Combustion in Air Breathing Aero Engines
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Lecture - 60
Combustion in Scramjets-III

Welcome back. So, here I will look into some of the very basic design considerations. So for So, in this thing in the same Engine if you want to design for a large mach number range, that it is say for mach number 3 to mach number 15.

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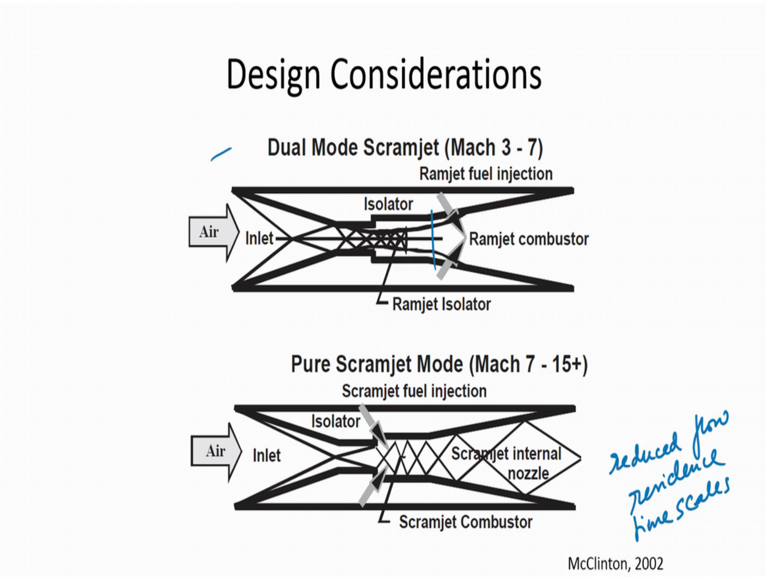

Then you have to have a range where it operates basically you can operate in a ramjet scramjet mode which is called the like dual mode scramjet. And then you can operate it in a pure scramjet mode when the mach number is greater than 7 ok.

So, in the dual mode scramjet what you have is essentially you have the air coming in and then you have this through this shock trains the flow gets compressed. And then you have the constant area isolator. And this flow that can essentially happen is can be will be can be subsonic in some parts. And then you add fuel and then this can be a ramjet combustor. What is in the pure scramjet mode this air passes through this the shock structure is of course, different because you have a mach number much higher and then this the shock trains are prevalent ever in the isolator which contains the shock trains, and then you have basically add heat you basically add fuel much upstream, because now you see that this has much reduced flow residence time scales.

So, you add fuel even before the isolator itself. And then you can have a design. So, one of the major considerations is that there are 2 things that is like the length of the isolator which can contain the shock train and the divergence angle and the length of the combustor.

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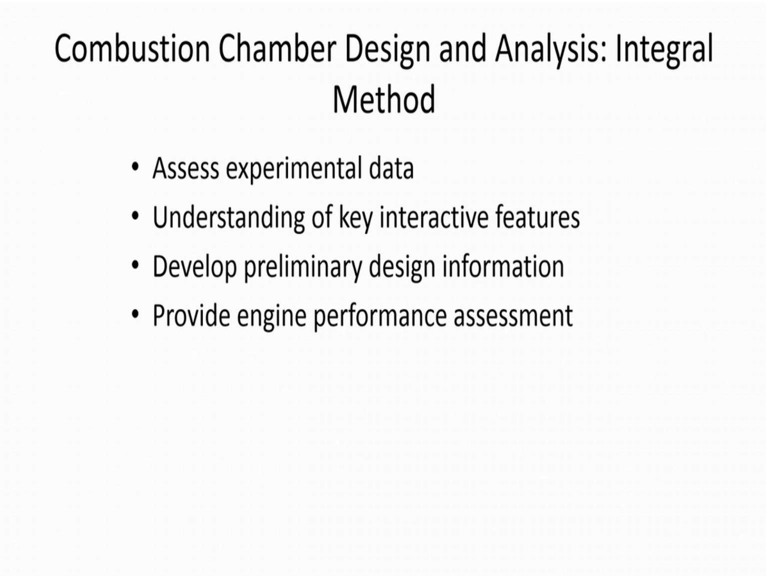

So, we will not as I said we will not go into this details, but these are the main things and there are like several correlations as well as empirical relationship semi analytical relationships that there. But there are people basically can use essentially 3 type of methods one is the integral method that like the rayleigh flow analysis that I showed you. One can use the differential equations to sol to solve the different processes, but the same things, but essentially the processes the equations that you need to solve are essentially the mass momentum energy and in if you want you can species equations can also be invoked. And even if you want to do further analysis they can of course So, you c f d to these do the design.

