Turbulent Combustion: Theory and Modelling

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Lecture - 23
Laminar Non-Premixed Flames (cont…)

Okay Welcome back, let us continue the discussion on different reacting system or combustion system. So, what we have been talking right now, looking at different kind of combustion system. So, the broadly they can be categorized into 2 different category like internal system and the external combustion system, most of the practical applications you find in the internal combustion system.

And then also the internal combustion system you can also look into different aspect of it, whether it is a steady or unsteady or charge these are the things that we have already discussed. And then, we looked at different kind of combustor like can combustor, these are gas turbine applications can combustor, can annular combustor. So now, we will continue the discussion from there.

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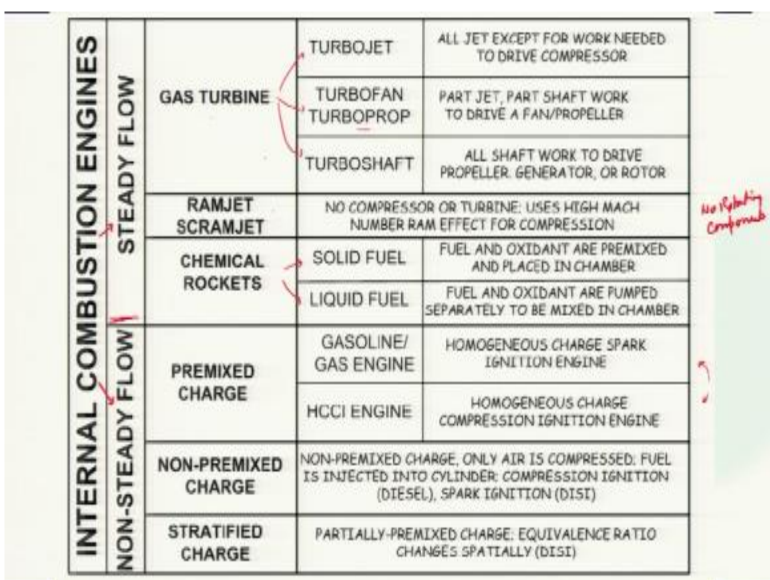

And then today, we will look at the other aspect of these things. So, just to summarize the whole thing, this is where we yesterday talked about mostly is that these are all your internal combustion system. So, as I said, there are 2 categories of the combustion system that you can broadly do one is internal, one is the external and this is pretty much that internal combustion system that we have talked about.

Now, the internal system also you can put in 2 segments, 1 could be steady flow segment another could be unsteady flow segment. So, this particular table actually summarizes everything for the internal system. So, in the steady flow, you have gas turbine, you have ramjet, chemical rockets, these are the things. Under gas turbine, you could have turbojet so this is an jet applications and the work which is produced by the turbine it is primarily used to drive the compressor and then you look at the turbofan or turboprop, turbofan slightly different from the turbojet there is a big fan sitting in front of the engine which actually sucks the air to the engine, one component goes to core another component bypassed. So that's why it's partly jet and the shaft work is to drive the fan and the propeller if it is turboprop. Then you look at the turbo shaft engine where all the shaft to drive the propeller generator or the rotor.

Now, when you come down to scramjet or ramjet or scramjet these are mostly for your space applications and in all these, there is no compressor or turbine. So, that means one of the difference from these gas turbine to ramjet or scramjet here no rotating component. So, if you are free from compressor or turbine, there is no rotating component which actually gives you a lot of advantage, because these rotating components are always an issue.

Because then your dynamical system the behavior of the dynamical system, they create a lot of problem for these kind of GT engines. So, here, but the compression is required. So, you get the compression done through the ram effect. Now, another category is the chemical rockets, where you could have another 2 subsection either solid fuel or liquid fuel. So, the solid fuel and oxygen they are premixed and placed in the chamber, whereas for the liquid fuel, you see the fuel and oxygen they are separated and pumps separately. Now, that all comes under your steady. When it comes to the unsteady you have a pre-mixed charged, non-premixed charged, stratified charge. If it is premixed charge, you have either gasoline or gas engine which is homogeneous charged spark ignition engine. HCCI this is also homogeneous charge compression ignition engine.

