Combustion in Air Breathing Aero Engines

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Lecture - 61
Combustion in Scramjets-IV

Hello. Welcome back to this series of lectures on combustion in scramjet engines. Now as we have discussed in the introductory lecture itself, one of the biggest reasons why combustion is used in air breathing propulsion is because of the high energy density of the liquid fuels. So, in any propulsion device that you see in any air breathing propulsion engine that you see whether it is gas turbine engine, ramjet scramjet engine the ultimate motivation the is to use liquid fuels, because of the very large energy density that it provides.

So, similar thing is scramjets also. So, for in the previous class we have discussed how the jet trajectory can depend on the dynamic pressure ratios, when we used gaseous fuels of course, scramjets in scramjets there has been many instances where gaseous fuel has been used, For example the x to 43 series of scramjets that was designed by NASA and Boeing that used gaseous hydrogen. Of course, the reason was that this gaseous hydrogen is most easier much easier to ignite and quickly it mixes because there is no such process as like liquid jet breakup atomization which are inherent in liquid fuels.

But then because of the energy density that because of the high energy dense is the liquid fuels if scramjets us to evolve as commercial propulsion engines. Probably it will move in the direction of liquid fuels. So, that is why it is very important to analyze or examine the feasibility of using liquid fuels in scramjet engines ok.

So, how do you inject liquid fuels inside a scramjet engines?

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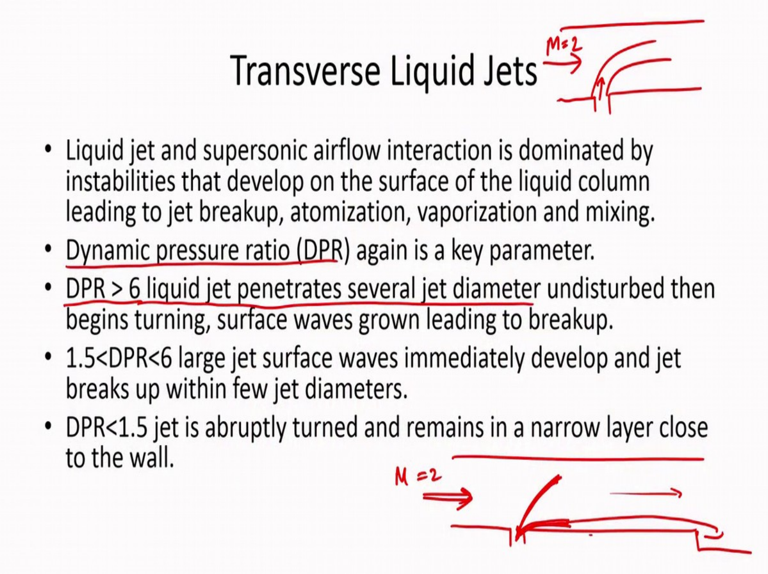

Transverse Liquid Jets

- Liquid jet and supersonic airflow interaction is dominated by instabilities that develop on the surface of the liquid column leading to jet breakup, atomization, vaporization and mixing.
- Dynamic pressure ratio (DPR) again is a key parameter.
- DPR > 6 liquid jet penetrates several jet diameter undisturbed then begins turning, surface waves grown leading to breakup.
- 1.5<DPR<6 large jet surface waves immediately develop and jet breaks up within few jet diameters.
- DPR<1.5 jet is abruptly turned and remains in a narrow layer close to the wall.

So, of course, one of the ways is to inject it in a as a transverse jet. That is suppose you have this as the scramjet engine like this and you and from here. So, you have the mach to flow entering into the combustor. So, perpendicular to the airflow direction you inject a liquid jet.

So, of course, now the liquid jet and the supersonic airflow because they come the air flow has to be supersonic because it is a scramjet. So, the now the liquid jet in the supersonic air flow will interact in a very complicated manner, and lot of research effort has is underway to understand what are the different instabilities that develop on the surface of the liquid column. And these instabilities are important to understand because ultimately these will lead to the jet breakup. And the air shear will lead to can lead to atomization.

And then of course, once droplet us are small enough they can evaporate and this after evaporation the liquid the fuel can mix with the air. So, this is this is the whole thing. It is very important thus to understand how a liquid jet essentially breaks up and atomizes in a supersonic cross flow, ok.

Now, what are the important parameters what does current what does the past research suggest. The past research suggests that the most important parameter that that controls the behavior of the jet of the of the B liquid jet where it will go how it will break up how it will atomize, and eventually the combustion properties the entailing combustion properties. Those are governed in this case also by the dynamic pressure ratio ok.

So, the dynamic pressure ratio once again is a very key parameter. Of course, you see that in the dynamic pressure ratio your momentum is also included. So, it is a static pressure plus is a p plus rho u squared that is the essentially the included in the in the in the dynamic pressure ratio ok.

So, this is the, thus both the static pressure as well as the momentum of the jet relative to the liquid jet relative to the relative to that of the supersonic airflow is a is a key parameter here. Now what research suggests is that that if the DPR that is a dynamic pressure ration is greater than 6. That is if the liquid dynamic pressure of the liquid jet is very, very large compared to that of the supersonic air. Then the liquid jet penetrates of course, several jet diameter. That is it is easy to understand that if this pressure if this liquid jet. So, suppose you are considering a scramjet and you are injecting the liquid jet here. So, your mach this is your mach 2 flow. So, if this if the jet momentum is very high of course, it will go in a it will penetrate much deeper, if the jet momentum is weak it will penetrate a much like this ok.

That is here of course, that the what I mean what I mean to say is the if the liquid jet momentum is much higher compared to this the airflow momentum. Then it will proceed in this manner if the liquid momentum is weaker compared to the airflow momentum, then it will be stay close to the wall ok.

Now, you when you are designing when you are choosing the injector and we are choosing the pressure that with which you are you going to inject the liquid fuel. Then the it is important to understand why are you want to inject your liquid fuel. Now in certain cases you might want to inject the liquid fuel So that it goes into the main airflow. In certain cases you might have a cavity as well see later you might have a cavity here. So, it might be a good idea to inject it close to the walls and allow it to stay too close to the walls.