So, the integral analysis is mainly used to do the assessing the experimental data and understanding the key interactive forces features and the development for preliminary design information and provide engine performance analysis. So, provide engine performance assessments. So, this these integral analysis this even if they are one d are very rudimentary this is extremely important and must be carried out before going into any sorts of complicated analysis ok.

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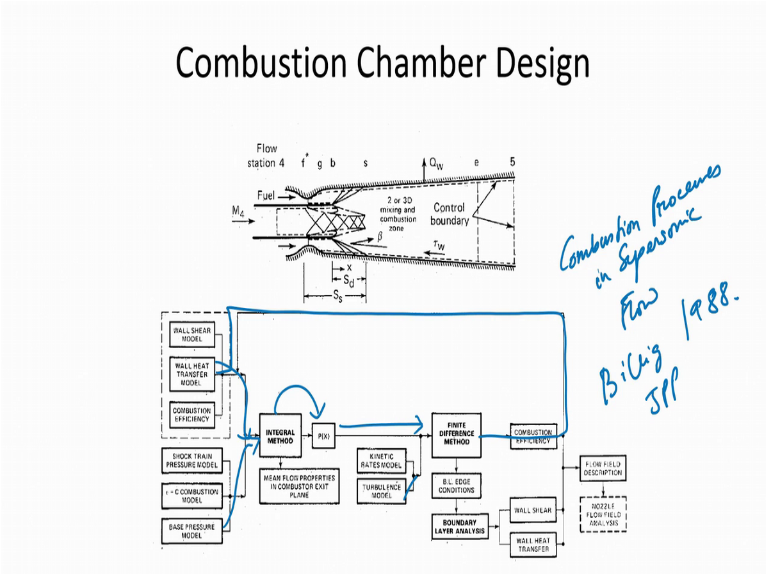

So, typically you can one can also couple this comes from bullocks paper scramjet combustion processes sorry, combustion this comes from this vapour combustion processes in supersonic flow by billing is one of the pioneers sub scramjet from this JP journal of propulsion power in 80, 1988.

So, what he says is that one can essentially couple the integral method and the differential methods to solve to develop a design. So, the integral method should he give you the pressure distribution and then that can the pressure distribution, but there was some of the integral method needs to be fed with the wall shear model the wall friction model the wall heat transfer model the combustion efficiency model. And the shock strain model the there can be base mission model all these things should go into the integral methods. And then the integral method can provide you the pressure distribution the pressure rise inside the combustion chamber. And then you can feed this information into the finite difference method.

So, the finite difference methods because it is like you can incorporate the rate kinetics model turbulence model etcetera. And then you can have the combustion efficiency and that is this can be 2 many other things also. But then this can be used to refine your integral analysis itself. So, in this coupled manner in an iterative manner the whole analysis process might evolve.

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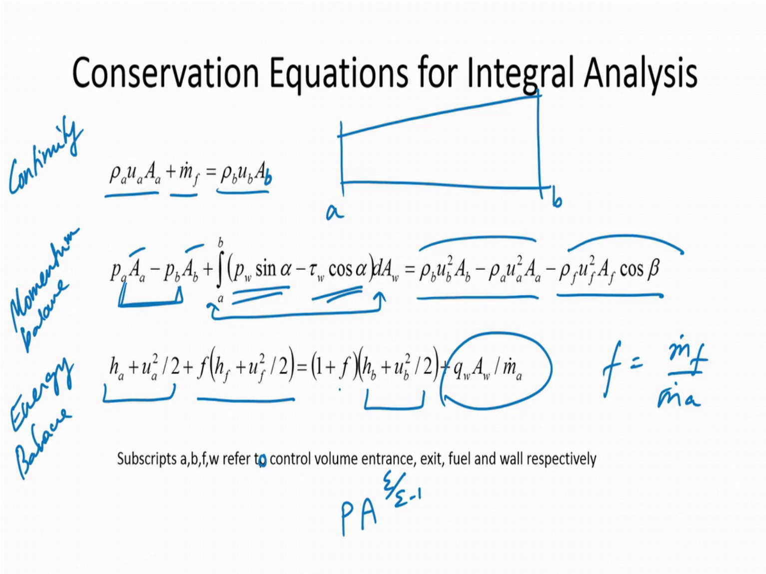

In the for the integral analysis the equations that you need to solve or essentially this the continuity energy and the momentum equations.

So, this is your continuity equation. So, where you have So, this is the say between say 2 stations a and the this is between 2 station a and b your total mass flow rate at station a plus the mass flow rate of fuel that is a is equal to the mass flow rate at station b. The pressure the force arising due to pressure differential must be balanced by the inertia forces and that due to the fuel and also there has to be like losses that can arise due to the friction as well as the fuel injection So, whereas, this a b f w refer to the refer to the control volume entrance exit fuel and wall respectively. So, the whole this is the force balance inside the combustor that is this is or the momentum balance, change of momentum balance or force balance. So, this is this is the force arising due to the pressure forces at the inlet and exit this force w sin alpha arises due to the due to the due to the fuel and the wall interactions and this is the shear stress that are resisted to the from the walls. And this is the inertia force changing due to the flow acceleration or deceleration and this is due to the fuel injection ok.

