**Fundamentals of Combustion for Propulsion**
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**Lecture - 03**
**Combustion in solid and liquid rocket motors**

Let us switch to solid rocket engine, some of our friends may be unhappy that we did not discuss solid rocket engine till now, let us do that. There are two kinds of a propellants used in the actual systems; we have double base propellants and composite propellants, but most high energy systems now use composite propellants for their operations.

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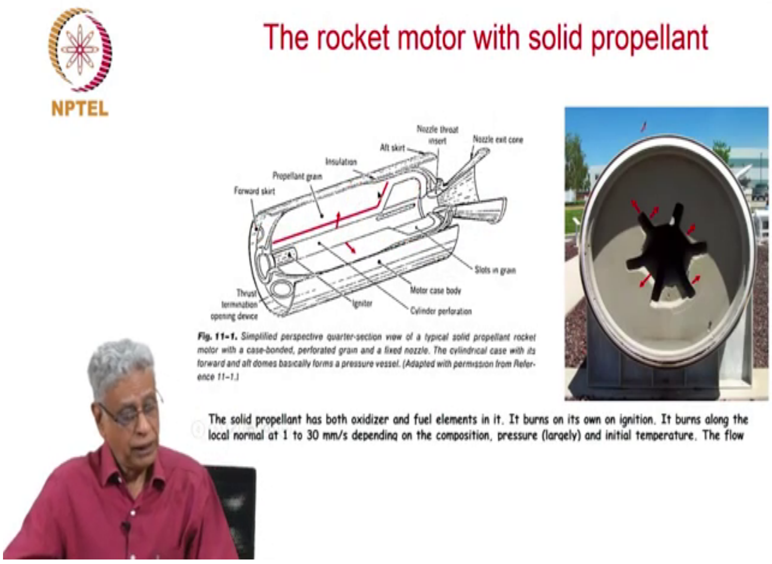

Typically a rocket engine for those who are not familiar with it will be like this, when outer metal casing is an inhibition system, a insulator, plastic insulator. Then the propellant you see the propellant here as you see cast into outer casing.

And, it is got various geometries, reason will be simple, you have to give the definite amount of burning area to the given thrust. Hot gas is going through the nozzle well need that amount of mass flow that is why you have various geometries. You have ignition system here, the propellant is a very important fundamental principle; every propellant burned along the local normal. So, you will discover that the if it is in this format you will find the propellant goes radially outwards, if it is at an angle is normal to that.

In fact, you see all the arrows that I have shown here this burnt along, this just burns along this direction. So, the geometry will expand in its own way and the entire propellant will get burnt up after while ok. This propellant which has both oxidizer and fuel elements in it, once you ignite you cannot do too much more. There ways of extinguishing, but that is a more complex process then you have to depressurize, you to do many other things. So, you once you ignite you how to accept the fact it will completely burn up.

Typically it burns at millimeter per second which is very small at low pressures around 10 to 11 millimeter per second a normal operating pressures of 40 to 60 atmospheres. Some propellants are designed to burn even faster 30 to 40 millimeter per second. The operation the burn rate depends on the composition, pressure and initial temperature and, this one key aspect which Dr. Varun will present in terms of modeling it, how to predict this burn rate given the composition and the conditions of initial temperature and pressure.

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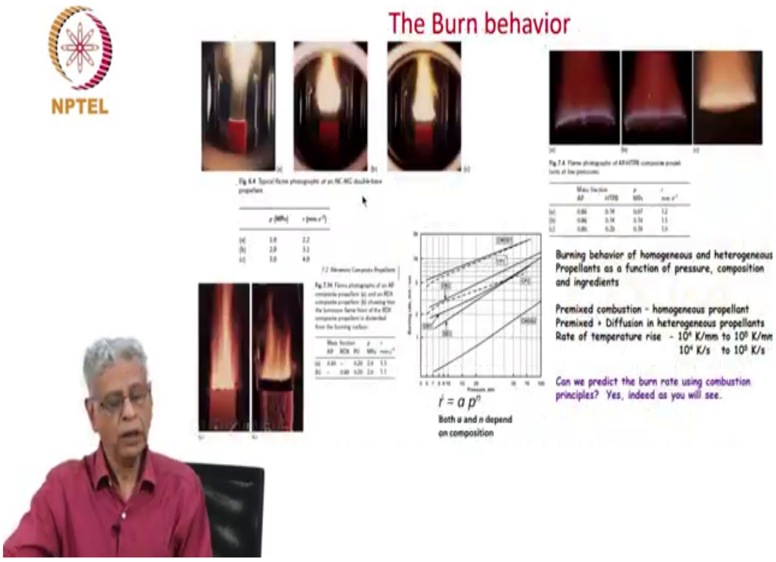