So there is a slight difference between these 2, 1 is the sparking ignition engine other is the compression ignition engine. Now, when you have the non-premixed charge there it is important to note here that air is only compressed and then this is like your essentially new diesel engine what happens air is compressed and then you inject the fuel and then because of this compression ignition, so the ignition takes place.

Now the stratified charge you have a partially premixed charge equals issues charged these are the system. So that's pretty much of your internal system you can classify and look at these things what in practically you see in daily applications.

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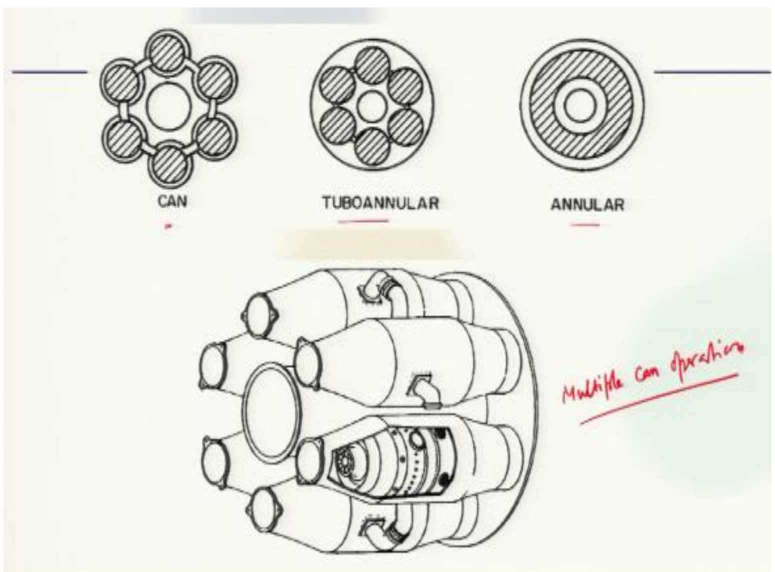

So, now we also talked about some combustors. Basically, specially which is used in your GT applications and these combustors are of like one could be can type, one could be annular type, turbo annular type and this is another schematic of your multiple can here you see 1 2 3 4 5 these are multiple can operation. So they do take part in the power generation of the thrust generation process.

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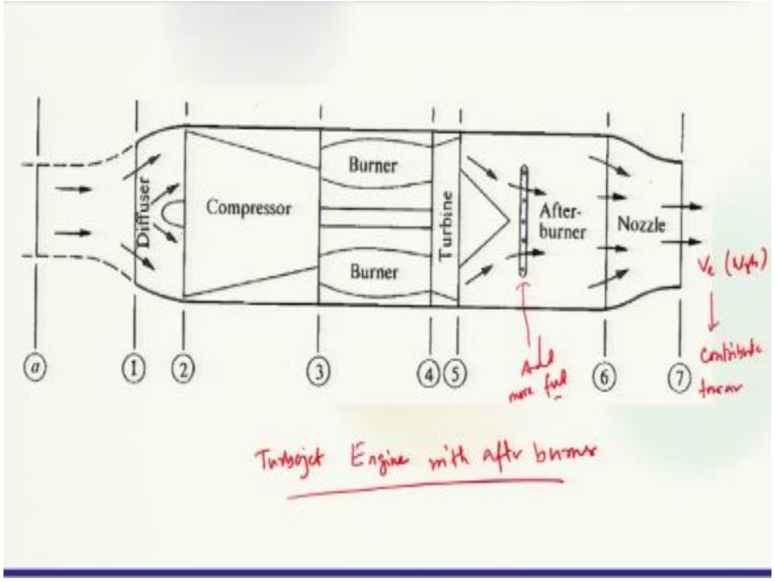

Now, this is another schematic or cut section of the engine with afterburner. So, this is a turbo jet engine with afterburner. So there you see the difference here, you have typically here comes through diffuser, then compressor, then goes through the combustion chamber or the burner then you pass through the turbine where the expansion takes place. And then after that you have afterburner which is second level of combustor which is there, where you add more fuel there.