So, these are the forces and then you can have of course, you have to use the energy balance, where the total you see this is the thus stagnation enthalpy at exit at station a and this is essentially the stagnation enthalpy at station b of course, the fuel mass fraction is to be added. And this is the fuel stagnation enthalpy, where f is the fuel to air ratio and of course, this is the heat addition because of the because the additional enthalpy that the fuel brings in with itself.

So, f is essentially your m dot f by m dot a that is a fuel to your mosperatory ratio. So, b using this integral analysis one can essentially derive the different design the engine, but of course, it as you see that this is much more complex one of the thing that is needed is that with the pressure area variation because the you see that the area at section a and area at section b is not same. So, the area is essentially has to have a divergence to accommodate the addition the heat addition in the supersonic flow. So, for that people do use different things like there are like krakows pressure area tailoring and like p times a divided by epsilon by epsilon minus 1. So, whichever as epsilon can be equal to 0 one and minus gamma minus gamma m square depending on whether it is a constant pressure process whether it is a constant area process or a constant mach number process.

So, those things are people do additional empirical correlations that people induce to develop this design, but it is essentially the solution of this 3 moment continuity momentum and energy balance that gives rise to this that with which one can go into that Design analysis.

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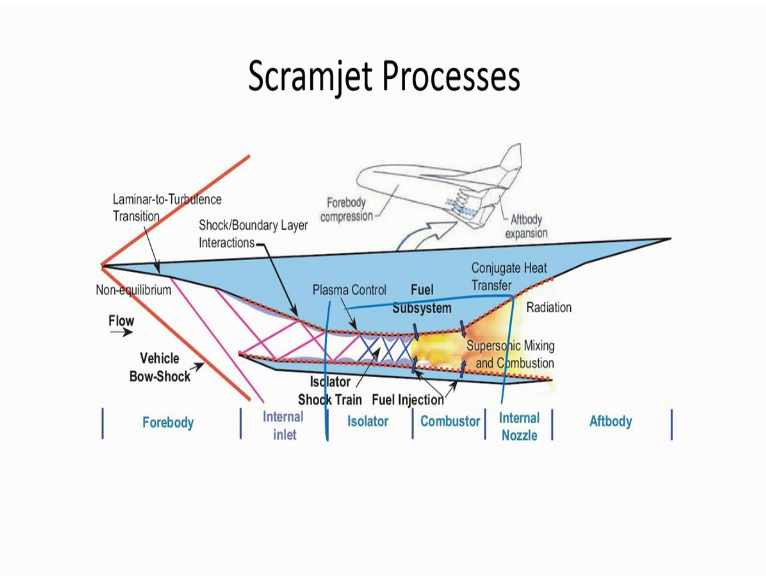

So, once again this to remind you these are the scramjet processes that which are of interest to us that if we are looking into the isolator and the combustor part that of course, we have a shock train and downstream of the shock train we inject the fuel. And the fuel must mix before it can burn and before it can burn there the fuel must ignite. So, mixing ignition burning these are the most important processes inside a scramjet combustor ok.

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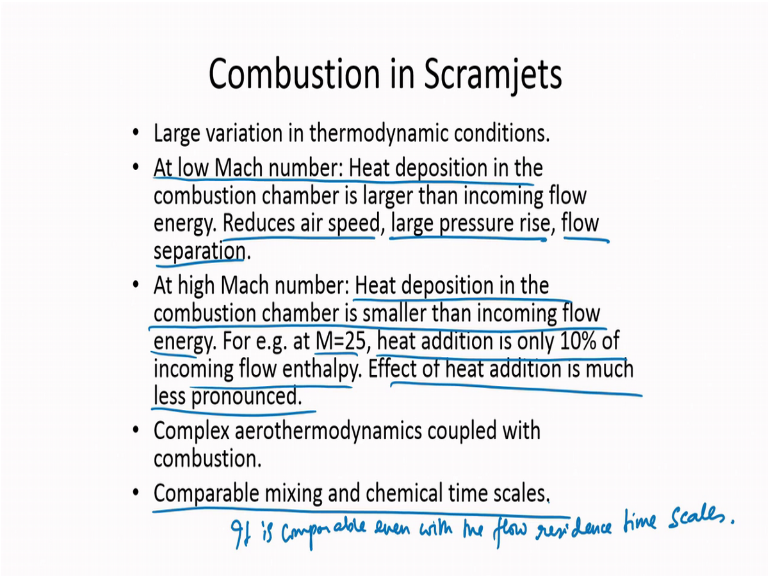

So, a such combustion in scramjets this is challenging because of the large variation in thermodynamic conditions you know. As I said before that you know gas turbine combustor it is as the flow is essentially conditioned by several things that is passes to a series of compressor blades rotor stator rotor starter plates and then it comes to the through the diffuser and they before then it goes into the to the combustor.