Just look at qualitatively burn behavior, I think everybody should just know that much. You see some three pictures here, this is the burning of a propellant of a double base propellant; nitrocellulose, nitroglycerin double base propellant. You see that the flame is far off; this is burning at 10 atmospheres, this burning at 20 atmosphere, this burns at 30 atmospheres. This is the flame is coming closer, the flame thickness is smaller.

As pressure increases the flame comes closer, flame thickness is smaller; that is the key point to observe here. And, nitrocellulose nitroglycerin propellant is essentially homogeneous; that means, the oxygen and fuel elements are together. So, there is no other process than combustion reactive process which controls the behavior, it is a pre-mixed combustion process. So, what we describe as premixed combustion in gases a place here to solid propellants.

Then we look at a ammonium perchlorate HTPB hydroxyl terminated poly butadiene, composite propellant typically used in all ISRO obligations. If you look at pressures here very small pressure 1 atmosphere in something like that, this is shown here for expressing the following behavior. This is at 86 percent solid loading, restore 86 percent. This is at 80 percent solid loading, you see the brighter flame; slightly more fuel rich compared to these two cases.

Burn rate is also low at ambient pressure is about 1.2 to 1.5 millimeter per second, the point which I mentioned a little earlier. But, only if you go to higher pressures say 650, 60 atmospheres, you will get burn rates of the order of 8 to 10 millimeter per second. You see the burn rate as a function of pressure is increasing like this and typically expressed in a format like r dot is equal to a p n, p is pressure, a is the coefficient, n is the pressure index. And, this is called Vielle's law, the standard way in which the propellants are processed and analyzed.

The only point to know is that a and then we will depend on the composition and initial conditions. So, the burning behavior of homogeneous and heterogeneous propellants as a function of pressure and temperature in ingredients are shown here. And, you will see that in this cases, in the case of n CNG is pre-mixed combustion, homogeneous propellant is pre mixed here. And, if I have a larger particle size then the oxidizer gases have to mix with fuel rich vaporized fuel fragments from HTPB and burn together, that is a diffusion process.

So, you have both pre-mixed and diffusion are taking place in a heterogeneous propellant, only premix process in the case of homogeneous propellant. Just remember the rate of temperature rise is extremely large, goes up to 10 power 5 K per second. If you see its 300 K at the surface around 1000 K and flame temperature is 3000 K. And, you see the time it takes for it to burn is 10 millimeter per second and this zone over which this occurs is about quarter of a millimeter or so, even less than that inside the actual peak temperature occurs at maybe 50 micron from the surface.

And therefore, temperature rise rates are very large, just keep it this in mind because many times tools which are used to analyze it are not necessarily compatible. And, this is the point which will be brought out by Dr. Varun later. So, I am asking a question can you predict the burn rate using combustion principle. Clearly yes and you actually you can actually do an exercise given a composition what the burn rate will be. And, this has been done for at least 100 compositions by them, including a team from VSSC quite successfully and you will see the results.

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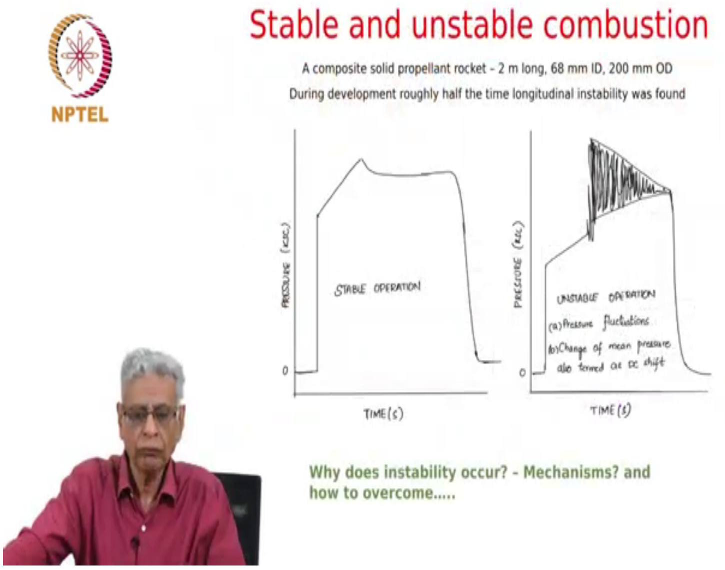