So, then the idea is that then depending on your choice where you want to put your maximum fuel, you have to choose your dynamic pressure ratio. So, what research suggest that is the if the dynamic pressure ratio is greater than 6 then the liquid jet enter several jet diameter undisturbed and then it begins turning and then. So, it goes several jets it goes straight into it is it is it is it is penetrates into the several jet diameter undisturbed and then it begins turning and the surface waves, grows leading to surface wave grows leading to it is breakup.

So, initially the if the dynamic pressure issue is very large initially the jet does not have been filled that there is a supersonic cross flow coming it proceeds on it is own before leading to breakup. If the dynamic pressure ratio is intermediate from 1.5 to say 1.5 to 6 then large jet surface waves immediately developed, and the jet breaks up with in the future diameters. And if the DPR is less than 1.5 then the jet is abruptly turned that is in this case, and remains a narrow layer close to the wall. So, this is the different behavior of the liquid jets ok.

Now, what fuel do you use of course, we one can use different kinds of fuels like JP10, JP7 etcetera, but here once again if we just recap. So, we discussed about jet fuel.

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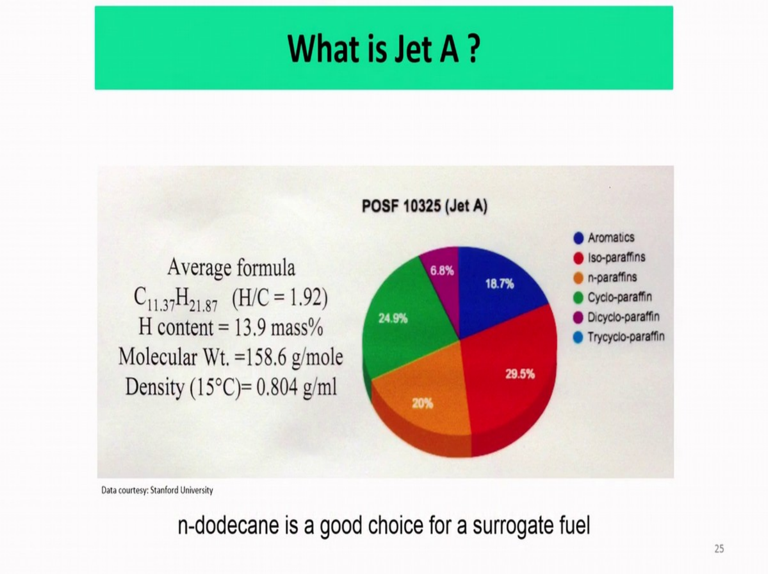

What is Jet A ?

POSF 10325 (Jet A)

Average formula
$C_{11.37}H_{21.87}$ (H/C = 1.92)
H content = 13.9 mass%
Molecular Wt. =158.6 g/mole
Density (15°C)= 0.804 g/ml

Data courtesy: Stanford University

n-dodecane is a good choice for a surrogate fuel

So, jet fuels is essentially like a mix of different things. But we want to now understand the reason why we come to jet A is that, we now want to understand typically what can be the characteristic ignition delay in a scramjet engine.

So, that is why let us say that if our jet A is a is a is a is a choice. Then we have to know that what are the basic the fundamental compositions fundamental constituents of jet A, and what kind of a surrogate feel we can use to represent jet A. And then we can find out the ignition the 0D ignition delay for that fuel air mixture and at the scramjet relevant conditions.

So, that will give us some idea about how much time does it take for ignition. And whether at all it is possible to have ignition in a scramjet at the where we can have an approximate idea about the flow residence time scale would be. So, what is jet A? Jet A as you see is a we discussed before in the kinetics class is an average formula of about C 11.37 H 21.87.

So, we can we can say that and it of course, contains a lot of like different kinds of paraffin n paraffin ISO paraffin's etcetera.

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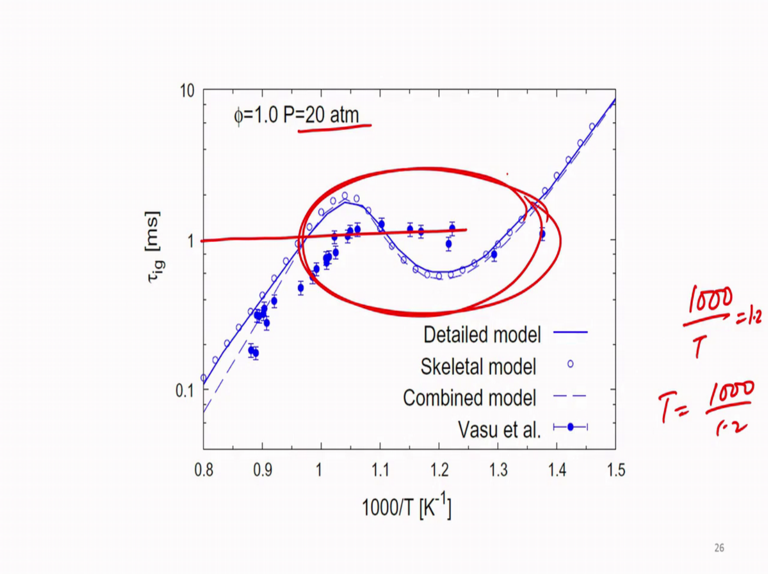

And of course, it has some amount of aromatics also. But the rest are reasonably paraffin. So, that is why people think that n dodecane this is a good idea to is a is a good is a good of alkane to represent jet A ok.

Now, if you do that what we see is that once again we come back to this to this negative temperature coefficient plot of course; this is a high pressure that you must understand. But you see that around this temperature this 1000 by 1000 by T is equal to about 1.2. So, T is equal to the 1000 by 1.2.

So, it comes to about the approximate scramjet static temperatures. So, in that region you see that we have these whole phenomena of negative temperature coefficient. So, that is why and another important thing is that you see the whole the time scale is of the order of one milliseconds, in this whole range.

