Jet and Rocket Propulsion
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Lecture – 38

Welcome back. So, in the last class we talked about solid propellant rockets, we discussed various aspects of solid propellant rockets including the prop type of propellants, the ignition, etcetera. Today we are going to talk about the liquid propellant rockets. Now as the name suggest, the liquid propellant rocket essentially uses liquid as propellant.

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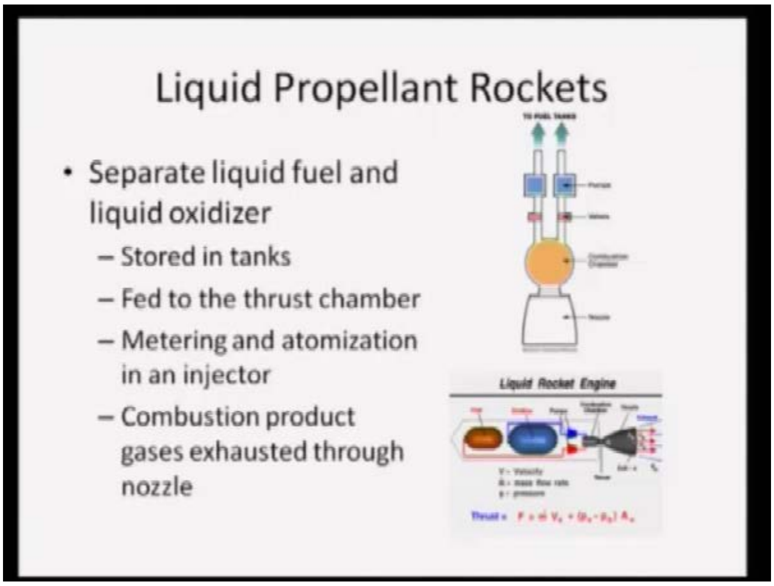

So, here we have a simple schematic of a liquid propellant rocket, where liquid separate liquid fuel and oxidizers are stored in the fuel tanks, then this fuels both fuel and oxidizer are fed into the thrust chamber through some pumps. There are pumps in between to control the flow rate of this and the metering and atomization is done in an injector, and then the combustion takes place in the combustion chamber and the gasses are exhausted through the nozzle.

So, that is the basic principle of operation of a liquid propellant rocket. So, if you see here in this picture, we have two tanks fuel and oxidizer, then the pumps this pump fed into this thrust chamber or combustion chamber, combustion takes place then we have this nozzle here. And after burning or expansion through the nozzle the exhaust goes out with a velocity v e at the pressure p e, and the exit area is p a e then the thrust produced from the thrust equation, which we have derived at the beginning of this course is equal to m dot v plus p e minus p naught a e; that p naught is the ambient pressure, p e is the pressure at this exit, a e is the exit area, v e is the exit velocity, and m dot is the mass flow rate. So, that is what into it in a liquid propellant rocket, but it is not that simple in operation there are lot of engineering issues involved in liquid propellant rocket.

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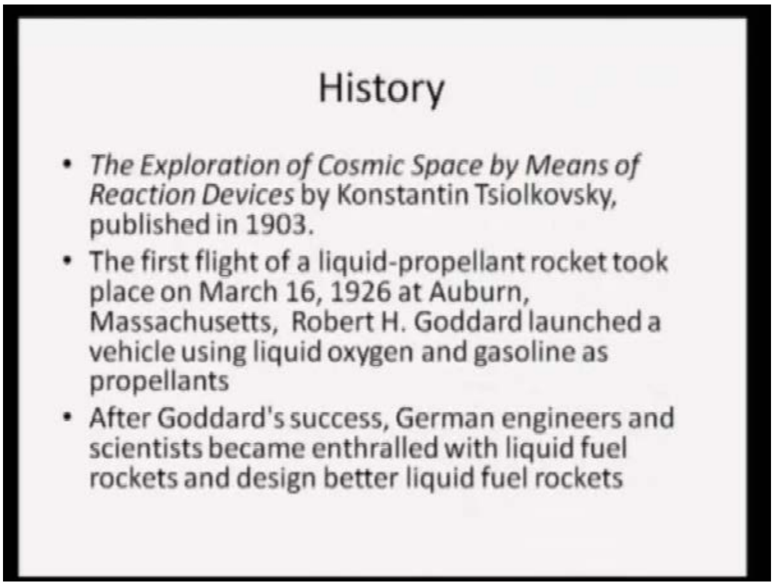