So, once you add more fuel there actually you have an extra burning taking place to generate more power and then finally, you pass through the nozzle. So that this either reduction in all these things produces the high exit velocity, this is quite high. So which essentially contributes towards the thrust production, towards thrust generation. So, that’s how it works, these are the things some of them already we have discussed just to show you in a schematically how they look like.

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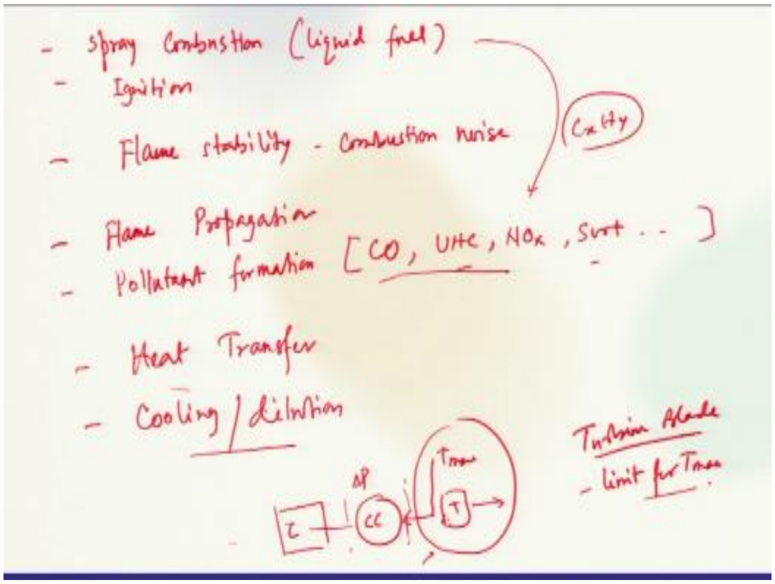

Now, once you put down the combustion in gas turbine, you can have other aspect of it like you have let's say spray combustion because your fuel is liquid. So, this is for liquid fuel spray combustion then you have ignition. So, you can have ignition also which is another important aspect of it because without the ignition fuel will not ignite. So, one more important thing is that stability that is your flame stability, this is quite important when you look at the gas turbine especially in the aircraft application.

Because flame stability is something which is very important. At given point of time, you cannot allow to start of your flame for then engine will get off and then there will be a huge problem. So, to avoid that issue in any of these aircraft applications, there is a pilot flame sitting there which acts as an ignite data. Now, this is for combustion noise now, then you have flame propagation and obviously there are issues like an emission.

So, pollutant formation which are CO, UHC, NOx, soot etc. So, these are obvious choice because we already have done quite a bit of discussion on this because you are burning some liquid fuels which is C_xH_y kind of category hydrocarbon fuels. So, once you burn a hydrocarbon fuel, the soot, CO, UHC these are obvious. Then heat transfer is another important aspect of it because all your combustor valves they are exposed to high temperature so, there will be huge thermal loading along with the liners.

So, the heat transfer and then cooling, so cooling of not only the combustor only but cooling of the turbine blade also so this is another aspect. So, it is both combustor and turbine so we need to look at the cooling aspect because turbine blade cooling is an important area of what people have been working for few decades and they come up with a new suggestion or design how one can improve the cooling and this cooling has a lot of effectiveness in the durability of these blades and all these things.