Stable and unstable combustion: I am showing here a motor with 2 meter long, 68 mm ID, about 200 mm OD. During the development of the system and I will not say what it is it here it, but well with the pressure time curve which is nearly same as what was predicted using normal principles; you will see achieved and predicted. Means half of them roughly during the development phase you found pressure time traces like this.

And, this you know we can infer later to be a longitudinal instability with the pressure going up along the predicted line until some point and shooting up substantially. And, there are two features here; the pressure is fluctuating and there was change of the mean pressure and it is called the DC shift that the shift of the pressure from here to some other value around which it fluctuates. These are the features which occur.

So, we should ask ourselves this question why does this instability occur at all? What are the mechanisms and how do you overcome them? Now, there are important points for you to note, there is existing literature on the subject which is I must honestly tell you is not correct. They have been analysis of this phenomenon which is directed to some non-linear wave propagation techniques which is really not right. It is related to combustion energy that coming from unstable processes to do conduction from the surface below, the below the surface and interacting with gas phase; matter again will be looked at later.

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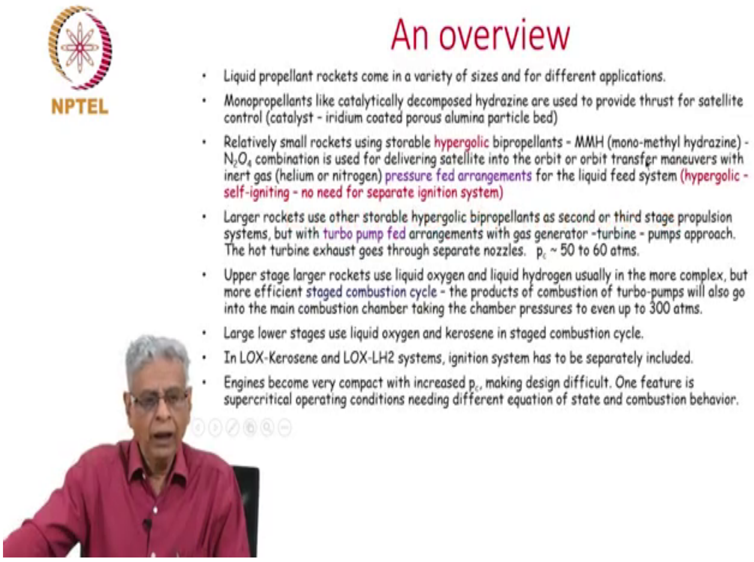


Let us switch to liquid propellant rockets. Its a last subject so, let me take a quick overview. Liquid propellant rockets come in a variety of sizes and for very variety of applications. Monopropellants like catalytically decompose hydrazine that used to provide thrust for satellite control, catalysts typically is called iridium coated porous alumina particle bed into which you spray the mono propellant, because the spray hits it and the surface decomposition occur.

So, the decomposition of the propellant in this case monopropellant hydrazine occurs because of the catalytic activities at the surface. And, you get gases generated, temperature exothermically temperature build up to reasonable levels around 1000 to 1200 K and then the gases go to the nozzle. Relatively small rocket using storable hypergolic propellants like mono methyl hydrazine and nitrogen tetroxide combination, these are used for delivering satellites into the orbit or orbit transfer maneuvers including inert gas and helium nitrogen pressure fed arrangements for the liquid feed system.

So, this combination is the hypergolic which means itself igniting, it means no need for separate ignition system. Larger rockets use storable hypergolic by propellants as second or third stage propulsion systems, but with turbo pump fed arrangements. You please see here its pressure fed because the sizes are small, these sizes are large. Sizes means in terms of both into the flow rate and the burn time that large; that means, the total impulse delivered by these engines is much larger than this.