So, before we go into the details. First let us look at the little history of liquid propellant rocket. Liquid propellant rocket was first proposed in 1903 by T siolkovsky in his book the exploration of cosmic space by means of reaction devices in 1903, he first proposed the use of liquid propellant rocket. The first flight of the liquid propellant rocket dates as back as 1926. In fact, 16 th march 1926 at Auburn Massachusetts by the father of modern rocketry Robert Goddard. I have discussed at the beginning of this course about Robert Goddards Robert Goddards and his contribution to rocket science. So, he essentially made the first liquid propellant rocket in 1926, and launched successfully using liquid oxygen and gasoline as the propellant. So, after Goddards success the German engineers and scientists become enthralled with this technology, and they started to design better liquid fuel rockets.

So, from 1926 till we come to the first second world war, there has been a rapid development in the liquid propellant rocket, because this was identified as the most promising technology to make a rocket viable.

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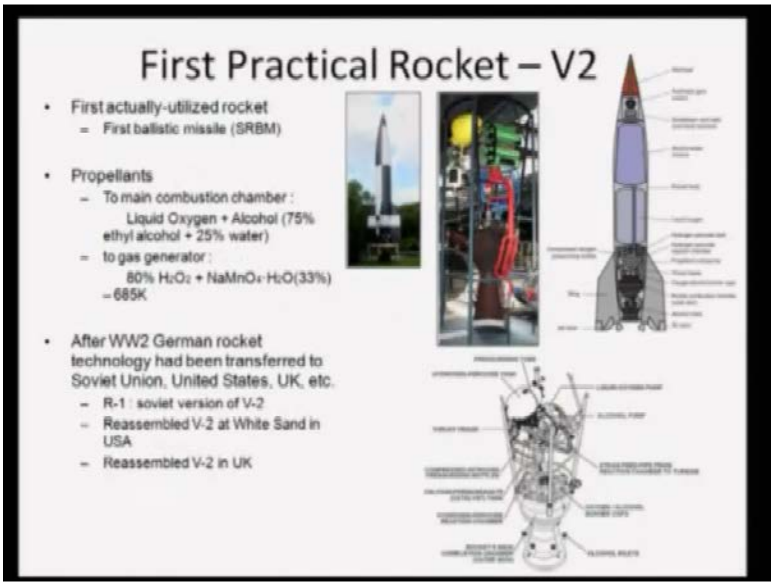

So, therefore, the first practical rocket which was ever used was V 2 V 2 rocket developed by Germans. So, this was first actually utilized rocket which was the first ballistic missile, short range ballistic missile a picture of the V 2 rocket is shown here. The propellant of this rocket were to the main combustion chamber we had liquid oxygen and alcohol, which is alcohol was 75 percent ethyl alcohol, and 25 percent water mixture was given to the main combustion chamber. To the gas generator, which essentially allowed the compression of the gasses to put into the combustion chamber or the turbo fan to run the sorry, run the turbo pump that used 80 percent H 2 O NaMnO 4 H 2 O, this was able to take it the temperature to 685 kelvin, this runs the pump which fed the propellant to the main gas chamber.

So, I will talk about different type of liquid rockets then explain this more. So, essentially the propellants were liquid oxygen and alcohol. Now, this was successfully fired during the second world war, after the second world war this German rocket technology was transferred to various allied countries like soviet union, united states, and UK, etcetera. So, R 1, sorry was the soviet version of V 2 rocket, USA reassembled V 2 at white sand in USA, and similarly UK also reassembled U 2 rockets. So, this is a full picture of a schematic of a V 2 rocket that was used during second world war. And the technology so far has not much changed it till remains almost similar technology, where all the main ingredients or components are already there in V 2. So, that has not been much of technology advancement beyond this as far as the rocket part is concerned, only this the component efficiency were increased, but the basic schematic remains same.