So, the combustor entry conditions are pretty much well defined it cannot vary too much. Whereas, in a scramjet there is no such rotating or in a machinery to control it and it is only the cross section radius that changes it. So, any small change in the upstream downstream can lead to a variable or even in the flight parameters like the flow flows which changes etcetera, those things and also lead to a large change in the change in the in the in the combustor entry conditions and the variation can be bought in thermodynamics as well as in the in the flow parameters ok.

Know now at low mach number the thing is that at low mach number the heat deposition in the combustion chamber is larger than the incoming flow energy, but then as a result of that the pressure rise is also higher and there are like more chances of like upstream shock formation. So, as a result of that the flow speed is reduced, because the heat release effect is very strong here and that can lead to very large pressure rise and that can also lead to flow separation. So, does not mean that the low mach number operation of a scramjet is simple that is a mach 2 operation is not simple in, but as at high mach number the thing is that your heat deposition in the combustion chamber is smaller than incoming flow energy for example, at mach 25, if you at all it is possible there is no such mach 25 scramjet engine whereas, the heat addition is only 10 percent of the incoming flow enthalpy.

So, this is not really useful and effect of heat addition is much less pronounced, but then why will you operate a scramjet engine at a mach 25 and the heat addition is only 10 percent with the flow enthalpy. So, simply not worth it and the another thing is that the complex aerothermodynamics coupled with combustion. So, here you see that just before that before combustion happens there is a series of shock trains even inside the combustion chamber of a of a scramjet engine is characterized by several kind of like oblique shocks expansion fans and short boundary layer interaction these are ubiquitous in a scramjet combustor. So, the in the aerothermodynamics is really complex and the combustion process cannot be learnt cannot be a mixing and the combustion process cannot be learnt in isolation from this complex aerothermodynamics and the shock combustion interaction shock boundary layer interaction.

So, one has to understand this in a much more integrated manner. And another thing is that the mixing time and the chemical times scales are comparable. And it is comparable even with it is it is comparable even with the flow residence time scales. So, mixing the flow residence time scales the mixing time scales and the chemical time scales are all similar. So, the mixing in the chemical time scales are similar. So, that since that the that is very strong turbulence chemistry interaction. When the residence time scale and the mixing are similar when they on the chemical times scales that that poses great challenge to flame stabilization.

So, these are the different challenges that one encounters in a scramjet combustor. So, what are the key processes, if we look into the scramjet combustor apart from the aerothermodynamics that is the in terms of the combustion itself.

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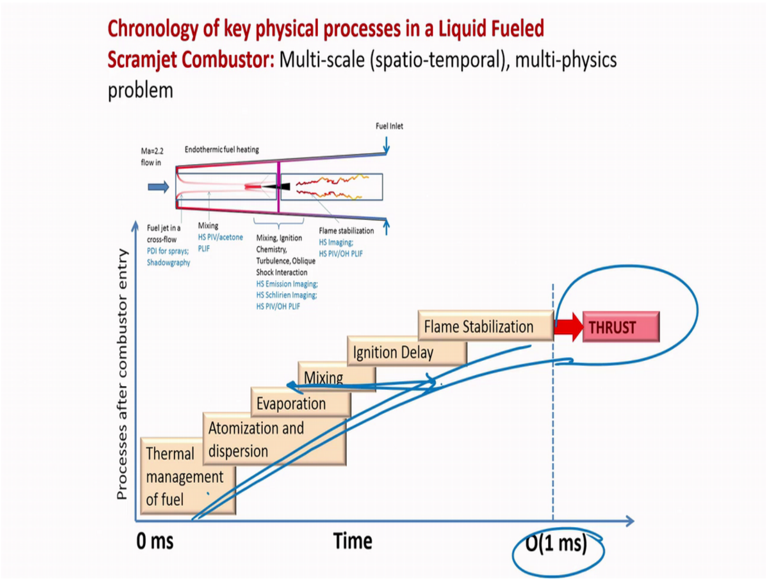

So, if you say that the Combustor has a total residence time of about one milliseconds. So, of course, you need to have thermal management of fuel if you are using a liquid fuels then of course, you have to it has to there has to be break up the liquid jet must break up there has to be atomization there must be dispersion. And there must be then you have to have evaporation then you have to have mixing. The mixing is actually a very long process and then you must have ignition delay So that you must have ignition and that takes some time and then you have flame stabilization.