So, without cooling the blades will fail very quickly, which one cannot afford to do that, because the turbine is one of the key component of this whole business because the turbine generates the power, but this will dictate the design for both upstream and downstream because turbine will dictate the maximum temperature here T_{max} so that will dictate your combustion chamber design then combustion chamber there would be not only temperature also ΔP across that which will dictate allow your compressor design how much ΔP_R will get across this.

So, these are and also turbine will power the compressor and if there is a fan sitting there and then these exhaust things pass through the nozzle and to producer. So, this is in GT application, this is probably one of the very key components which do take part in the design process actively, because it allows this side of the design, this also dictate that downstream of the design. So one has to look at and that is why now these T_{max} in the turbine, the T_{max} in the turbine is controlled by the blade essentially the turbine blade.

Because these has a some material which has a limit for T_{max} what it can withstand on what it cannot. So, this T_{max} will actually control then this is coming from the material perspective and that is why one has to cool down that material, so that the failure does not occur. So, once that is dictated, so you can see that in a bigger picture how that dictates the whole business.

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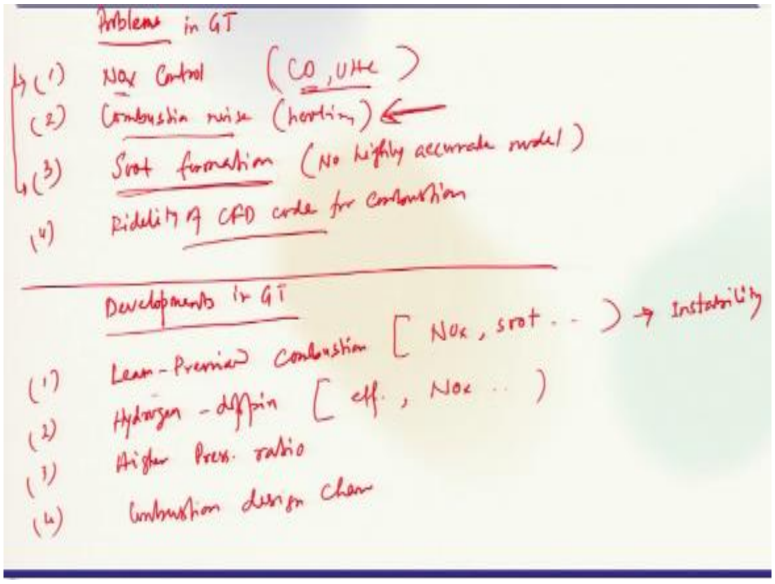

Now, some problems in GT application, so, some of them are still an existing problem, some of them are quite a bit of handled. So, for example, if you look at NOx control, this is an still in problem one has to actively look at it and rather the GT industry they look at it but obviously, you know NOx is not something which is decoupled from another issue is a CO or UHC, because the behavior of CO and UHC slightly different compared to your NOx and that is why some level of freedom is required.

Because NOx primarily if it is not fuel bound, it is because of the temperature in the post flame region, the thermal locks formation is quite active and that is what dominates but then at the same time, if your temperature is high, CO completely gets oxidized. So, that helps, but if you go to low temperature NOx could be low, but at the same time, CO could be quite high. So, it is basically in a situation where one hand these goes up, this comes down the other and it goes down it goes up. So, it is a balancing act between these 2, then your combustion noise or sometimes people call it hooting so, this is again an instability, but this has been kind of addressed by a lot of GT manufacturer, but still it is not hundred percent perfect because some level of noise still comes in. But all said and done, this is something which has actively pursued and people have come up with some control mechanism so that you can reduce the combustion noise.

Then the bigger issue is the soot, soot formation so this is something one has to work on because this is a serious problem even today, because any of these gas turbines when they are flying if you look at it or any automobile engines and all this in the back side of it, this is one thing people have to seriously work on these because one of the major issues is that these are so small, so capturing soot particles is not that an easy task.

Now through experiments or rather testing, it is also becomeing quite difficult because the cost involved, manpower involved, fabrications and all these things and also the equipment which is so sensitive to capture these things. Then the option which is required is the simulations or high fidelity simulation, but in that case also so that point that fidelity of CFD code for combustion this is another area.