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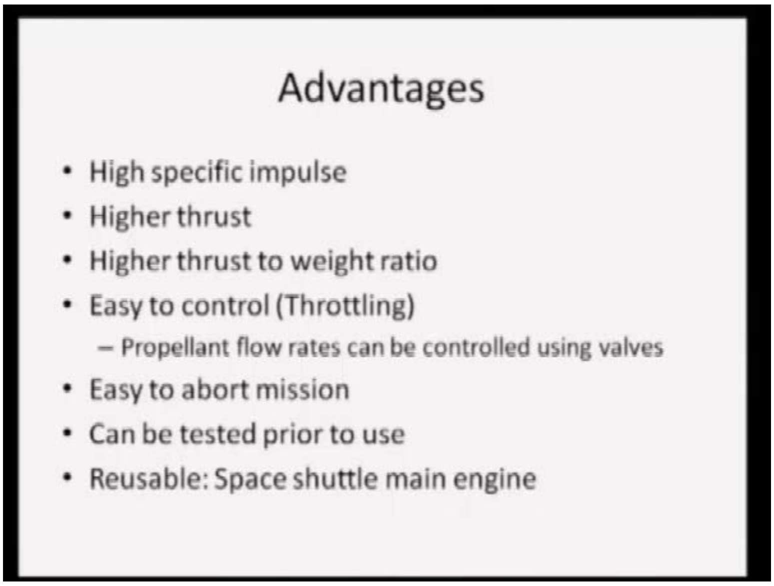

So, what are the advantages of a liquid propellant rocket? First of all its high specific impulse compare to the solid rocket as we have discussed in the previous class, they have much higher specific impulse going up to as much as 450 seconds. On top of that the fairly high thrust, because the liquid propellants have pretty high energy density as well because of that we have a high thrust to weight ratio, the best biggest advantage of a liquid propellant rocket is easy throttling or easy to control. We can control the propellant flow rate that is the both fuel and as oxidizer flow rate by using control valves, which are used in line after the pump and the combustion chamber, we can control the flow rates.

So, that essentially gives us control over the entire energy or heat release rate, because we can change the mass flow rate, we can have control over the entire heat release rate or the heat flow rate produced by the combustion process. And because of this it is very easy to abort the mission, also we just need to cut off the supplier of supply of fuel and the combustion will stop. So, mission can be very easily aborted it. And another thing is that unlike liquid solid propellant rocket, once you create the grain if you fire it, it is gone you have to produce another grain to test the system, whereas liquid propellant rocket can be tested before the fire also. We can still refill the tanks and test the system. So, the testing of the system is possible, which is not possible in solid propellant rocket solid propellant.

Then you have to make a new grain and burn it again, whereas liquid propellant rocket you can just have need to change the fuel and oxidizer and test the system. So, that advantage even gives us flexibility to test different types of fuel oxidizer combination also right. So, the development is much more scientific, and it is very, very reusable. This technology this rockets can be used again and again, and because of that space shuttle main engine uses a liquid propellant rocket. So, we can have the main thrust chamber everything pump and everything can be retained except the tanks can be thrown out if needed otherwise you can retain the tanks also, but typically tanks are thrown out. So, just tanks need to be put in and the rocket remains the same. So, now different type of liquid propellant rockets are possible.

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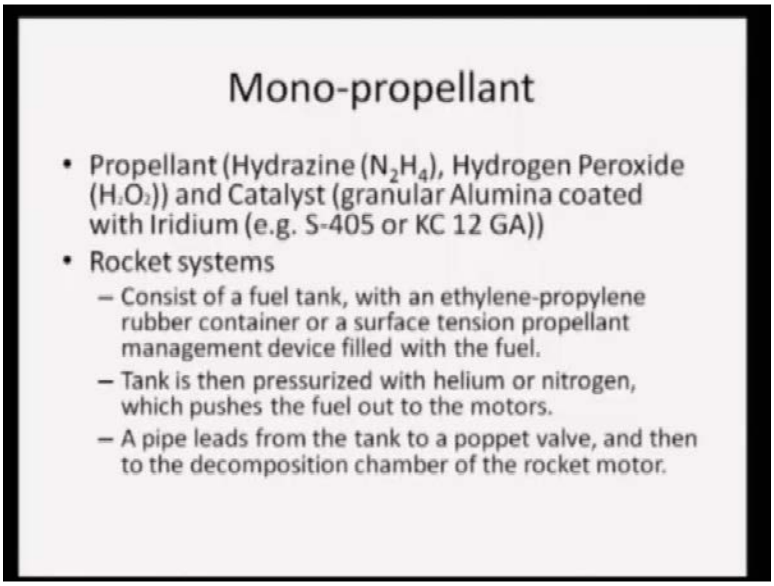