So, e you have a negative temperature coefficient and your time scale is also quite large relative to the scramjet flow residence time scales. In a one meter long scramjet if the flow velocity is 1 kilometers per second. Then your the residence flow residence time scale is about of the order of one milliseconds. So, here also from the 0D ignition delay where you have not considered mixing where you have not considered anything else atomization evaporation anything.

So, the pure ignition delay time scale for our 0D mixture where it is only the homogeneous mixture of n dodecane air is undergoing auto ignition, and there itself that the tau the tau ignition is one milliseconds. So, that is why, but you have to understand that now if you want to you design a scramjet engine or you want to predict the performance of a scramjet engine which uses kerosene as fuel. It is imperative that we use detailed reaction model because this time scale of one milliseconds of this ignition delay and this NTC behavior that you see here it cannot be captured by one step chemistry.

So, that is why in scramjet engines often it is suggested to use detailed reaction mechanisms, but of course, if it is one is using very different very reactive fuel like hydrogen where these things are not important.

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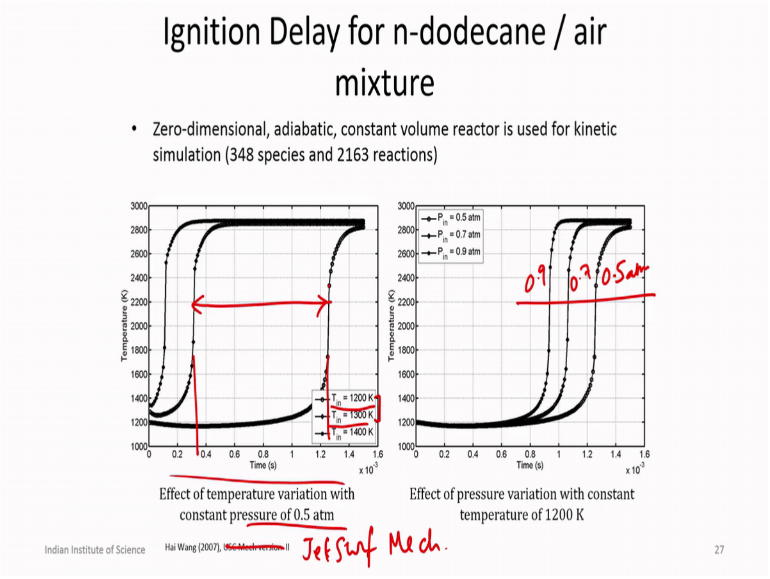

Ignition Delay for n-dodecane / air mixture

- Zero-dimensional, adiabatic, constant volume reactor is used for kinetic simulation (348 species and 2163 reactions)

Effect of temperature variation with constant pressure of 0.5 atm

Effect of pressure variation with constant temperature of 1200 K

Indian Institute of Science

Hai Wang (2007), ~~USC Mech version~~ II Jet Surf Mech.

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So, then in that case one step chemistry might be good enough. So, once again this is just a we discussed this before just to recap.

So now this gives us a idea of the auto ignition timescales which is about one milliseconds. Now if we go to the to the to the scramjet relevant conditions that is if we go to the temperatures which are little higher, that is in this range in this range which are more scramjets relevant conditions, that is then this is how the temperature the versus time behavior happens in our auto ignition calculation.

So, this is these calculations are performed using (Refer Time: 10:53) which is which is one of the suit one of the models inside chemkin for calculating the auto ignition the ignition delay for a 0D reactor where only where you only compute the change of temperature with heat release along with the species equation, but there is no transport.

So, you see that when the when your T in is about T starting. Initial is about 1200 Kelvin, then you get then you then you get this plot of about where you get an auto ignition delay about 1.2 million seconds. Whereas, if you increase it by 1300 Kelvin then it becomes quite drastically changes and it becomes of the order of 0.3 milliseconds.

So, in this range as you see that this is at a given pressure of a 4.5 atmosphere that this is a huge variation right it is a variation of from about 1.2 milliseconds to about 0.3 milliseconds. And this difference can make can render ignition possible or impossible, that is you might have a situation where ignition is impossible that if you are a 2 2 T in is equal to 1200 Kelvin, but you might have a situation where ignition is possible when you are T in is about 1300 Kelvin. Because it changes by an order of magnitude in this range it is very, very sensitive.

So, that is why it is important to use detailed reaction mechanisms. Typically for n dodecane one uses a jet fuel mechanism not this one this is a there is an error one use the jet surf mechanism by the same with same author Hai Wang. So, this is the thing that here you see the effect of pressure variation also, but that here also you see that if you go from 0.5 atmosphere to 0.9 atmosphere ok.

So, your so this is at 0.5 atmosphere and this is at 0.7 atmosphere and this is at 0.9 atmosphere. So, as you as you increase the pressure of course, the ignition delay reduces. So, the ignition delay reduces. So, from about 1.25 milliseconds it goes to about 0.9

milliseconds, but of course, pressure has some effect, but it is not as sensitive as that of temperature where you see that here with the difference once again to recap, with that with the change of temperature of just 100 Kelvin. In combustion 100 Kelvin is nothing right so, but just by a change of temperature of about 100 Kelvin from 1200 to 300 your ignition delay drops by from 1.25 to essentially 0.3. So, it is a factor of 4 almost drop that you get in the ignition delay ok.

So, this has to be has to be remembered when you do this kind of calculations and when you calculate the ignition delay time of a scramjet engine.