And, in these cases you need turbo pump fed systems to reduce the weight of the system and the size of this system. And, then they also use a gas generator turbine essentially to pump the fluids to higher pressures. And, the hot turbine exhaust goes through separate nozzles, this is one form in which the you know engines are constructed; chamber pressure is typically 50 to 60 atmospheres typically. Their upper stage larger rockets which use liquid oxygen and liquid hydrogen these are usually more complex, but there is a more efficient stage combustion cycle.

The products of combustion of the turbo pumps will also go into the main combustion chamber taking the chamber pressures to as high as 300 atmospheres. Now, I say 300 atmospheres in one engine and the development at LPSC it around 170 atmospheres or so. But, there was a you know you know Elon Musk has developed any as used an engine from Russia and that the chamber pressure goes up to 300 atmospheres. Larger lowest stages use liquid oxygen and kerosene again in a stage combustion cycle.

In LOX-kerosene and LOX hydrogen systems, the ignition system has to be separately included because the fuel oxidizer combination is not hypergolic. The engines become very compact with increased choice of pressure, chamber pressure making the design difficult. In fact, in state combustion cycle the peak pressures go right up to 700 atmospheres and you have to be very concerned about the pumps, seals to make sure no leakages occur. It is a very tough engineering call on the design of the systems.

One of the features in terms of combustion is that it is a super critical operating condition and in fact, it needs a different equation of state. You know equation of state is good at conditions where temperatures are high, pressure is not too high. When pressures become higher including supercritical conditions, the equation of state and the vapor will become very different and the gas will be different. And, this has to be treated in the design process at the analysis process.

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Look at I am just showing the 3 engines; F 1 engine is too well known in the literature it is Saturn V. It took the mission to the moon which happened several decades ago, this was the engine used. And, the Space Shuttle Main engine which is the work hours for this pay what which was the work hours for this space shuttle. And, the RD-170 engine now left in Russia which was the work hours for them. All of them have various trust levels shown here

LOX-kerosene, LOX-hydrogen and LOX-kerosene or the few of these combinations used in them.

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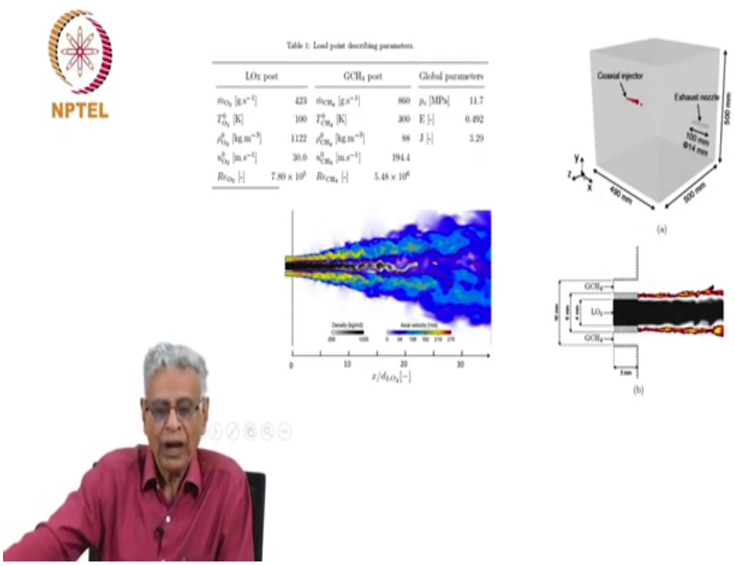


Ok. I am just showing you in terms of development variety of things have been done in terms of small scale engine experiments. And, there is a particular reason why I want to show you the diagram drawn from one of the research efforts. You will discover that the process of combustion you will find fragments. You know portions where there is no flame and then there is a flame and you will see that you may not see it right here, you will see some mixing zones shown here.

