Combustion in Air Breathing Aero Engines

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Lecture – 50
Aero Gas Turbine Combustors III

Welcome back. So, we were talking about the combustion chamber inside a gas turbine engine and inside an aero gas turbine engine and as we have seen that of course it contains several components which has to be designed in a very precise manner and which has to be designed in an integrated manner because as you have seen that the first component inside the combustor is diffuser and that diffuser has to be designed, so that it can divert the flow in the required proportions into the dome region of the combustor into the primary zone as well as it can provide enough air in the same required proportion in exactly the same amount that it is desired into downstream region of the combustor which is called the dilution zone.

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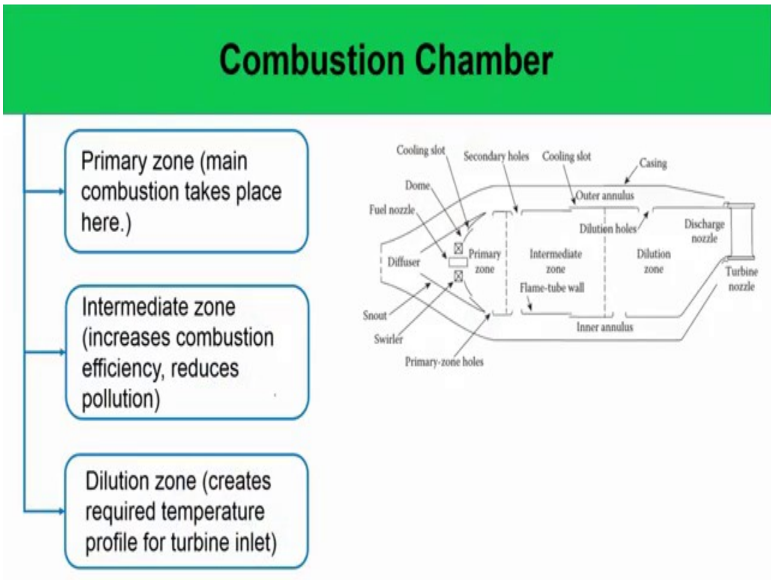

Combustion Chamber

- Primary zone (main combustion takes place here.)
- Intermediate zone (increases combustion efficiency, reduces pollution)
- Dilution zone (creates required temperature profile for turbine inlet)

So, we have essentially three zones. As you have seen the primary zone, where the main combustion takes place. The intermediate zone which increases the combustion efficiency and reduces pollution and then, the dilution zone.

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Primary Zone

- Anchors the flame , to provide sufficient time for achieving total combustion of incoming air-fuel mixture.
- It creates a toroidal flow reversal, that entrains and recirculates a part of hot combustion product to provide a continuous source of ignition to the incoming reactants.
- This toroidal flow can be created with proper swirler, baffle, bluff-body.
- Strong and stable primary zone air-flow can provide wide stability limits, good ignition performance, reduce combustion noise and instabilities.

We have seen what the requirements of the primary zone are.

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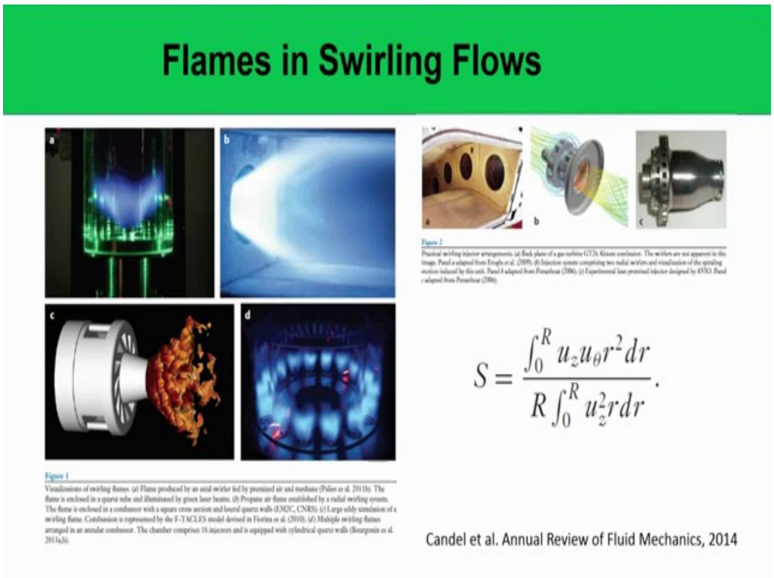