So, all these processes you see take time and all these processes has to be completed within this one milliseconds and, but all these processes this processes functioning properly in an interacting manner is required to generate the thrust. So, all this process must function perfectly and they must function satisfactorily within one milliseconds. So, that proper thrust can be generated. So, this is the basic bigger biggest challenge of a scramjet engine that you have to have all these processes in a in a that done a very, very short amount of time which is extremely challenging.

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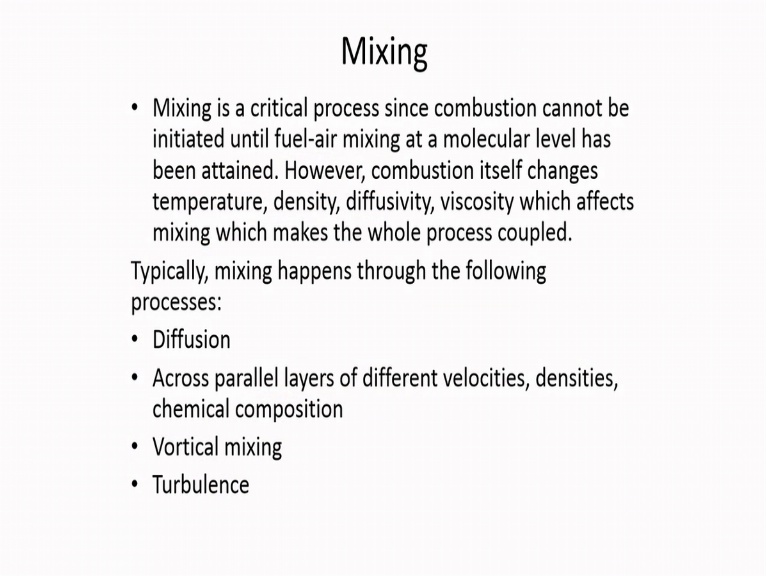

So, we will go into mixing the mixing is a very, very important process inside a scramjet. As you see here that a mixing is a very, very important process and mixing as suggest the process often is the process that takes most amount of time. Now mixing is a critical process why because we all know that combustion cannot happen it cannot even be initiated only fuel layer mixing at a molecular level has been achieved.

Now you cannot study mixing in isolation inside a scramjet because ultimately the your mixed of fuel are mixed state must undergo combustion and when it under goes combustion it that local temperature density diffusivity viscosity everything changes. And then that affects mixing itself we will see that mixing essentially in this scramjet combustors are controlled by essentially mixing layers and large roll ups of the shear layers and of course, very strong turbulence mixing is there.

So, all this process is essentially controlled the mixing and the subsequent combustion. So, in this scramjet assuming you can say that mixing happens to diffusion, it can it happens to parallel layers of different velocities densities and chemical composition. Or it happens a vertical mixing and of course, it happens to turbulence.

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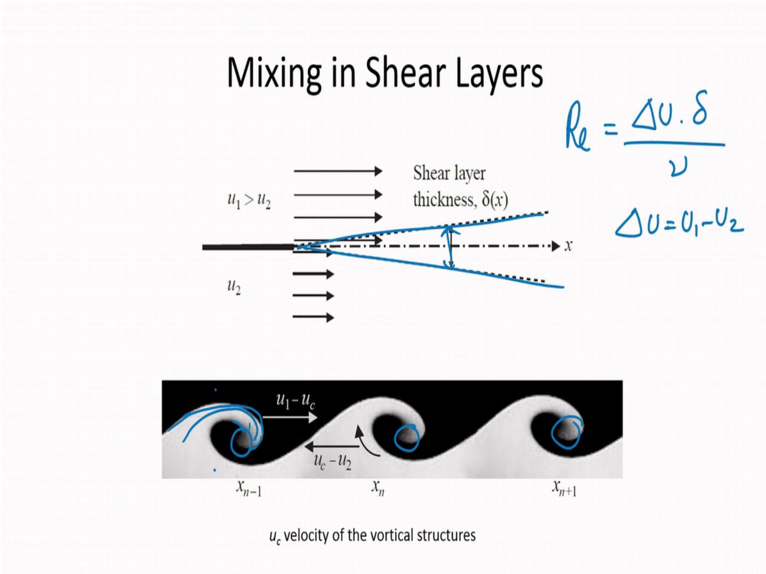

So, if we consider the mixing in shear layers. So, what is the shear layers shear layers is essentially that region in the flow which is characterized by strong velocity gradients and essentially which results in strong shear forces. And that is caused by when that is that happens when you have 2 parallel layers which are moving at different velocities as in this case.

So, in that case if you have 2 parallel layers moving at different velocities u 1 greater than u 2 one moving with u 1 another moving with u 2 and u 1 greater than u 2, then you will have a shear layer developing between them and this is governed by the shear layer thickness. Now the Reynolds number that is typically characterized used to characterize essentially this delta u times delta which is this shear layer thickness divided by n u and whereas, the delta u is essentially u 1 minus u 2 ok.