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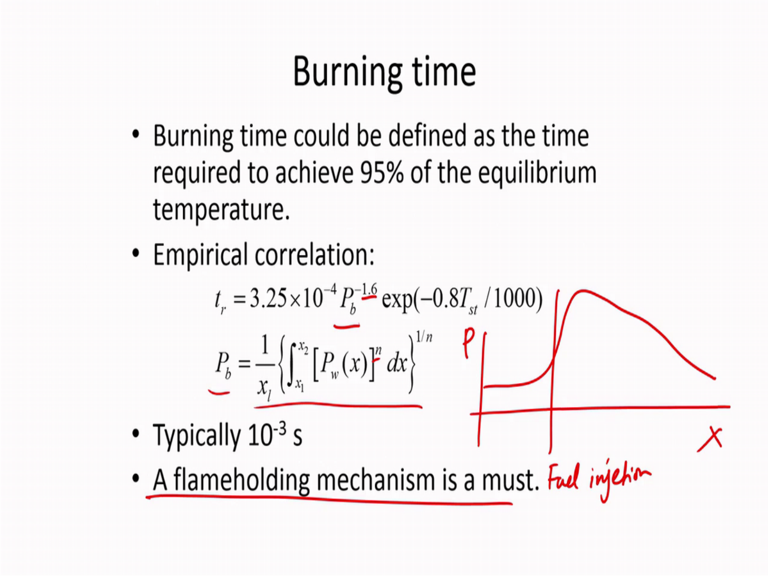

Burning time

- Burning time could be defined as the time required to achieve 95% of the equilibrium temperature.
- Empirical correlation:

$$t_r = 3.25\times10^{-4} P_b^{-1.6} \exp(-0.8T_{st}/1000)$$

$$P_b = \frac{1}{x_l}\left\{\int_{x_1}^{x_2} [P_w(x)]^n \, dx\right\}^{1/n}$$

- Typically 10^{-3} s
- A flameholding mechanism is a must. Fuel injection

Now the burning time that was just ignition delay time burning time these are empirical correlations which with which one could estimate the burning time, this is comes from the paper by mitani where he use the burning time he defined it as the burning time could be defined as the time to achieve time required to achieve 95, 95 percent of the equilibrium temperature. And the empirical correlations suggest that this is the time where of course, it is dependent on pressure and, but in a scramjet engine the pressure varies ok.

So, if you plot the distance versus pressure in a scramjet engine you will see the pressure varies like this whereas, this is the point of the fuel injection. So, what to be what he suggested is that you can define an average pressure Pv which is defined in this manner which is an integral which is basically some form of an average pressure.

And this exponent n is essentially the pressure exponent that is here. And from that one gets an estimate estimated burning over 10 to the minus 3, minus 3 seconds which is one milliseconds. So, this suggests that once again if you recall that what I said that in a scramjet come in a scramjet engine the flow residence time scale is of the order of one millisecond in a combustor it is it might be even smaller than that it is of the order of that.

So, it might be one milliseconds 2 millisecond 3 milliseconds to 10 milliseconds. So, 1 to 10 milliseconds depending upon the flow conditions, but if there burning time is of the order of one milliseconds then of course, you cannot expect that you can just have inject fuel into the into the oncoming high speed supersonic air or at mach 2 and it will burn on it is own and though there we cannot have flame stabilization that way.

So, this calls for a need of a flame stabilizer and in scramjets we can have either like a cavity stabilized flame or a start stabilized flames which will come. But before in going into that just to give you an idea of how the flame inside a scramjet looks like. So, when you inject the fuel of course, as you have seen that it leads to the formation of a bow shock.

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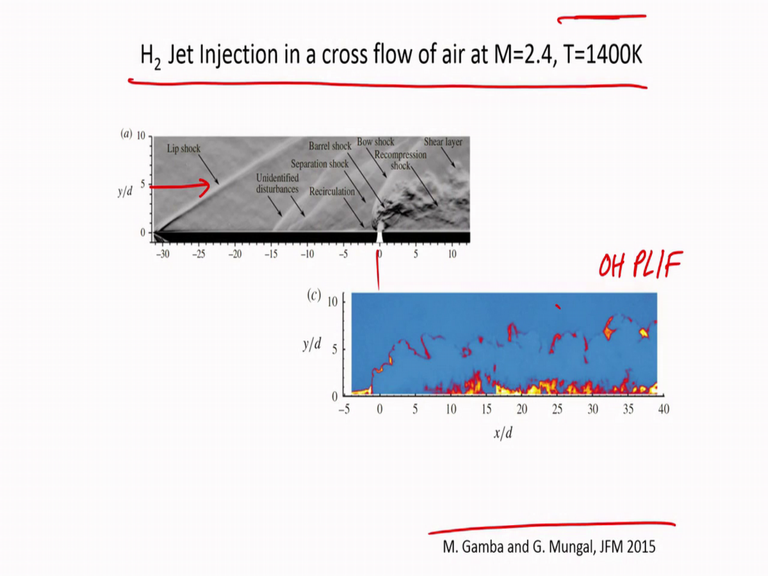

H_2 Jet Injection in a cross flow of air at M=2.4, T=1400K

M. Gamba and G. Mungal, JFM 2015

And surrounding the barrel shock, when you inject a fuel because the fuel posses the fuel jet posses an obstruction.

So, this is a hydrogen jet injection in a cross flow of air about 2.4 at static temperature of 1400 Kelvin this comes from the work of Gamba and Mungal recently published. So, when you inject this hydrogen jet at this point you see, this is the OH PLIF images by the same technique we described previously.

So, you see that this due to the high temperature of the of this air stream that comes here, So the flow is coming from here and you are injecting the jet here, and you see this bow shocker forming and then there is a barrel shock forming here. And of course, there are like different other structures forming all throughout.

Now because of the this jet induces compression and this shock induces compression and also it induces temperature rise. And that causes immediate auto ignition of course, actual static temperature of the flow is also quite high. And as you see here we will see this kind of flame being forming. But the flame that you see here is a very strange looking flame is like this OH normally does not happen in bulk instead it is like it is like in a threaded form like this, you see the flame being scattered all the way along this both in the both in the front of the jet and as well as in the back of the jet.

And people think that this can be the examples of broken reaction zone regime these flames belong to the broken reaction zone regime of the turbulent combustion regime diagrams that we have discussed. So, as such that happens when the chemistry and the and the when the reaction time skills that when the are very, very are much larger compared to the combo (Refer Time: 17:58) of time scales that is when you get this kind of broken reaction zones and people think that this is probably what is happening here ok.