Flames in Swirling Flows

$$S = \frac{\int_0^R u_z u_\theta r^2 dr}{R \int_0^R u_z^2 r dr}.$$

Candel et al. Annual Review of Fluid Mechanics, 2014

This is how essentially the different kinds of flames in the dilution, in the primary zone should look like because in the primary zone what you have is, essentially you have the injector, the liquid fuel injector and the liquid fuel injector is surrounded with the solar blades which provides the tangential momentum or on to the otherwise axial flow, ok.

Now, why do you need this tangential momentum? It is because when you have this tangential momentum, then what happens is that of course due to the centrifugal forces, the flow essentially diverges and essentially when the flow diverges under, when the swirl number that the tangential momentum is sufficient and the flow can essentially recirculate. So, when it recirculates essentially what do what you do is that what you are actually doing by making the flow recirculate is that you are increasing the residence time of the flow.

If you remember that in the earlier discussion on the limit phenomenon, the S curve that Damkohler number which is the ratio of the flow timescales to the chemical timescales that should be substantially high for steady combustion to take place. If it is small, first of all you will not be able to ignite in the mixture and then, even after we ignite if it becomes small in certain cases after ignition, then it will extinguish.

So, to have steady combustion which is pretty much required because if there is no steady combustion inside the gas turbine combustor, then you have basically no source of power, right. You do not have the chemical to thermal energy conversion taking place. So, you must have steady combustion inside the combustor at all times and to ensure that your flow should not be at such of high velocity that there it is not enough for the chemical reactions to take place. So, this is very important and the very basic principle of a combustor design that the residence time of the flow must be greater than the corresponding chemical timescales which means that Damkohler number should be high.

So, to make the Damkohler number high, you will employ this recirculation in certain cases. You can employ a bluff body also. Now, as you will see later that typically in an afterburner, not the augmenter, we people use bluff bodies, but in the main combustor which we are discussing right now, you essentially use this kind of swirling flows and here the swirling flows is characterized by the small number which is the axial flux of azimuthal momentum divided by the axial flux of axial momentum. So, these are the different types of swirling flows in laboratory combustor. Of course, you have to understand that in a real gas turbine engine whether Reynolds number of the order of turbulent, turbulence Reynolds number is of the order of 50000, then of course the flow is swirling, but it is also intensely turbulent, ok.

So, the flame essentially decides in a swirling turbulent flow and then, there are numerous things can happen. There can be non-linear feedback, there can be feedback between heat release and pressure of fluctuations and if they are in phase, then this can lead to instabilities. So, those are important things to be looked at, but in this course we will not go into thermo acoustic instabilities because that is very involved thing itself and there are other NPTEL courses, you can take a look for if you are interested in the thermo acoustic instability. So, in this course we will not cover that.

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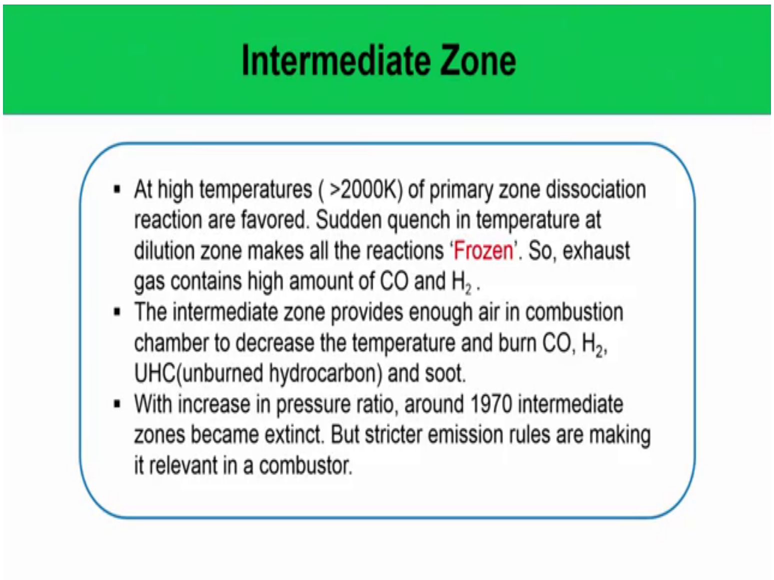