And then of course, when you have this kind of a situation then this shear layer does not develop like this itself. What happens is that it leads to development of this instabilities here you see like a kelvin Helmholtz instability we formed. And when there is instability there in a large scale vortex roll up. And you see that this is a one fluid this is another fluid of course, there is velocity difference between them and there is composition difference between them. And you see that how mixing is happening there is not much mixing happening through here, but there is this rolls up and then there are like large strain that is formed. And then there are because of the when there is a large species gradient and large velocity gradients then you see that mixing has happening is happening along these regions ok.

So, it is this type of like roll ups vertical roll ups that assist in mixing when in high speed flows, eventually it is there has to be diffusion that at the smallest scales which has to mix the 2 fluids. But then the diffusion process is assisted by creation of these large species gradients which is accomplished through this different roll up of this of these different structures which assist in creating these large species composition gradients in the flow itself. So, this is the thing and where you see in this we can do different kinds of analysis you can define a convective velocity which is the velocity of these vortices of that are moving etcetera.

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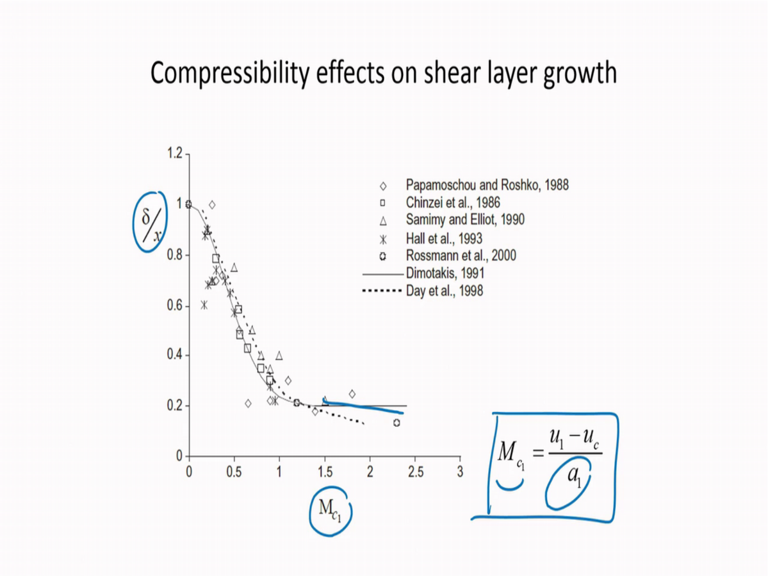

Now, one of the thing is that here we u n d want to understand the effect of compressibility on shear layer growth that is you can define as I said that you can define a convective velocity here. And which is the velocity of this vertical structures which are moving. Now if this becomes large mach number that which is typical in a scramjet combo in a scramjet engine. How does really the shear layer development happens? Now why are we developing interested in the shear layer development, because even if there is composition difference the mixing layer that will be formed or the reaction layer that would be formed will be essentially embedded inside this shear layers.

So, this embedding we need to do understand what happens how that what is the thickness of the mixing layer or what is the thickness of the reaction layer. The bigger parameter is essentially the shear layer look at this thickness. So, since this reaction layers mixing layers are always embedded in the shear layers which is of interest to know how does I mean shear layer develop in this kind of compressible flows, such as such it turns out that it is a very non intuitive that if we define a convective mach number like this where M c 1 is equal to u 1 minus uc.

Whereas, uc is the convective velocity divided by the sound speed and the fluid one that is this is this is the fluid one and this is the fluid one this is the velocity of uc. And if you define a convective mach number based on that which is defined as that difference between u 1 that is the free stream velocity of one minus uc divided by a one and that is my convective mach number and if I plot the delta by x that is the shear layer growth this as a function of the as a function of distance at M c 1 as a function of mach number, we see that at after mach number equal to one this essentially asymptotes.

So, there is not much of a shear layer growth. The shear layer growth is important for mixing because once the shear layer becomes very large then the essentially that is where inside which the 2 fluids essentially meet and can mix. So, but this is a kind of an asymptote at about mach number of starting at which is reached the mach number of 2, says that with the compressibility essentially has a has a limiting effect on the shear layer growth and the corresponding mixing. So, one has to one cannot rely only on shear layer development for to achieve mixing one has to think of some other processes also in a in a in a in a compressible flow.