So, but even then you have capability the mechanism or the governing equations and the models which are available even today, they are not that I would say a high fidelity model that can capture. So, no highly accurate model which can capture there are models which does predict things correctly, but then when you take it to the real applications, they are so expensive that one cannot afford to do that and there are simple models, but they are not accurate enough.

So, it is an again unbalancing problem because some models which can capture it to some extent accurately or reasonable enough accuracy, it can provide you but problem is that they are highly expensive. So, for realistic applications at that level of turbulence of the flow it is becoming quite difficult. So, this is another area where the even shaped is a sort of resistant sudden mature state, but for the commercial applications still it requires a lot of essentially the fidelity part it has to be looked at.

Now, some developments as also these are some of the problems, few of them are addressed and few of them are still being addressed. Now the developments also there so, you can look at those in GT applications for example, one try to do that lean premixed combustion, so the lean premixed combustion which will control obviously NOx, some level of soot these things would be controlled, but again lean premixed means it can goes to some or other instability.

So, you can see there to control these 2 parameters, you have a solution where you people can go to the lean premixed, but then you come back with this problem the instability So, this is always as I said it is a balancing act between one of the other. One you can control, the second one will create trouble or second you try to control the other one will be a problem then which is another is that you do some sort of a hydrogen doping.

Which will sort of increase your some sort of an efficiency controller NOx so some advantage it will provide and the other thing is that higher pressure issue and obviously combustor design change. So, you can use some sort of combined combustor things. Whether it is a sort of like annular or can annular, turbo annular they can be used in that way combinely and that can give you better situation.

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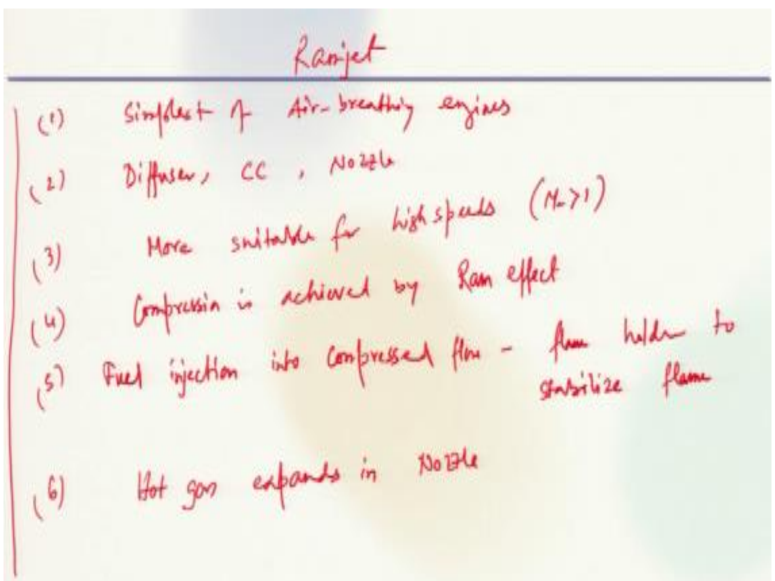

Now, when you go to ramjet kind of situation it is simple and rather simplest of air breathing system or air breathing engine. Now only thing it contains some diffuser that is one thing CC combustion chamber and nozzle, exhaust nozzle so these are the component it has. But the application is sort of more suitable for high speed or rather supersonic speed where Mach number is greater than 1.

Because the compressibility or compression is done so compression is achieved by ram effect only. It does not have any rotating component like compressor or turbine or fan or anything like that. One and that is an advantage because one can afford this rotating machinery, rotatable machinery, those turbo machinery gives you a different kind of challenge altogether. So, another obvious is that the fuel injection into compressed flow.

So the flame holder is used to stabilize the flame and then finally hot product or hot gas expands in nozzle. So that is how it works basically it gives you an idea about the working principle of this ramjet system.