Intermediate Zone

- At high temperatures (>2000K) of primary zone dissociation reaction are favored. Sudden quench in temperature at dilution zone makes all the reactions 'Frozen'. So, exhaust gas contains high amount of CO and H_2 .
- The intermediate zone provides enough air in combustion chamber to decrease the temperature and burn CO, H_2, UHC(unburned hydrocarbon) and soot.
- With increase in pressure ratio, around 1970 intermediate zones became extinct. But stricter emission rules are making it relevant in a combustor.

So, then in the intermediate zone, you have to essentially ensure that the complete combustion takes place. So, the intermediate zone essentially provides enough air in combustion chamber to decrease the temperature and burn the carbon monoxide and hydrogen, but typically I mean in modern combustor, you go straight into the dilution zone.

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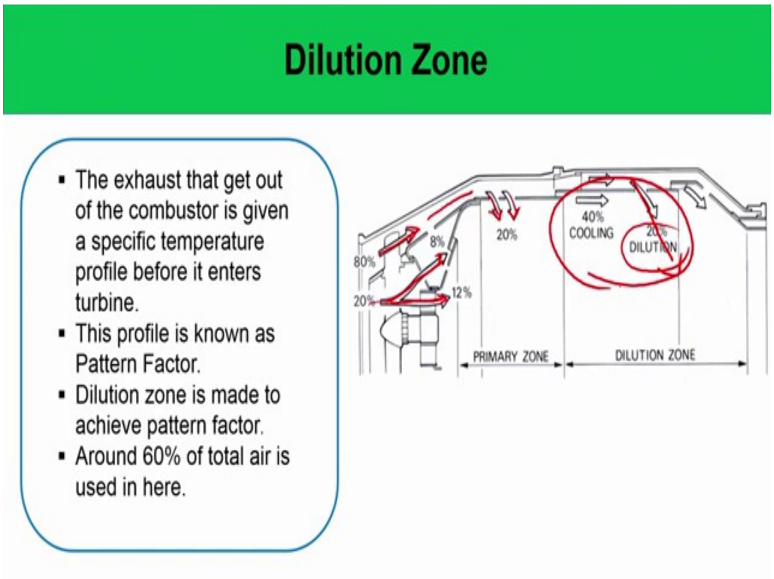

Dilution Zone

- The exhaust that get out of the combustor is given a specific temperature profile before it enters turbine.
- This profile is known as Pattern Factor.
- Dilution zone is made to achieve pattern factor.
- Around 60% of total air is used in here.

This is the dilution zone you see here what this picture depicts exactly what I was talking about that the whole combustor should be designed in a very integrated manner, that is you see the diffuser you have to design it in such a way, so that 20 percent of the air is only going into the combustor. Of course, this actual number differs for different combustors. This is just typical numbers and out of 20 percent, 12 percent goes to the swirlers. These are the swirlers and then, 8 percent goes to the surroundings and then, for cooling purposes where does the 80 percent of the main air which comes out of which exits the compressor and actually it can also be the bypass air. It need not only or always come out of the compressor.

So, the 80 percent of the total mass flow rate of the air that comes into the combustor is essentially diverted to the cooling for cooling purposes. Out of that 20 percent of that enters, the 20 percent of that of the full air enters into this primary zone for cooling and then, later 20 percent interest into the dilution zone. So, first we need to essentially focus here that this purpose of this dilution air is that the exhaust that get out of the combustor is given a specific temperature profile before it enters the turbine and this temperature profile comes from structural considerations of the turbine blades because the turbine blades are under immense centrifugal forces because they are rotating at so high velocities and not only they are under centrifugal forces, they are under both centrifugal as well as high thermal stresses.

