective velocity and p i will have a relation to p which is the order of l over c. So, the total thing from with respect to the p i will have a delay with respect to p as in.

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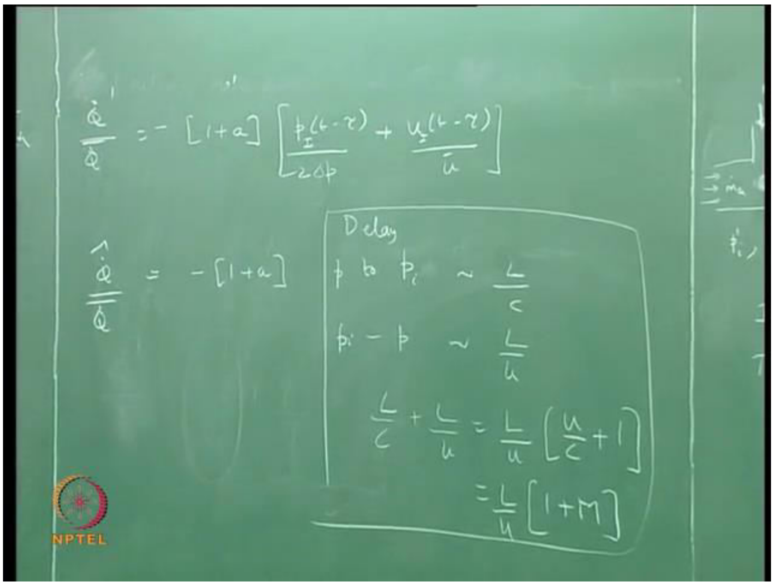

So, p i is delayed with the combustor p i, p to p i would be like to c over no sorry, l over c and p i to p would be of that is back, would be lot of l over u. So, l over c plus l over u equals l over u into u over c plus 1, right l over u into 1 plus m. For m is small, it will be of the order of l over c, if m is small then m is let us say 0. o or something then it is l over 1.1 is closed here. So, as I will give you a reference ((Refer Time: 39:54)) Ph.D. thesis there he has given various examples, in time process and heuristically calculated many things when things are not stable. When things will become stable, even before you does this calculation of Eigen values and so on.

So, I think it is a good exercise to walk though that, I answered your question? Can you speak loudly?

Student: Yeah, o this is not related to the topic. Acoustic flow, is it generally laminar or it can there will be acoustic flow in the new prime?

Yeah, this is a very tricky question so, how to, ((Refer Time: 40:37)) and so on, but people are so, it all depends on what you see also. So, we need scale at so, if you have hydrodynamics and acoustics decoupled then, there is no problem. Hydrodynamics has turbulence and we have much number acoustics, it is not couple, but then they are couple. So, if you, the way to see acoustics would be, you do some phase locking or condition assembling and you know the acoustics frequency. So, you know look at the signal at the various times and then reconstruct the signal together and then.

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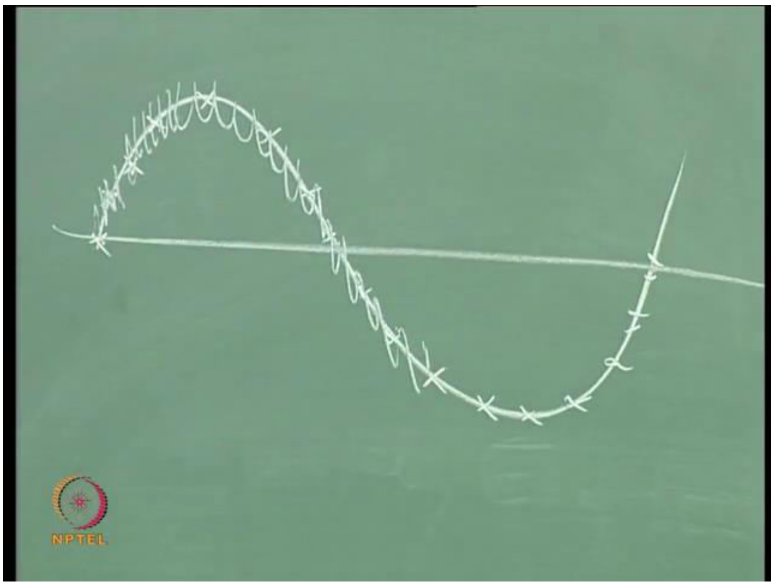