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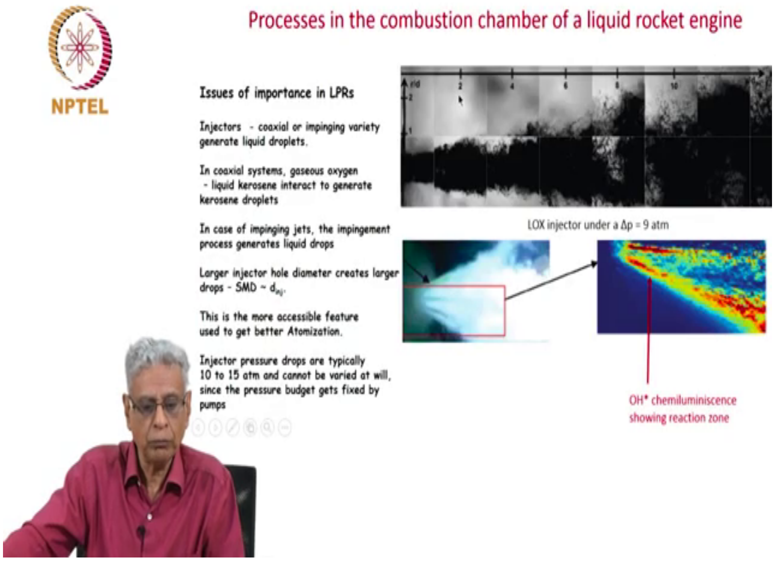


Let us see something more. So, what are the process which occur in the combustion chamber of liquid rocket engine? Injectors would be could be coaxial or impinging variety which generate liquid droplets. In coaxial systems usually it is the gaseous oxygen and liquid kerosene interact to generate the kerosene droplets. You see where you have oxygen coming at the center, your liquid droplets coming, you will kerosene injected in the periphery and then you create droplets along the way.

In the case of impinging jets, which is what F 1 engine was about; the impingement process generates liquid droplets. Larger injector whole diameter creates larger drops ok. This is sorter mean diameter this is a volume to surface ratio based diameter. It its dependent on the injector hole diameter. This is a more accessible feature used to get better atomization.

Injector pressure drops are typically at and 10 to 15 atmospheres across the injector and cannot be cannot be varied at will, since the pressure budget gets fixed by the pumps.

What I mean by that is you cannot arbitrarily demand, like in diesel engine you remember several thousand bars, but here you cannot do it; because it means the pumps have to pressure build up your pressure. So, that injector pressure drops are limited because of that, you will see something interesting in the diagram. You will see the chemiluminescence picture of the combustion process here. You see OH stars being tracked, their portions very there is combustion, where there is no combustion; let us keep this in mind.

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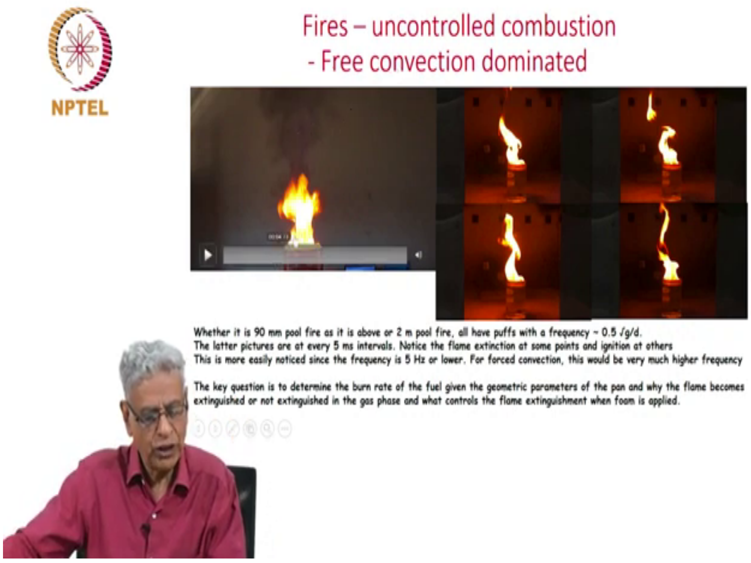


Very different environment, you are looking at fire which is essentially uncontrolled combustion; something which we do it at Jain university. What you see here is this 17 70 millimeter diameter pool fire and also you can also do the same thing at 2 meter pool fire as well; you will find the same behavior. You will find here a flame extinguished and another flame here ok.

There is flame therefore, the flame extinction at some points and ignition at others. This more easily notice since the frequency is only 5 Hertz are lower in these cases. But, force convection which I showed you little earlier, this will be at much higher frequency. You will find patches where there is extinction, there is patches where there is a combustion. The key question is to determine the burn rate at the, in this case you have to determine the burn rate of the fuel given the geometry parameters of the pan and why do flame becomes extinguished or not extinguish in the gas phase and what controls the flame extinguishment process when of course, foam is applied and in the gas phase as well.