So, circumference that your temperature and to maximize the life of the turbine blades, of course the turbine blades are one of the most expensive component of the entire engine. They have to be really manufactured in the, manufacture with themselves one of the most difficult challenges inside the gas turbine engine.

Then, of course you as an engineer your focus should be to design the turbine blades in such a manner that their life is maximized and to ensure that their life is maximized, you have to ensure that the temperature profile that this turbine blade sees an average temperature profile and the fluctuating temperature profile that this turbine blade sees, they are exactly designed so as to minimize the thermal stresses or to optimize or you provide them a temperature profile which will maximize their life and this profile is known as a pattern factor. This dilution zone, this cooling is essentially achieved, is designed to achieve a particular pattern factor and essentially as you see 60 percent of this air is used in here.

So, this is 60 percent, that is 40 plus 20 by 60 percent that is used for achieving that thing now.

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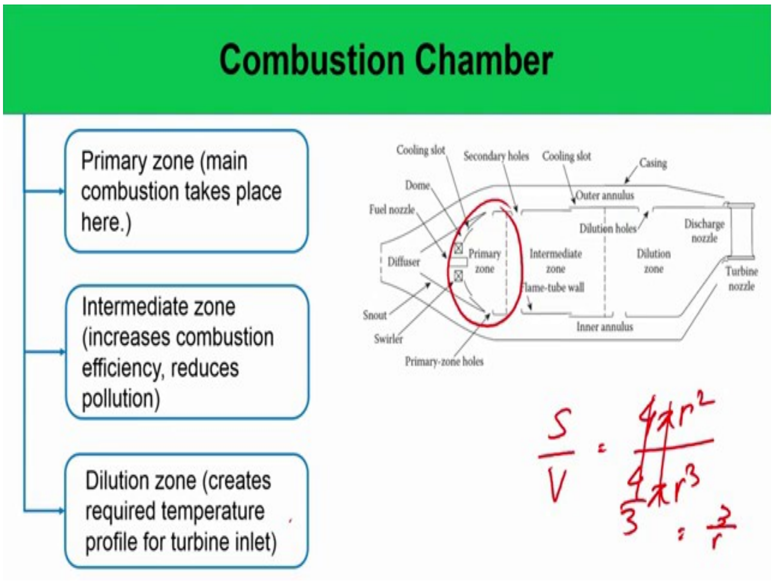

Combustion Chamber

- Primary zone (main combustion takes place here.)
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$$\frac{S}{V} = \frac{\cancel{4}\cancel{\pi} r^2}{\frac{\cancel{4}}{3}\cancel{\pi} r^3} = \frac{3}{r}$$

You know then we go into the details of the primary zone. We need to go into some details about the primary zone and essentially let us see what happens inside the primary zone. Now, if you remember that there are one of the most important goals or one of the most important reasons why combustion is used in gas turbine engines is because of the immensely high energy density of the liquid fuels, right. Liquid kerosene or its variants, different types of these variants of kerosene are essentially used in the combustion chamber which is the complete fuel source.

So, kerosene is optimized fuel for gas turbine engines and of course, the reason we do not use a battery in an aircraft, in a large aircraft and we use fuel, liquid fuel is because of very high energy density of the liquid fuels, fine. We understand this, but you see there you cannot just burn the liquid fuel directly inside the gas turbine combustor. You just cannot have because in gas turbine combustors or the score so far we have seen we have only talked about reactions in gas phase. In the gas turbine combustor also, even though we use liquid fuels, the combustion reactions strictly happens in the gas phase, ok.

They do not happen in the liquid phase. There are examples of reactions happening in the liquid phase. For example, if you talk about rocket engines where do you use like MMH and RFNA for your fuel oxidizer, there are reactions can happen in the liquid phase which are called hypergolic reactants, but in a gas turbine engine in air breathing engines, in gas turbine engines, in afterburners, in scramjets slam jets, everything typically when you use a liquid fuel reactions must happen in gas phase. This is absolutely what happens in all occasions.