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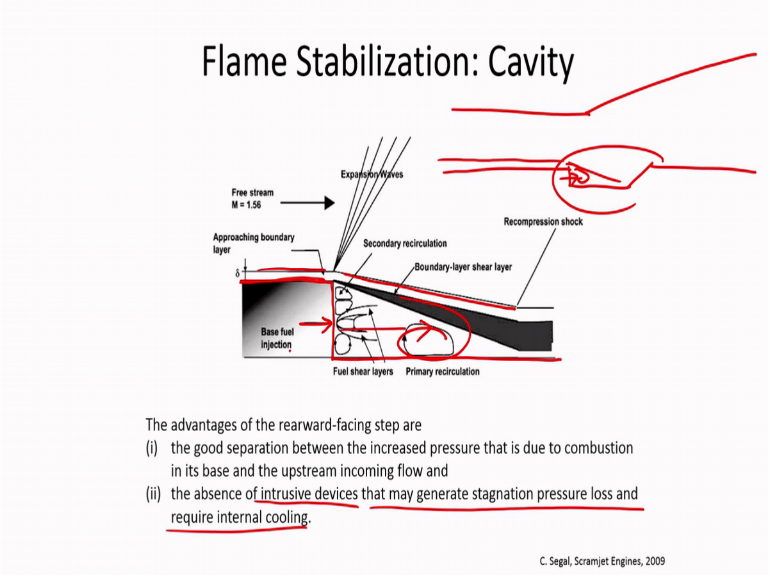

Flame Stabilization: Cavity

The advantages of the rearward-facing step are

(i) the good separation between the increased pressure that is due to combustion in its base and the upstream incoming flow and

(ii) the absence of intrusive devices that may generate stagnation pressure loss and require internal cooling.

C. Segal, Scramjet Engines, 2009

Now So, this as you see that if you just inject in this thing it is very difficult to realize a robust flame So that calls for a need of flame stabilization. So, one of the flame stabilization mechanism is by using cavity. So, what you have is that you have this scramjet combustor this is this is the isolator and then you have the divergent section, and then you can have a have a have a cavity like this. And then the flow comes and it essentially as you see it can recirculate here and you can inject fuel into this cavity.

So, this is what being shown is that. So, this is the bottom wall where this boundary layer is developing. And now as the flow this supersonic flow encounters divergence yet this expansion waves form with this the flow and the flow can expand and which causes is the expansion waves. And this boundary layer bends, and also between this bends into this cavity.

So, this is the So, let me just explain. So, what we have is that So, this is this cavity is represented here. So, the flow is coming from the from the left to the right and it as it comes there is a boundary layer being formed. And here you have a cavity which is formed like this. So, as the flow is coming it encounters divergence and when divergence you have a divergence you have got this expansion waves. And these expansion waves for the terms of flow and you have a boundary layer coming inside the cavity.

Now, inside the cavity you do not have a direct flow of course So, there is a shear layer being formed because the velocities of these 2 of inside cavity and outside cavity are widely different. And then the flow essentially comes and recirculates like this. So now, in this recirculating flow because there flow residence times are very high, you can inject a fuel.

Now, you can inject a fuel and this fuel can mix with this with this recirculating flow, and this can lead to combustion. And it can have a reasonably steady flame inside this cavity. So, this is one of the strategies that are being adopted inside a scramjet combustor. The advantage of this kind of a rearward face stepping face step cavity is that that whatever the pressure rise happens this pressure rise does not you can essentially shield the flow from the pressure rise that happens due to combustion.

And second is that the absence of intrusive devices that if you include a flame holder, that might generate stagnation pressure loss and require might require internal cooling. Because this strut if you put just like the bluff body what we have seen before in the afterburner, that can lead to a very high that the leading edge of the strut will see will see is temperature which are equal to the stagnation temperature of the flow, because the flow has been stopped there.

So, and if that is of the power of 1600, 1700 Kelvin for long term operation you might need some cooling. So, and also it can lead to some pressure loss. So, that is why some people prefer cavity, but the only issue is that in the cavity or combustion is restricted to the sides. So, the main flow does not see combustion.

So, if you want to generate a lot of thrust by accelerating the flow you have to somehow ensure that the main flow gets a lot of the main flow gets into the cavity, and if you cannot have a very large divergence immediately. So, then it can lead to flow separation. So, these points there are advantages and benefit is disadvantages of cavity, but this is definitely one of the 2 ways by which flame is stabilized inside the inside the scramjet combustor.

So the next one, we will talk about is essentially the flame stabilization using struts.

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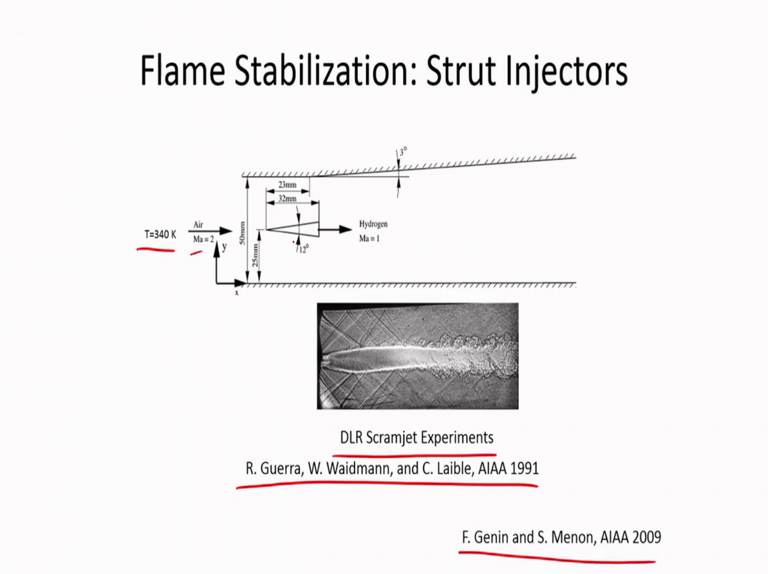
Flame Stabilization: Strut Injectors

DLR Scramjet Experiments

R. Guerra, W. Waidmann, and C. Laible, AIAA 1991

F. Genin and S. Menon, AIAA 2009

So, this work will essentially report the DLR scramjet experiments reported here, by Guerra at all and the computations have been reported by Genin and Menon in Aiaa 2009. So, we will just examine this as a case of how combustion how a flame is stabilized by a strut in a scramjet in a scramjet type of combustor.