First and foremost is a mono propellant rocket where we have a single propellant, which essentially is a mixture of both fuel and oxidizer, typically these type of propellants are hydrogen and hydrogen peroxide, and of course some catalyst is required to start the or initiate the ignition process, typically it is a granular alumina coated with iridium this used as the catalyst. So, this is a mono propellant rocket, which will; mono propellant means the propellant is single is a propellant itself will burn when energy is provided. So, the rocket system since it consists of fuel tank, now in unlike the bi propellant system we can have a single fuel tank right single fuel or oxidizer we do not need two tanks, we need a single fuel tank, but since these are highly reactive you need to have some special lining. So, ethyl propylene rubber coating is given inside this or a surface tension propellant management devices used, which is filled with the fuel. And then this tank is specialized by an inert either helium or nitrogen which pushes the fuel out of the out to the motors, and then the pipe leads from the tank to a valve, and then to the thrust chamber of the rocket motor, and then this propellant when fed into the rocket chamber it will burn on its own, so this is a mono propellant system. Other system is a bi propellant most widely used liquid rocket are bi propellant.

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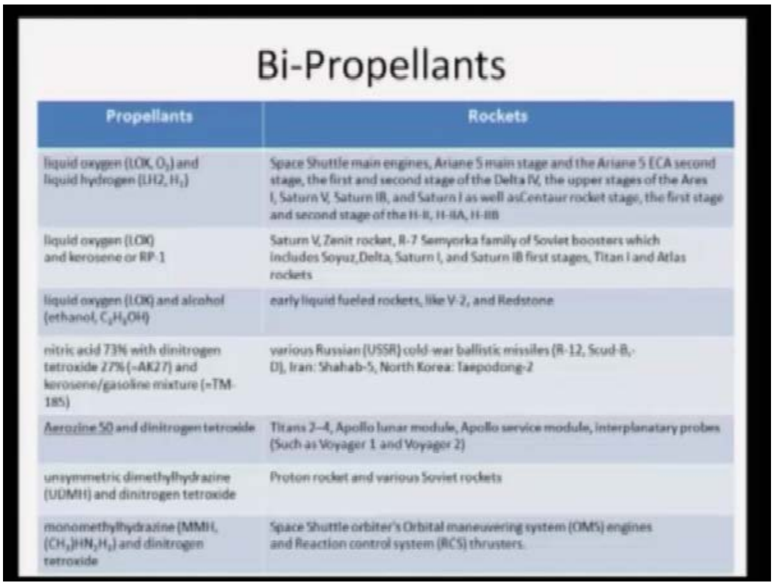

Bi-Propellants

Propellants	Rockets
liquid oxygen (LOX, O_2) and liquid hydrogen (LH2, H_2)	Space Shuttle main engines, Ariane 5 main stage and the Ariane 5 ECA second stage, the first and second stage of the Delta IV, the upper stages of the Ares I, Saturn V, Saturn IB, and Saturn I as well asCentaur rocket stage, the first stage and second stage of the H-II, H-IIA, H-IIB
liquid oxygen (LOX) and kerosene or RP-1	Saturn V, Zenit rocket, R-7 Semyorka family of Soviet boosters which includes Soyuz,Delta, Saturn I, and Saturn IB first stages, Titan I and Atlas rockets
liquid oxygen (LOX) and alcohol (ethanol, C_2H_5OH)	early liquid fueled rockets, like V-2, and Redstone
nitric acid 73% with dinitrogen tetroxide 27% (=AK27) and kerosene/gasoline mixture (=TM-185)	various Russian (USSR) cold-war ballistic missiles (R-12, Scud-B,-D), Iran: Shahab-5, North Korea: Taepodong-2
Aerozine 50 and dinitrogen tetroxide	Titans 2–4, Apollo lunar module, Apollo service module, interplanatary probes (Such as Voyager 1 and Voyager 2)
unsymmetric dimethylhydrazine (UDMH) and dinitrogen tetroxide	Proton rocket and various Soviet rockets
monomethylhydrazine (MMH, $(CH_3)HN_2H_2$) and dinitrogen tetroxide	Space Shuttle orbiter's Orbital maneuvering system (OMS) engines and Reaction control system (RCS) thrusters.

So, that is why I can see there are as you can see there are various rockets listed, typically propellant like say cryogenic propellant liquid oxygen liquid nitrogen is used or we can have liquid oxygen and kerosene, which is semi cryo, then we have liquid oxygen and alcohol, nitric acid with dinitrogen trioxide, and kerosene then aerozine 50, then UDMH then MMH, all kind of MMH and dinitrogen trioxide, UDMH and dinitrogen trioxide, all type of different combination of fuel and oxidizers are present. So, different countries use different propellant for example, isro uses a isrosene which is a propellant fuel developed by isro with liquid oxygen. So, you have a semi cryo engine liquid oxygen, and isrosene burning together.