Let us say we have a reference signal somewhere here, we have reference signal which keeps repeating. So, I take values at this phase, I take values at this phase, I take values at this phase, here, here, here and like that all over and then, if you construct velocity from this bin. So, you will actually have if you look into the velocity it will have lot of fluctuations varying on the mean so, we have a let us say clean pressure single or you can even turn on a, you can take a tube connect a loud speaker to this combustors and drive it with some sine wave all that. So, let us say we phase lock the single to with that, I have seen some experiments like this, one of my friends used to do and you will see lot of fluctuations on top of this signal, which is phased average at the acoustic period.

So, could you call this turbulence perhaps, but I mean that is difficult because, we cannot quite separate that non-uniform flow under heat release fluctuations, hydrodynamic acoustics are very coupled. So, what is acoustic would be like a average, everything which are, one second you average all the fast scales and then you see hydro dynamics and you in space you average and then what you see would be like acoustics. That is one crude way of answering, but I think we have.

Student: ((Refer Time: 43:00)) order of acoustic, like velocity of sound will be which has a time.

So, I think what you have to do is if you are looking at the thing clearly, you have to look at the Eigen values of the operator, linear operator and if that is seeing and then you can call that fluctuations or acoustics. So, if it is experimentally determined, you have to let us say put you pressure on 2 locations and do find out, you cross correlate them and see what is the delay between them. And if that is speed of sound then, you can say okay there is something acoustics to it, but there could be, this could be mixed more and I think these are not analyzed I mean these are topic of our current research.

So, I cannot give you a proper answer, but it is like a half big answer, but this is very good topic to do research on. Any other things?

Student: Acoustic field does not have a convective mass so, we cannot actually about laminar.

A purely acoustic field cannot have any others things so, here we are in general we have acoustics which we have leant in the first class and then we have learnt fluid mechanics and so on. But this is acoustic is where then, acoustic is coupled to hydro dynamics because, a non-uniform flow heat release rate. So, then these I can practice which are originally distinct, but now energy system is not energy in acoustic plus hydro dynamic plus entropy plus some interaction terms. So, this interaction come because of this coupling.

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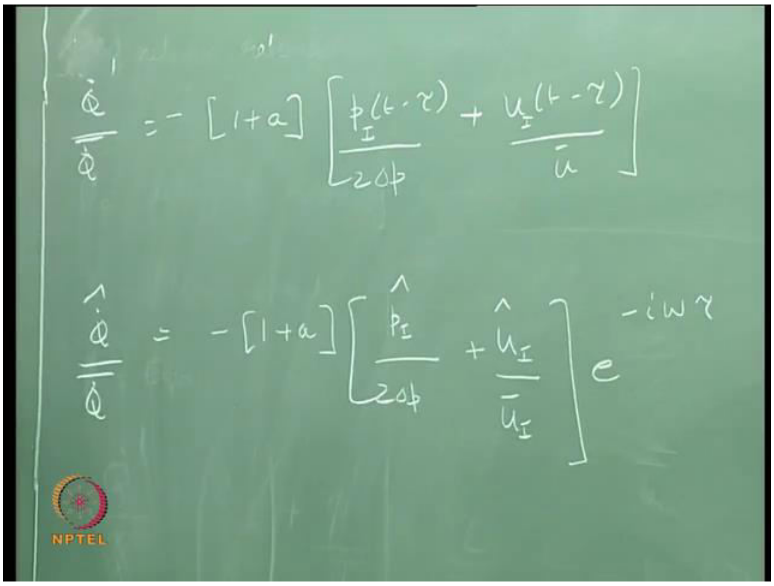


When the frequency domain, this t minus tau translate to e power minus i omega tau.