So, here we have a mach 2 flow coming in from the right to the left. And the temperature is 340 Kelvin. So, we needs additional ignition mechanisms. And the struties of the order of with the divergence angle of 12 degree. Now you see here you cannot place a bluff body like what you place in an afterburner.

So, because if you place a bluff body then immediately there will be normal shock formed. And this normal shock will make the flow downstream subsonic and the whole thing breaks down the whole concept of the scramjet combustor breaks down. So, you have to design this strut very, very carefully and it can only have a very narrow edge angle. And it cannot always also block the flow too much. So, that needs to be carefully chosen ok.

So, here because you will have weight release so they designed a combustor with a 3 degree divergence as you see it is not straight it is not these the top wall. And the bottom wall are not parallel the top wall diverges at an diverges at an angle of about 3 degrees. And the strut has a divergence angle of about 12 degrees.

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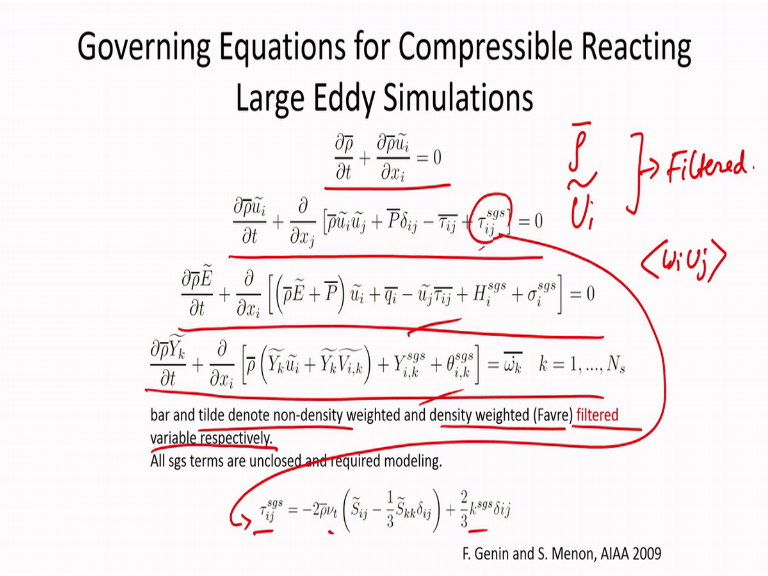

Governing Equations for Compressible Reacting Large Eddy Simulations

$$\frac{\partial \overline{\rho}}{\partial t} + \frac{\partial \overline{\rho}\widetilde{u}_i}{\partial x_i} = 0$$

$$\frac{\partial \overline{\rho}\widetilde{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left[\overline{\rho}\widetilde{u}_i\widetilde{u}_j + \overline{P}\delta_{ij} - \overline{\tau_{ij}} + \tau_{ij}^{sgs}\right] = 0$$

$$\frac{\partial \overline{\rho}\widetilde{E}}{\partial t} + \frac{\partial}{\partial x_i}\left[\left(\overline{\rho}\widetilde{E} + \overline{P}\right)\widetilde{u}_i + \overline{q_i} - \widetilde{u}_j\overline{\tau_{ij}} + H_i^{sgs} + \sigma_i^{sgs}\right] = 0$$

$$\frac{\partial \overline{\rho}\widetilde{Y}_k}{\partial t} + \frac{\partial}{\partial x_i}\left[\overline{\rho}\left(\widetilde{Y}_k\widetilde{u}_i + \widetilde{Y_k V_{i,k}}\right) + Y_{i,k}^{sgs} + \theta_{i,k}^{sgs}\right] = \overline{\dot{\omega}_k} \quad k = 1, ..., N_s$$

bar and tilde denote non-density weighted and density weighted (Favre) filtered variable respectively.

All sgs terms are unclosed and required modeling.

$$\tau_{ij}^{sgs} = -2\overline{\rho}\nu_t\left(\widetilde{S}_{ij} - \frac{1}{3}\widetilde{S}_{kk}\delta_{ij}\right) + \frac{2}{3}k^{sgs}\delta ij$$

F. Genin and S. Menon, AIAA 2009

$\overline{\rho}$, $\widetilde{U}_i$ → Filtered.

$\langle u_i u_j \rangle$

And from the center of the strut you are injecting hydrogen at mach one, whereas the incoming air is coming at mach 2 ok.

So, this is how I essentially the silirian image of this hydrogen air flame looks like, but will go into that. So now, we have not really discussed large eddy simulations for doing compressible reacting flows. So, in this last lecture will just show you that this kind of complex scramjet combustor can be simulated using large eddy simulations ok.

So, large eddy simulations in large eddy simulations are kind of intermediate between direct numerical simulations and rance. So, in for example, in direct numerical simulations you solve for all scales from the combustor size to the komo graph length scales. In rance you solved for only the average either the arithmetic average very ensemble average variables or the favre average variables. In LES what you do is that you solve for filtered variables ok.

Now, in this filtered variables what is contained is the information from the largest scales to some intermediate scales in the which belong which belongs to the inertial range. So, these variables that you see this all this bar and tilde this bar variables for example, this rho for example, this rho bar is essentially the non density weighted filtered variable.

So, in les large eddy simulation is solve your governing equations you, you make you create first governing equations. That describes the evolution of these filtered variables.

And they still they denote the density weighted filtered variables for example, u tilde here denotes the filtered, these are like filtered variables.

So, with this you can capture large scale dynamics and by and have models for essentially the small komo graph scales. So, this is your continued integration once again for this filtered variable u I tilde this is the momentum equation. You see emergence of this tau i sgs terms. These are similar to the reynolds stress terms that you encounter in rance and you have 2 essentially have 2 essentially model for this.

So, this is your energy equation I will not go into that and this is your species equation. So, once again these equations will look very similar to the actual governing equations, but they have many more terms they are more complex because they have many more terms to do to this sub grid scale sub grid scale terms that arise. This that is which are like kind of this reynolds stress terms ui uj term which you remember arrived when we averaged the reynolds the navier stokes equation ok.