So, therefore, different I have listed here different rockets, which use these propellants. As you can see it pretty much covers most of the rockets used over the world. So, at a very depending on the mission requirement, all these propellants have these own energy density own I s p for depending on the mission requirement you choose, which one to use; that is why you can see that I have a big list of different types of rockets and different type of propellants alright.

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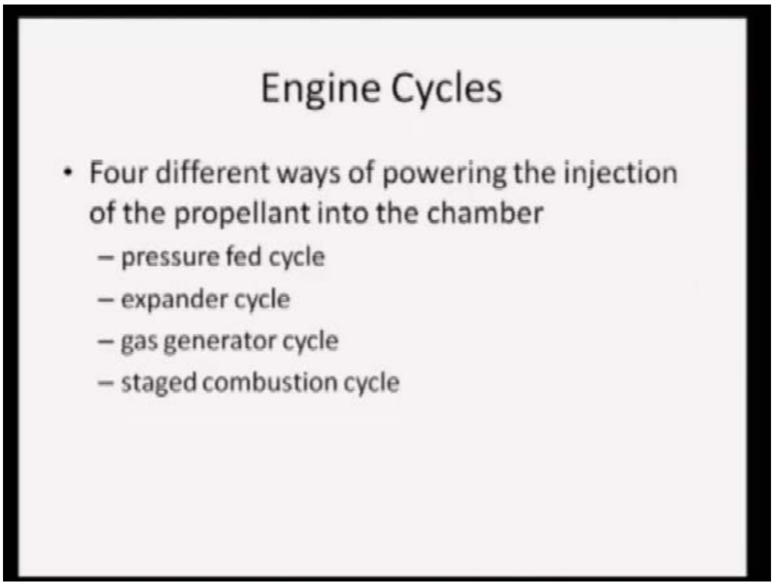

Now, let us look at how this work in reality, how this liquid propellant rock rockets work in reality? We talk about the engine cycles. There are typically four different ways of powering injection of the propellant into the chamber, and that essentially dictate what type of cycle it will follow; one is a pressure fed cycle, then an expander cycle, then a gas generator cycle, and staged combustion cycle. So, these are the our type of cycle cycles that are used to feed the injector into the combustion chamber.

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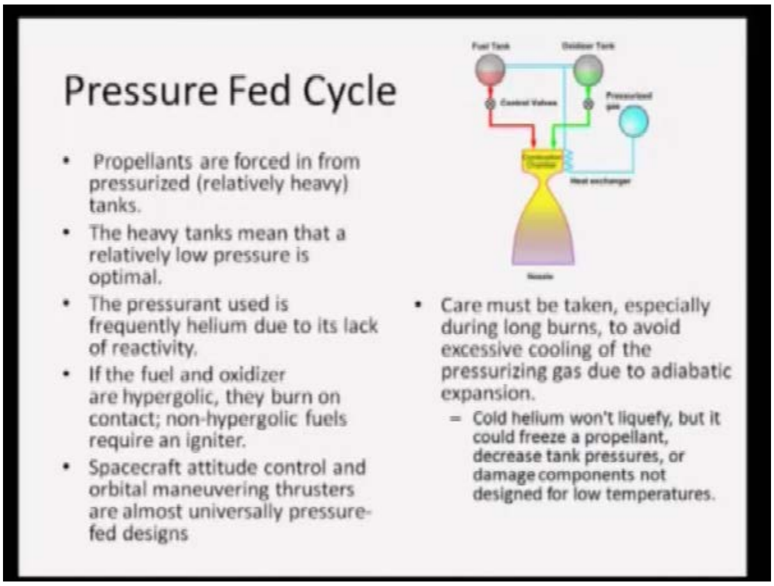

So, now let us look at one each of these one at a time first a pressure fed cycle, here is the schematic of a pressure fed cycle, this is our combustion chamber, the fuel tank and oxidizer tank, and we have the control valves here. What we have is a pressurized gas, it can be helium, it can be nitrogen, it is stored at high pressure into a container, and this is fed into the fuel and oxidizer to push it full push the fuel and oxidizer at high pressure into the combustion chamber.