Student: Sir, what is the general range of values of a, between 0 to 1?

a can be higher than 1, if the good lean I do not often remember the values maybe

I can tell you in the next class. So, we have time demand, we have a heat release expression in time domain, we have an expression for heat release in the frequency domain. And now we have two different methods on analysis on time domain and frequency domain. So, plug this in and then we can calculate Eigen value over a time series and so on and then you can look at the Eigen vector or you can see your evolution system and so on.

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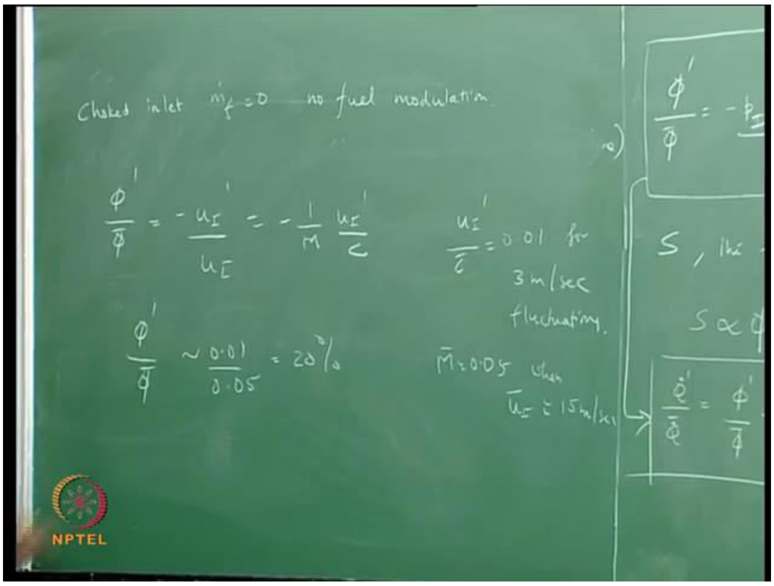


Now let us look at some numbers, we look at choked inlet where there is low fuel fluctuations. This is an example given in Lumens thesis so, no fuel modulation phi prime by phi bar equal to. So, let us look at how these numbers over a u prime by c bar is 0.01 per 3 meter per second fluctuations of that order and m bar will be 0.05 when u i bar equal to 15 meter per second if the flow rate is, if the flow velocity is 15 meter per second then m bar is 0.05. So, phi prime by phi bar is of the order of 0.01 by 0.05 equal to bracket 20 percent. So, you have, we cannot substantial phi prime by phi bar and that can be lead to substantial heat release of oscillations.

There is one more issue that is involved here, other than this instability leading to oscillations, when you have large amplitude oscillations and you are at the lean law. Now the flame whether stays or not, depends on whether locally somewhere the radicals are there and you are having the flame velocity match the flame velocity, but then if you have a very large amplitude oscillations, flame may blow out. So lean, under very lean conditions, the amplitude oscillations can have, can lead to lean blow out. So, we cannot quite oscillate, we can quite operate the combustor as close to the lean limit as you want.

Because, we can blow out so, you will have to always have a factor of safety where, you the oscillation do not trip the flame to have blow out.

Student: In this case even there can be situation where the mixing becomes proper because of the acoustic.

Mixing becomes?

Student: Because, here there is the, that thing where mixing happens and the blow of can be because ((Refer Time: 49:19)).

Mixing will be very good actually I think when there is an acoustic oscillation so, that is not the reason. I think the stability itself will be altered so, blow off happens when yeah, I think it needs some elaborate explanation, but I think the flame cannot be stabilized under large amplitude oscillations.

Student: Mixing will be better?

Much better, okay so, that is not the reason, any other questions?

Thanks.