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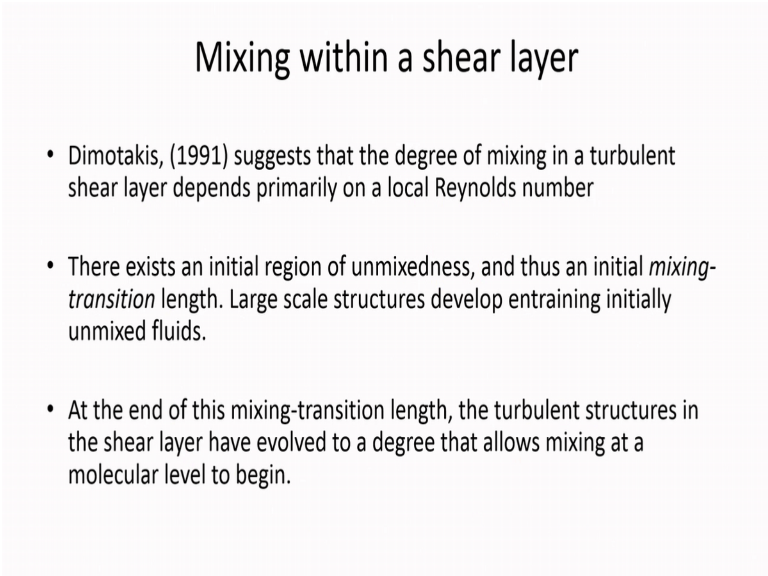

Now, a such more there are more to mixing within a shear layer whereas, dimotakis suggested that that it is essentially the local reynolds number which is this guy can define the mixing within the within the shear layer or the development of a or the or the or the mixing inside the shear layer can we develop can be defined by this. Now, but the thing is that he said that there exists an initial region of unmixedness. So, just after the shear layer is developing when this large scale roll ups are happening it does not mean that mixing start immediately ok.

So, he says that there is an initial region of unmixedness and which is this region of unmixedness is called the mixing transition length. So, there is no mixing in this mixing transition length or very limited mixing that. The reason is that this is at this region this large scale structures develop and then train initially unmixed fluids. So, for this the large scale structures essentially roll up. And So, they create the strain on this on this the fluid elements and essentially create a large grandee and through which mixing through which mixing can happen, but then that tax takes some time to develop. So, only this fluid mechanical development of large scale structures immediately does not allow for mixing, and only after this develop and some straining has been inflicted and some large gradients of species has been formed then the mixing can start.

So, as you said here that at the end of the mixing transition length. The turbulent structures in the shear layer evolve as a as a shear layer develops the reynolds number also increases. So, it undergoes there is a turbulence also develops and this turbulent structures since the shear layer have evolved to a degree that allows mixing at a molecular level to begin. As you know turbulence helps in mixing through similar to a energy cascade process that is first this large eddies are formed and then this creates essentially large strains the different the fluid. And this as the fluid is strained then this the gradients become large and large ok.

So, even if there is a large gradient So, the way turbulence mixes is that if you have a large gradient of a species of a of a scalar. So, essentially turbulence creates large scale structures which really does not help in mixing and at as it is, but then these large scale structures develop into small and small scale structures to the cascading and as this cascading happen this small scale structures have very large strain dates. So, this large strain needs essentially creates stretches the fluid and this as the fluid is stretched it develops composition gradients across the 2 different species. And then at the small scales this composition gradients can essentially diffuse by molecular diffusivity and then these 2 can mix ok.

So, mixing essentially is a small scale phenomena and in turbulence, and because ultimately it is diffusivity or diffusion that has to control the mixing, but then what turbulence can do is that because of this because of this multi scale and the cascading processes, it can quickly form this small scale structures from the large scale structures. So, where by which the a mixing is essentially enhanced. And of course, you can see that the turbulence has a diffusive very strong diffusive nature also. That if you have 2 particles in a in a in a in a in a quiescent environment if you have a large cloud of particles in a quiescent environments, they essentially they their distance the dispersion the paired dispersion distance that is the distance between any 2 particles statistically changes like as a function as like as a proportional to t proportional to time. But if it is turbulence then this disk this distance squared change this proportional to t square or t cube.

So, as a result the turbulence essentially is very diffusive in nature and it that also helps in mixing.

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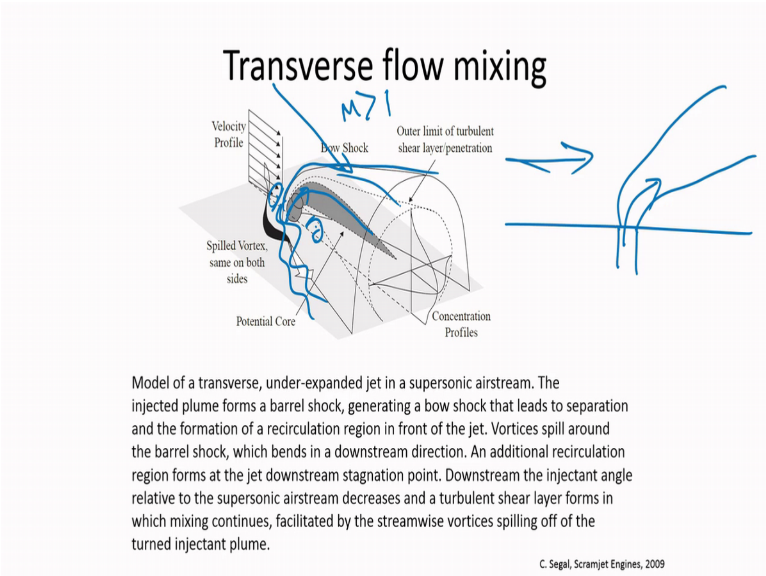