Similar to that this terms arrived everywhere in this momentum equation in this energy equation in this species equation, and one has to have a closure model. For that for example, in this case this tau i sgs that arrives here is closed by this eddy viscosity type of closure and then you solve for a this k sgs similar to the kf sgs model also. But this is this is much more involved, but has it gives you much more insight.

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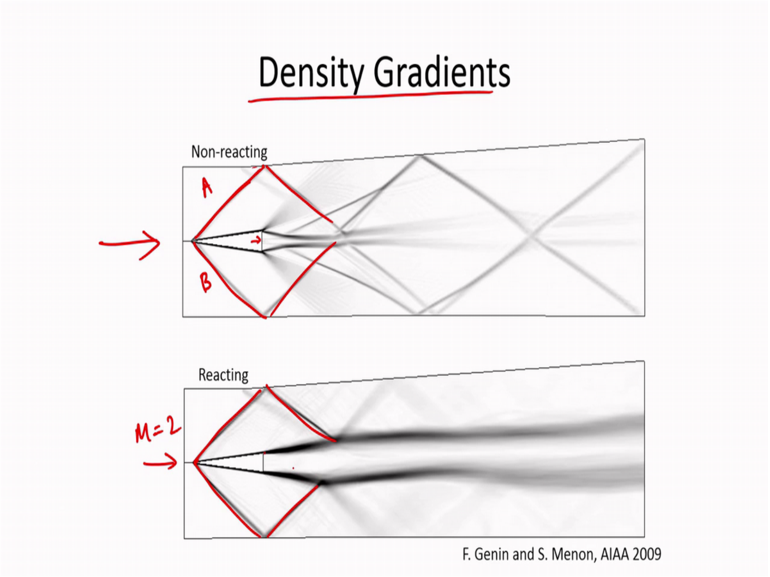


Density Gradients

F. Genin and S. Menon, AIAA 2009

So, this is just to show that the simulations what these simulations can do and it captures can capture essentially very many of this interesting physics that that is the that is they are present in these kinds of flows. So, here you are showing the density gradients that is obtained from these large eddy simulations. And often these are close to experiments and sometimes they are not So, still now this large eddy stimulation for high speed turbulent combustion is a research is a research topic.

Lot of advancements has been made, but it is not closed and still there is room for a lot of work that can be done. So, both fundamentally as well as developing algorithms as well or developing numerical schemes and as well as in terms of fundamental understanding.

So, what I want to show here is that that here we compare the from the from the solutions we compare the density gradients from the non reacting and the reacting flow. Of course, you see that they are different, but first if we just define the non reacting flow part. So, you see that here the supersonic flow is coming from the right, from the from the left to the right. And here also as you see that the supersonic flow is coming from the from the left to the right ok.

So, here as it encounters as it comes from the left to the right, here it is encountering this wedge shaped body. And as it is deflected by the tip of the wedge we have these 2 shocks which are being formed. These 2 oblique shocks which are formed, let us call this A and let us call this B. Now what happens is that as they impact this upper and the lower walls they reflect back ok.

Then they reflect back towards the centerline of this test section. And the impact of the shock on the upper wall occurs downstream of the location of the divergence. So, you see that this wall this wall interacts with this shock interacts with the wall after the divergence started. So, as a result of this whole shock structure does not remain symmetric with respect to the centerline anymore ok.

So, this changes the symmetry and you see that this is this whole line the centerline of the shock structure has deviated from the centerline of the from the from the centerline of this of the of the constant area section. So, but you see here that what happens is that this, the this the impact of the shock on the upper wall occurs of course, the downstream of the of the location of the wall divergence. And as a consequence the oblique shocks interacts with the upper wall expansion fan that is created due to at the at this corners of this flame holder.

So, these are the expansion fans which are created because the flow is diverging. And these reflected shock structured interacts with this with this with this expansion fan. And because of this inherent asymmetry this whole thing becomes asymmetry downstream. Now what happens is that you see the at the base of the wedge ok.

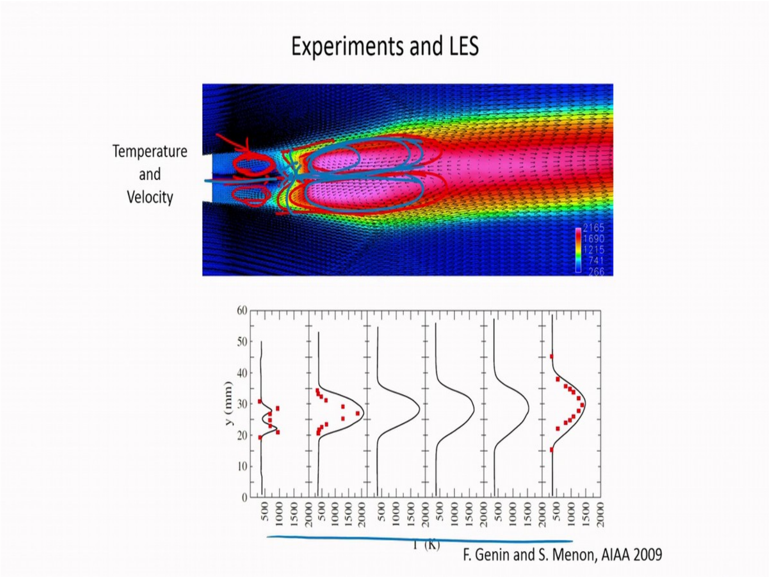
There are this boundary layers being formed. And this base of the wedge of this boundary layers are formed, but because the pressure inside the recirculation zone is lower these boundary layers essentially these shear layers which are formed here now essentially try to converge. And then these 2 essentially try to converge towards the centerline, and at the as this tries to converge towards the centerline then what happens is that because of the low pressure inside this recirculation zone the jet the hydrogen jet the mach one hydrogen jet that you are getting you are injecting is essentially becomes under expanded. And this forms this whole nice diamond shock patterns ok.