See these processes have commonalities, something which we will address later that is why does the flame get extinguished, when the flow is taking place; why these reignite later? These are the important questions and in a turbulent flow it may mean simply an averaging process, but if it is not exactly so, you may find it is as a expression of an unstable combustion as well ok.

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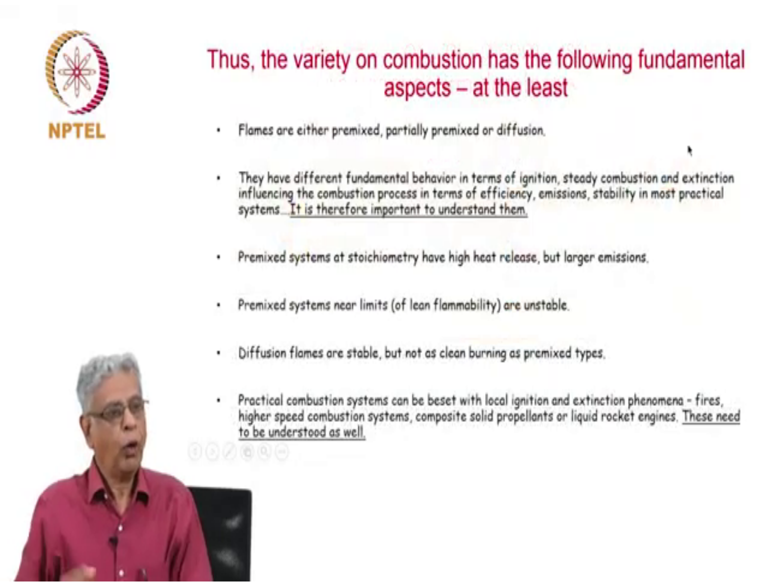


I want to summarize now, there is a variety of combustion of processes following fundamental aspects at the least. Flames are either pre-mixed, I did not mention partially pre-mixed, they could be partially pre-mixed or diffusion. They have different fundamental behavior in terms of ignition, steady combustion and the extinction. All these processes are influenced by whether something is pre-mixed or diffusion. They will influence both efficiency, emissions, a stability in most practical systems therefore, important to understand them.

Premix systems at stoichiometry have high heat release, but larger emissions. Premix systems near limits are also unstable. Diffusion flames are more stable, but not as clean burning as pre-mixed types. Practical combustion systems can be beset with local ignition and extinction phenomena as I showed you including in fires, high speed combustion system, composite solid propellants or liquid rocket engines.

These need to be understood as well. So, I just have told you what are the aspects which occur in actual practical systems, that we by understanding the fundamentals we will be able to derive the benefit of resolving issues which if they arise.

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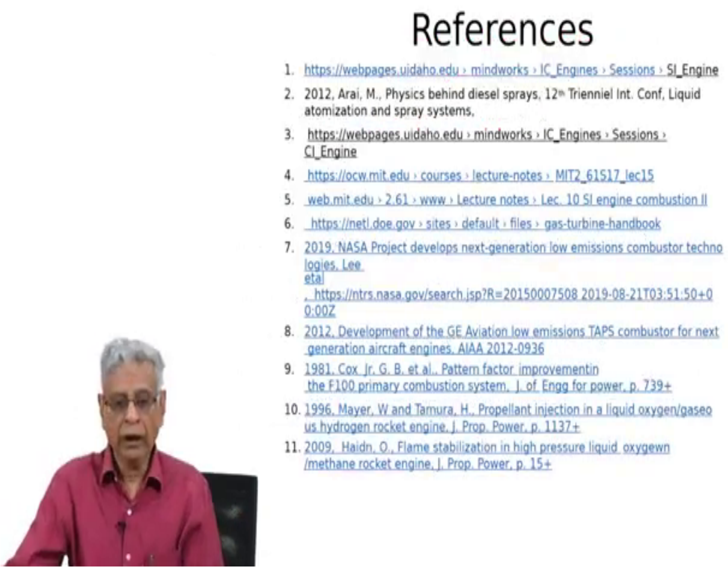


I think that is all I need to say on the subject at this point of time.