So, but then as I Said that we cannot only rely on the shear layer mixing, because incompressible flows shear layer has a has a limitation because that mach number this shear layer growth becomes limited. So, one can often use the transverse flow mixing also where they essentially inject. So, if the this is a flow coming. So, they inject perpendicular to the flow and in jet form So, like this. So, that is called a typical jet in a cross flow. But when you, but if this flow is supersonic and even if this jet is under expanded that really leads to a very complex fluid mechanical and shock structure fluid mechanical structures developing all around it.

now as you see in this model of a transverse under expanded jet in a supersonic stream. This first injected stream forms a barrel shock, and that generates this bow shock around it. Essentially we are we think of the bow shock as a 2 dimensional structure, but here you see it says essentially, because the flow field is very strongly see dimension it has a full 3 dimensional structure, and the bow shock that has formed. And it leads to formation of this recirculation region in front of the jet. And this vortexes spilled around the around this around the barrel shock and this bends in the and also this jet bends in the downstream direction.

Because there is a very strong momentum of here that is that is coming which immediately bends down the jet. And there are the additional recirculation zone forms in the both recirculation zones are from both upstream in the downstream locations here and here. And the downstream inject and angle relative to the supersonic airstream decreases and the turbulent shear layer forms when the mixing continues. And this is facilitated by the stream was vertexes spilling off from the inject and plume.

So, it is a very complex structure that you can see that this there are recirculation zone forms here recirculation zone formed here and there verticity structures formed around this. So, it is a complex structure, but then this leads to very nice um mixing because of the strong introduction of this jet into the incoming flow.

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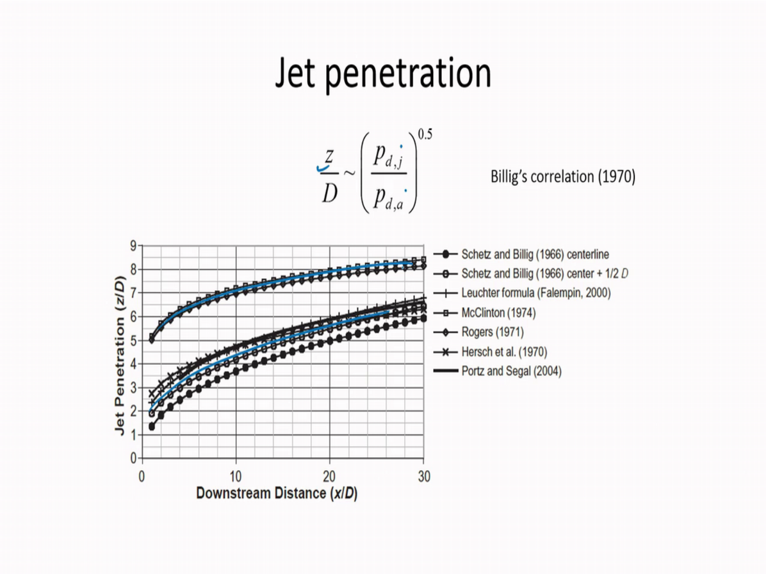

And this jet penetration is often given by the ratio of the dynamic pressures, and often this is the height of the mach disk with respect to the wall, and this is the diameter and this is the ratio of the dynamic pressure of the jet divided by the dynamic pressure of the air. And it is scales like they said by d the height from the wall divided by d scales like the ratio of the dynamic pressure of the jet to the air to the raised to the power of 0.5. And you see that this is how the jet penetration trajectories in this z which is the height from the wall bottom wall varies according to x.

So, this is how typically and there are several correlations that one you can find and literature to develop this jet trajectory. So, it is of important to understand how this when where this jet is going because you need to you need to ensure or you need to inject the jet in such a manner that it goes into the region where you want combustion. So, this formulating these jet trajectories and characterizing these jet trajectories experimentally and analytically is a very high interest.

So, with that the gaseous mixing is we have covered and then in the next step you in the next classes will cover the liquid jet injection and the essential features of the combustion process in a scramjets scramjet engine. So, till then goodbye.

Thank you.