And this again then pattern continues and then this shock diamonds are essentially formed, which leads to the interaction between the between the with the (Refer Time: 31:04), but the most important feature here is that this low pressure inside the inside the recirculation zone causes this the convergence of the low pressure of the recirculation zone causes the convergence of this whole the of the shear layer into the toward towards the centerline.

So, that is the that is what you are what you are seeing here. But on the other hand when you have when you have this when you have a reacting flow for example, in this case, here also you see that as the mach 2 flow comes here it is deflected indeed by the wedge. And this oblique shocks are being formed and which again reflects back into the shear layer. But here what happens is that now because there is combustion now, because there is now we have you have you have got heat release, the pressure inside the recirculation zone is higher ok.

So, as a result of that the since the base of the since the pressure at the base of the wedge has increased as the reaction has been initiated, the shear layers do not converge anymore, but rather expand with an angle which is even slightly greater than the 12 degree angle of the wedge. So, this is the striking different feature ok.

(Refer Slide Time: 32:38)



Experiments and LES

Temperature and Velocity

F. Genin and S. Menon, AIAA 2009

Another thing that you will see essentially in the next slide that where we have essentially plotted the temperature contour which is available from the simulation in the simulation we have got all parameter is essentially superimposed with the velocity vectors. You see as this hydrogen jet is coming now because of the because of the pressurize at the because of the because of the pressurize at the base the jet penetration becomes limited into this recirculation zone.

As a result you see that there is not of course, there is this large vortex is being formed, but the jet as such does not penetrate immediately into the recirculation zone. And as a result of that So, here the jet can penetrate further downstream. So, this the this jet can the this jet essentially penetrate up to this point, where essentially you have this recirculation zone also of this entire flow recirculating. And this creates essentially a stagnation point ok.

So, this recirculation of the of the of the products which is formed here and this whole jet essentially forms a stagnation point and then essentially you see that the flame is starting from here at this shape. So, the hydrogen jet you see that what happens is that that because of the pressure rise at the base of the wedge, this leads to a lower penetration of the jet into the recirculation zone.

And the mixing region is you see in this in this time averaged field which is shown here from here. We can show that we can find that the jet has a rather low penetration. And these 2 vortices on each side of the jet only enhance the mixing of the hydrogen with the recirculating fluid. That is that is what is happening.

So, this only this vortices that are being that is that are being present here mixes this hydrogen with the with the air, but as such in a normal recirculation zone you get hot products. So, here you do not see those things here you just have fresh hydrogen mixing with the oncoming air which is coming here. And only for the downstream the this the reaction of the volumetric expansion create a bubble with hot products, which is this thing which is which is if you see here. Only for the downstream this recirculation of this bubble of this hot products form.

And this create a bubble of hot products and this circulation is imposed by the outer flow, which creates a reverse flow along the recirculation towards the injection. And thereby the flame is essentially initiated. So, this hydrogen jet essentially can penetrate up to this point, where it essentially meets this recirculating products and that creates the stagnation zone from where the flame is essentially starting ok.

And these recirculating hot products essentially provides energy thermal energy to the to the to the flame, which essentially conducts upstream to essentially initiate the initiate reaction in the oncoming mixture. So, this is the dynamics of the strut and as you see here of a strut stabilized scramjet flame.

And as you see here that that if we plot if we if we extract the temperatures from different locations the temperature profiles from different locations, and validate that the from different locations from the simulation and validate that with the experimental measurements. The experiments does correlate well with the with the with the simulations ok.

So, it says provide some amount of confidence in the simulations, but then of course, you have to one has to be very careful this simulations are hard simulations and there is a lot of effort that goes into modeling as well as in the algorithm development for these kinds of things.

So, with that we have we come to the final some of this instantaneous temperature fields of how it looks like. As you see that because the flame is essentially stabilized here and the recirculation bubble is essentially formed here, do you see that in the instantaneous picture also where you see that the flame is essentially lifted up from the bluff body? Unlike the case of like subsonic flames where the flame is essentially attached to the bluff body, or the here the flame is essentially lifted off from the strut. And that is happening because as the jet is penetrating into this, it meets with the recirculating products somewhere around and that creates the stagnation zone and that becomes a stabilization location on the flame.

But occasionally this flame structure that is formed due to the some low velocity regions can occasionally pinch it and it can get attached, but normally it is it is lifted of from the recirculation zone and from the from the from the recirculation zone immediately downstream of the strut and it forms it is own recirculation zone downstream, which recirculates the hot products ok.

So, this is the then the typically the structure of the a of a of a of the of the flame, as you encountered in a in a scramjet combustor. So, with that we come to the end of this discussion on scram jets, where we have essentially discussed one dimensional flow, one dimensional of one mention of friction less flow in a constant cross section with heat addition. And we have seen that the addition of heat what happens to is that the addition of heat tries to make the mach number of the flow to more and more towards sonic.

So, that is the most important consequence that we saw. And then we looked into the different design considerations of a of a scramjet engine. We looked into we looked into the different phenomena that involves in a scramjet engine like whether what happens when you inject a gaseous fuel jet what happens when you inject a liquid fuel jet.

What are the different mixing mechanism that takes place. And then we looked into the different ignition delay times which are of the order of one milliseconds often. Or and is often comparable to the flow residence timescales. We looked into burning time and then we looked into the different mechanisms of flame stabilization.

We looked into the cavity based flame stabilization and looked into the start based flame stabilization, and we looked into how the different like shock structure interacts with the recirculation zone and the shear layers. And how that how it is different for the non reacting case versus a reacting case. And if you inject the hydrogen strut how it changes the flame structure from a normal bluff body stabilize flames.

And you can have a stable lift it of lifted flame, which is just a little bit further downstream of the strut than it is under normal circumstances of under different circumstances of subsonic flow, where you have a flame essentially attached to the to the strut. So, we have discussed these things fundamental aspects of combustion in scramjet engines. And with that the technical part of the course is over.

We have come to the end of the technical part of the course and we will finish it off in the in the next class with a recap of all the topics that we have covered in the last 12 weeks.

So, goodbye till then.