So, you have a tank of liquid fuel which you are carrying and then, in the combustion chamber you are basically sending out the liquid fuel in some form. So, one important process is basically how you convert these liquid fuels into gas phase, so that this liquid fuel in the gas phase can mix with the oxidizer which is the air and then, combustion can happen. Now, you will ask what is the problem? I will send out the liquid fuel and then, it will allow it to vaporize or evaporate and it will burn and then, we can create a fuel air mixture and then, we can get it burning.

The problem is that the time available in the combustor is not large; it is very short. So, what you need to do is that we have to design a process by which we can send the liquid fuel into the combustor and it can get converted from the liquid to the gas phase to the vapor phase of that fuel very quickly and in the vapor phase, it can mix with the air and then, it can burn. How do you achieve that? We cannot just rely on the process of evaporation. So, what we need to do is that this liquid that is stored in the fuel tank, we need to basically increase the surface area of this liquid to the maximum possible surface area, ok. How can you achieve the maximum possible surface area? If you can somehow convert this liquid in the tank to very small droplets because as you know in the droplets, droplet surface area by droplet surface area by volume is equal to 4 pi r square divided by 4 pi r cube, right. So, this cancels. So, then this goes by 3 by r. So, as radius decreases, the surface area to volume ratio increases. So, for a given volume, you can have maximum surface area if your radius is very small and then, of course we know that this will lead to a very fast evaporation also, ok.

So, you need to increase the surface area. So, for that you need to make very small droplets. How do you make very small droplets and that is the process basically what is called the liquid jet break-up and atomization. So, in this primary zone apart from combustion, you have to have a very important process which is the droplet, the liquid jet break-up and atomization. So, this is what we are going to study.

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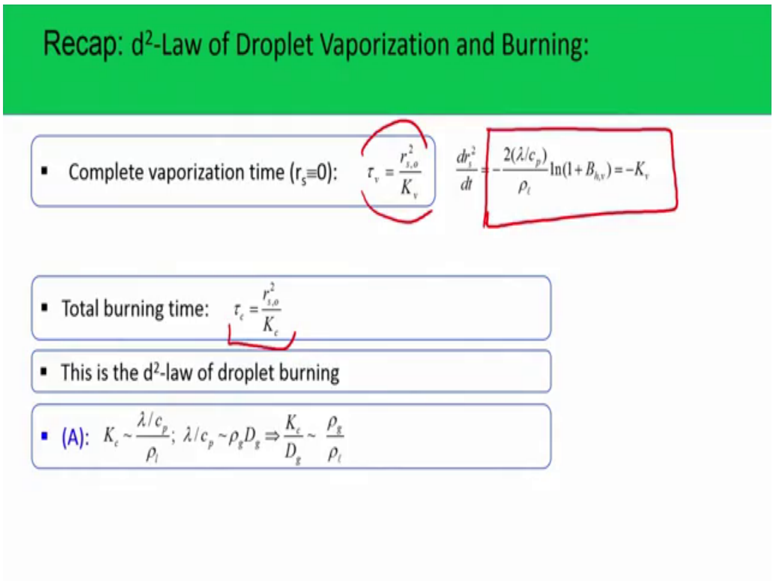

Recap: d^2-Law of Droplet Vaporization and Burning:

- Complete vaporization time ($r_s \equiv 0$): $\tau_v = \frac{r_{s,o}^2}{K_v}$ $\frac{dr_s^2}{dt} = -\frac{2(\lambda/c_p)}{\rho_l}\ln(1+B_{h,v}) = -K_v$
- Total burning time: $\tau_c = \frac{r_{s,o}^2}{K_c}$
- This is the d^2-law of droplet burning
- (A): $K_c \sim \frac{\lambda/c_p}{\rho_l}$; $\lambda/c_p \sim \rho_g D_g \Rightarrow \frac{K_c}{D_g} \sim \frac{\rho_g}{\rho_l}$