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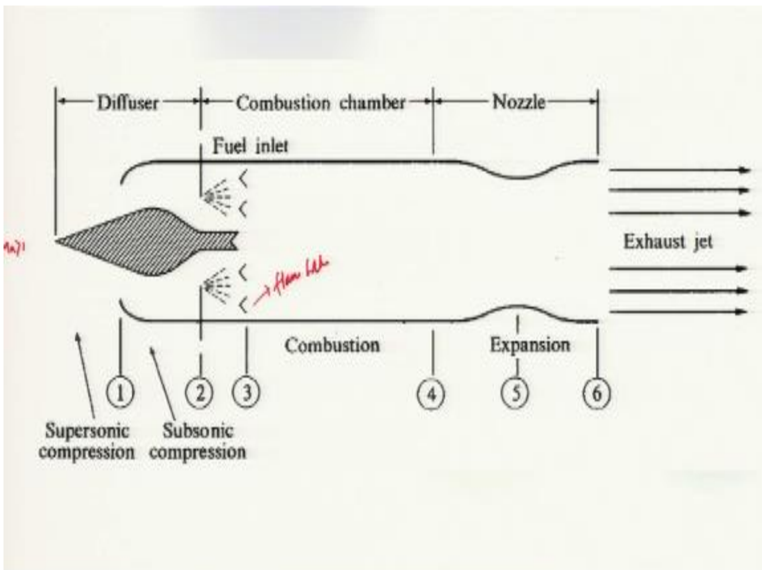

And this is what it is, I mean you can look at this schematic and find out so this is the diffusion portion. This protruded ports creates an high speed case. So because of this the diffusion takes place and then there are flame holders where fuel is injected, this is your combustion chamber. So it is not typically what do you see in a gas turbine application there can, turbo annular some kind of a combustor.

It is more like a very simple shape, annular kind of shape was the nozzle which has and there are the flame holders, these are flame holders actually. So, one obvious issue which becomes bit critical here is the flame stabilization behind the flame holders because the air speed is too high and due to diffusion it does not come to a level where the flame stabilization became. So, that is one of the again challenging areas for this kind of applications of the ramjet application.

Because flame stabilization and then you have also sort of a limitation of the field I mean it is all the fuels I mean each fuel has its own or different calorific value. So, that will tell you what kind of fuel one can use at the speed that the flame stabilization is very effective. So, that's an area which requires a lot of attention then finally to pass through the nozzle to get these things.

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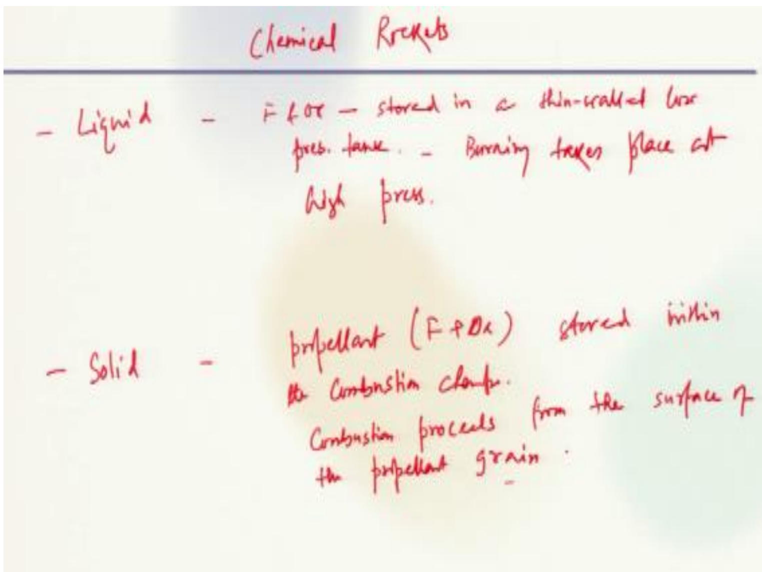

Now, when you come to the rocket application or rather I would say chemical rockets, what you have? You have 2 categories of that: 1 is the liquid fuel rocket here, we have already told that fuel and oxidizer they are stored separately and they are stored in a thin-walled tanks at low pressure. So your fuel and oxidizer they are stored in a thin-walled low pressure tank. So, they are pumped into the turbine.