So, a recap that also we need a small droplets because if you remember that the droplet vaporization time, this droplet vaporization time was essentially proportional to the initial droplet radius divided by this droplet vaporization constant and it was given by this thing. It was given by this constant K v was essentially given by this thing, but all this property is lambda by c p liquid rho by rho l times l on A plus B u droplet. Heat transfer number with all these things you see that smaller the droplet, smaller is the evaporation time and it goes like squared. So, if you reduce the size of your droplet by 10 times, the time for evaporation reduces by 100 times. So, a very important function of the liquid injector inside a gas turbine combustor is to produce droplets of very small size. The ultimate product of this thing is that I will take the liquid, I will connect this injector to my liquid tank in such a manner, in some manner and then, I will make some arrangements, so that this injector can spray and can send out liquids and they can create a mist of very small droplets, but how does that happen. So, this is also a very important fundamental part of a gas turbine combustor and we are going to look into that.

Even if the droplet burns, once again as you know that combustion happens in the gaseous phase. The time for a droplet combustion is also proportional to or the initial radius squared divided by K c, but this is the core droplet, a burning constant. This is a droplet combustion constant. It is also proportional to this kind of thing. So, this is a lambda by C p divided by rho liquid times lon of 1 plus B h c. So, the droplet heat transfer number for a combustion.

So, this is the thing. So, it is imperative that you produce very small droplets inside the combustor. So, for that to understand that we are fortunate in one sense that even if we send out a liquid jet, the liquid jet is not a very stable configuration. A liquid cylindrical jet is not the stable configuration because I will show that that the liquid jets tends to minimize the surface energy essentially trends to form small droplets, but those droplets are not, it tends to form droplets which is proportional to the radius of that jet, ok.

So, you will see how that happens. So, we are fortunate in one sense, but we cannot only rely on that process on the spontaneous breakup of a liquid jet process. So, we need to do something more to achieve even smaller droplets and that will be called atomization.

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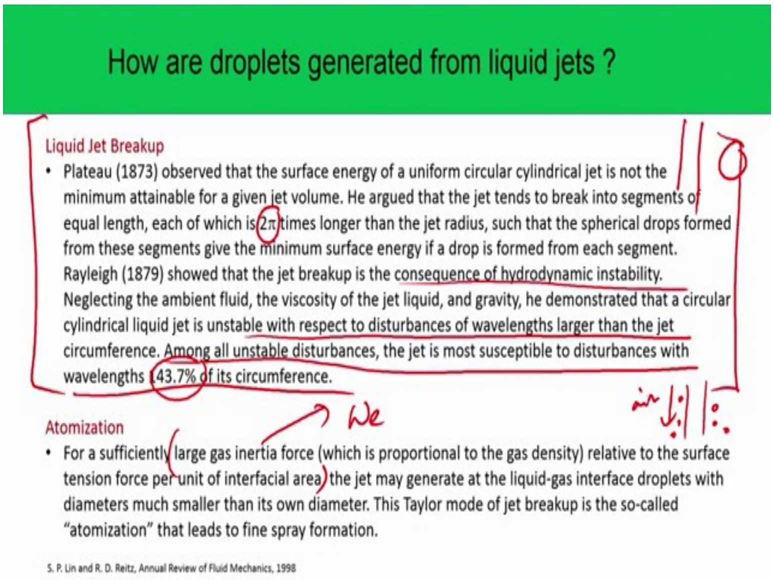

How are droplets generated from liquid jets ?

Liquid Jet Breakup

- Plateau (1873) observed that the surface energy of a uniform circular cylindrical jet is not the minimum attainable for a given jet volume. He argued that the jet tends to break into segments of equal length, each of which is 2π times longer than the jet radius, such that the spherical drops formed from these segments give the minimum surface energy if a drop is formed from each segment. Rayleigh (1879) showed that the jet breakup is the consequence of hydrodynamic instability. Neglecting the ambient fluid, the viscosity of the jet liquid, and gravity, he demonstrated that a circular cylindrical liquid jet is unstable with respect to disturbances of wavelengths larger than the jet circumference. Among all unstable disturbances, the jet is most susceptible to disturbances with wavelengths 43.7% of its circumference.

We

Atomization

- For a sufficiently large gas inertia force (which is proportional to the gas density) relative to the surface tension force per unit of interfacial area the jet may generate at the liquid-gas interface droplets with diameters much smaller than its own diameter. This Taylor mode of jet breakup is the so-called "atomization" that leads to fine spray formation.

S. P. Lin and R. D. Reitz, Annual Review of Fluid Mechanics, 1998

Then, the question as you see here is what I am talking about that we need droplets from liquid jets, how does that happen? It essentially happens by two processes; liquid jet breakup and atomization. Now, I will read these two paragraphs because it is important that it was discovered by plateau that the surface energy of a uniform circular cylindrical jet is not minimum attainable for a given jet volume, ok.

So, he argued that the jet tends to break into segments of equal length and each of which is 2 pi times the jet radius. That means that it tends to form droplets which is equal to the circumference of the jet radius or not droplets. It tends to break-up into segments and this length of these segments which it wants to break-up is essentially equal to the circumference of the jet. We will show why it is so.

So, as the spherical droplets are formed because once you break the jet up, even if it was cylindrical or distorted cylinder, it immediately tends to form a spherical drop from this segment because that gives it the minimum surface energy if a drop is formed from the segment. Even though when a liquid surface is formed, then there is surface tension which essentially tries to minimize the surface energy and in trying to minimize the surface energy, it forms the spherical drop. Then, Rayleigh showed that the jet break-up is essentially the consequence of hydrodynamic instability which is called Rayleigh plateau instability and if we neglect everything that is the ambient fluid viscosity of the jet and gravity, he demonstrated that a circular cylindrical jet is unstable with respect to the disturbance of the wavelength larger than the jet and among all the unstable disturbances, the jet is more susceptible to disturbance with the wavelengths which is 143.7 percent of its circumference.

Now, it is important for you to ask this question that where does this number 2 pi times larger than this jet radius 143.7 percent comes from. So, we will do the analysis of this liquid jet breakup simplified analysis which will show you that why does a liquid jet breakup happens, but this is very important. This is fundamentally of course you understand that you know in a gas turbine combustor when you inject a liquid jet, it is a very complicated process because you have a swirling flows, you have a very high pressure flow where the turbulence is very strong, but once again if you remove all these complexities and look into the very fundamental aspects, if you look into your kitchen sink and you allow the liquid jet to emerge, you will see that this jet initially stays very laminar smooth jet, but at the end after sometime, it develop some distortions and eventually droplets are formed. Now, this is what is called Rayleigh plateau instability and we will show that this jet can break-up even when there is no gravity, ok.

So, we will do the analysis of this and then, you have atomization. This is also important because in the gas turbine combustor, we cannot rely on the liquid jet break-up process itself and also because there is so much air around the surrounding, it swirling or in high flow or high axial flow velocities, high tangential velocities that you have sufficiently large gas inertia force which is proportional to the gas density relative to the surface tension per unit area of the interfacial area.

The jet may generate that is what we want to say is that if the gas inertia force is large related to the surface tension force which is characterized by basically large weber number, weber number is defined in terms of the gas density. This whole thing is essentially called weber number and jet may generate liquid gas interface droplets with diameters which is much smaller than its own diameter because you see here the droplet that will be formed is essentially of the order of the diameter of the liquid jet, ok but here when there is air, then the droplet that will be formed can be much smaller than these things essentially that you can think of it like the droplet is being peeled off from the jet surface by forming ligaments etcetera which is essentially teared off from jet surface and deforming ligaments and this Taylor model jet breakup is called so-called atomization that leads to fine spray formation.

So, essentially in the final jet that we have in a gas turbine engine that contains droplets of different sizes, it contains droplets, a large population of droplets which are of the order of the jet diameter. It contains droplets which are of the order of much smaller than the jet diameter and you do different processes that are being involved, ok.