Basically turbine driven pump, they actually pump the thing to the combustion chamber and there the burning takes place at high pressure so that is how it works. Then other one is the solid fuel system, where your entire block of the propellant that is both fuel and oxidizer. So, they are stored inter block of the propellant stored within the combustion chamber. So now, combustion actually proceeds from the surface of the propellants so from the surface of the propellants grain.

So, one can note that combustion proceeds from the surface of the propellant grain. So, that at a given rate depends on pressure and temperature. So, combustion will have an impact from the pressure temperature and also the geometry of the grain.

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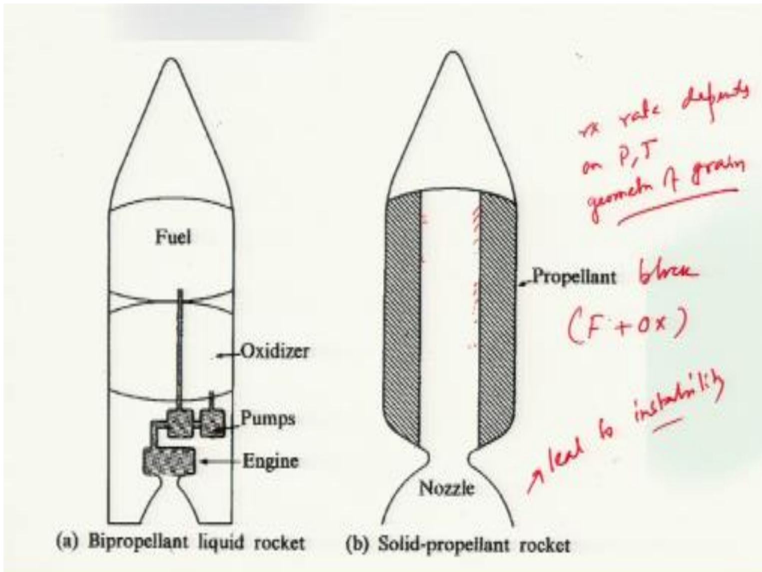

Now, this is just to give you an idea what kind of schematic it has been, I mean they are much more complicated than what you seen here with these are very simple schematic diagram to just give you an idea how things are. So, this is a liquid rocket where there is a pump sitting there, you have oxidizer, your fuel, so these pumps are actually injecting this into the engine. So, this is the engine and then finally passed through this nozzle where it generates that huge amount of thrust and when you look at the solid this is the propellant block.

The total propellant block where fuel plus oxidizer they are already premixed. Now, they are sitting within the combustion chamber and the reaction starts from these surface and this reaction rate depends on a certain temperature and specifically the geometry of grain that is a propellant grain, because the geometry has a huge impact on the propellant grain, how these combustion will proceed and what will be the rate?

But again here the issue is that the solid propellant the control of these things is not very easy, because they are already within the combustion chamber and once it ignites the control of the propellant is not that easy, but whereas, when you look at this liquid one and when the fuel and oxidizer they are injected separately to the system to the pump, turbine driven pump mechanism to some extent you can control the flow of these liquids or the fuel or oxidizer.

But here there is no such mechanism which exists in the solid case once it is ignited that’s sort of a self-driven system or self-sustaining system which will keep on bonding these propellant. So, the control of these things are not that easy and then top of that when that happens, it leads to instability. So, combustor instability in solid propellant rocket are quite common that because the things are not that control, so, okay we'll stop here today and continue the discussion in the subsequent lecture.