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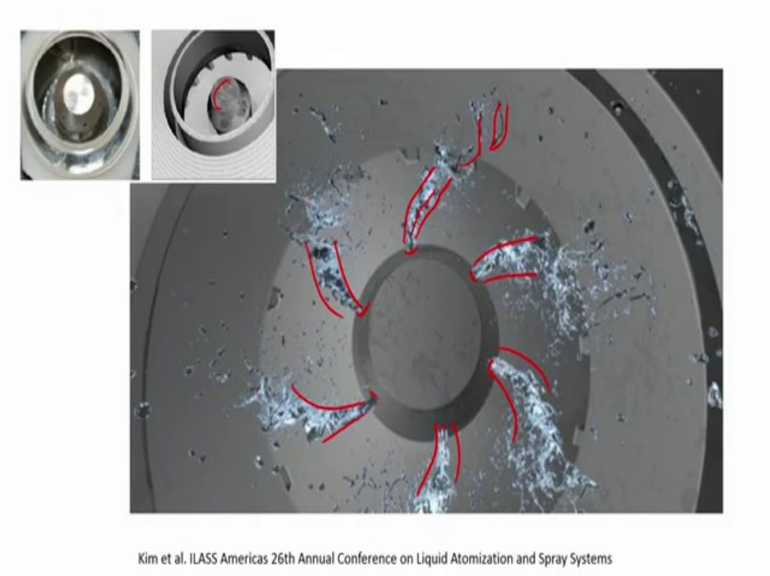

Kim et al. ILASS Americas 26th Annual Conference on Liquid Atomization and Spray Systems

So, this is how an injector in a gas turbine engine essentially looks like you see and this is how this atomization process happens. So, this is the injector, this is the actual picture of injector, this is the mesh and this is a simulation. So, you see that this injector has different pores like this and this liquid jet is coming out and as you see that here essentially this jet structure is maintained to some height and then, it breaks up in a different form of ligaments etcetera into various different shapes.

So, it is a very complex process as you see, but once again this process is complex because the flow is also very complex. So, what we will do first is that we will take up this thing and this can be analyzed. So, we will take up the analysis of this liquid jet break-up which is called Rayleigh plateau instability. So, in this thing, in this we have done essentially if you remember we have done there are two parts. First you have to do the jet break-up and then, once jet breaks up, you form droplets and these drain droplets can evaporate and this can mix with the fuel. This fuel can mix with the air and then, you can burn it, but first the jet break-up process is important and then, that is why we need to do it.

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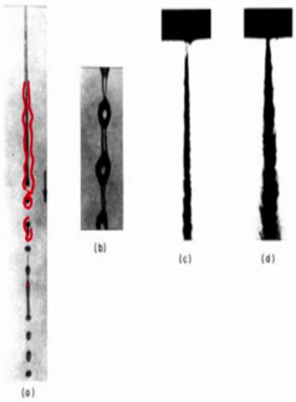

Figure 1 (*a*) Rayleigh breakup. Drop diameters larger than the jet diameter. Breakup occurs many nozzle diameters downstream of nozzle. (*b*) First wind-induced regime. Drops with diameters of the order of jet diameter. Breakup occurs many nozzle diameters downstream of nozzle. (*c*) Second wind-induced regime. Drop sizes smaller than the jet diameter. Breakup starts some distance downstream of nozzle. (*d*) Atomization regime. Drop sizes much smaller than the jet diameter. Breakup starts at nozzle exit.

S. P. Lin and R. D. Reitz, Annual Review of Fluid Mechanics, 1998

So, here is another slide. Before we go into the analysis, here is another slide that shows you the different modes of how these small droplets can be formed. So, this is essentially this Rayleigh break-up where you see that this laminar or smooth jet is coming up coming down, where there is no disturbance and then, after sometime small perturbations essentially gets amplified into this and then, this disturbance forms and then, you see this formation of these droplets which sometimes smudge etcetera.

Then, there is a wind induced regime wind, wind as the surrounding gaseous flow and this can be a wind induced regime. This can be the second wind induced regime and this is like atomization, where essentially is very small droplets are peeled off from the surface of the liquid jet and very fine mist is formed. So, this is the primarily, this liquid jet breakup and this atomization of the two basic modes by which small droplets are formed, but there are other more complex processes, different break-up, break-up mechanisms, back break-up mechanism, etcetera, but those we will not cover in this. This is outside the scope of this class and you should take a detailed course on atomization or sprays. You need to understand that.