So the propellants are forced in a form of in from pressurized tanks, which are relatively heavy tanks, and because of the heavy tanks relatively low pressure is optimum, we need to have. And typically the pressurization is done by helium due to its lack of reactivity, because it is fairly inert. If the fuel and oxidizer are hypergolic they burn on contact immediately, otherwise you need to have an igniter to burn the fuel and oxidizer. The space craft attitude controls a small rockets used for space craft attitude control or orbiting maneuvering orbital maneuvering thrusters are almost universally pressure fed designs, because this pressure fed gas can be maintained up to a long time. So, it can be operated in outer space also.

Now however, there is a problem with this, you must take enough care essentially during long burn hours or long burn times to avoid excessive cooling of this pressurizing gas, because as the gas comes out it expands right. And as it is expanding the temperature will go down, as the temperature down goes down the cold helium will not liquefy, but your oxidizer and fuel that may get frozen, it may freeze the fuel and oxidizer and if that happens the flow will be of course ((Refer Time: 13:22)). So, flow will not be smooth, it will not come the same flow rate will not be maintained. Similarly it may damage the components like valves etcetera, and these devices are not designed for low temperature application. Now to be a system safe from this problem is to have a heat exchanger in between. So, as you can see this is the heat exchanger.

So, it will be wrapped around the combustion chamber, it absorbs some of the heat from the combustion chamber. So, that the helium temperature does not go to very low levels. In that case this problem of freezing will not occur, but that precaution must be taken, otherwise there is a practical probability or chance of having the fuel or oxidizer frozen then it is not going to work. So, this is as I said most widely used during in the spacecraft attitude control or orbital maneuvering thrusters.

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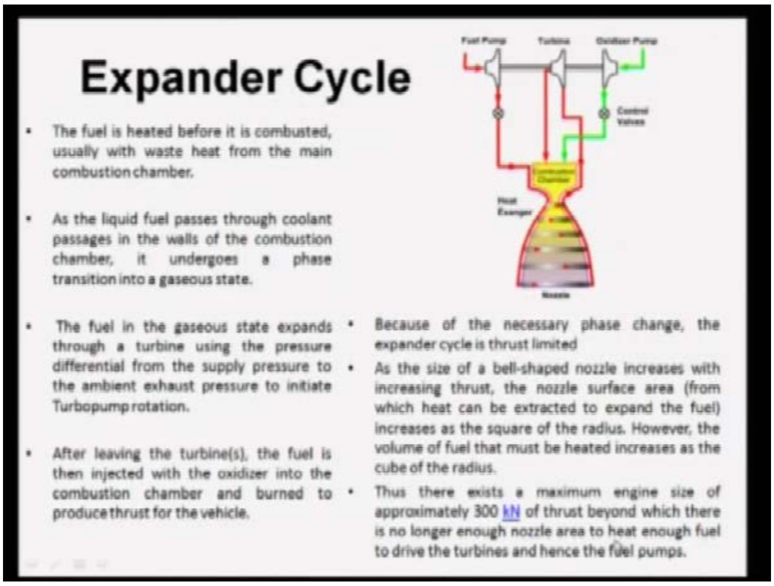

Next let us look at the another cycle, which is called expander cycle as the name suggest there is some kind of expansion taking place in expander cycle. So, here what happens, there is a schematic fuel comes through a valve, and then it is channelized all around the combustion chamber, and the nozzle. So, the fuel flows through this channels and absorb some of the waste heat, because of this absorption of this heat - the fuel gets expanded, and gets converted into gas. And there after that this gas is supplied across a turbine, and because of that the turbine starts to rotate, this turbine is connected by a shaft to this fuel pump. So, the pump starts to volt and therefore fresh fuel is sucked in.

Now, the gas after it crosses the turbine is fed back into the combustion chamber. So, therefore, there is no wastage of fuel and everything is essentially burnt. So, this is the cycle entire cycle of a gas expander cycle; however there is one problem with the cycle of this cycle, because we require a phase change where the liquid fuel must be converted into gas in order for this to work, otherwise a turbine is not going to work. So, because of this phase change requirement, the operation is thrust limited, it cannot operate beyond a certain amount of thrust. Now let us understand why that happens?How do we increase the thrust for the same combustion chamber we do not change p c naught and t naught. So, only way we can increase the thrust is by increasing the nozzle right, nozzle size. As we increase the nozzle size, the nozzle surface area increases we need to have more volume to heat it up to rather more volume of fuel to absorb the heat produced by this right.

So, the volumetric flow rate requirement increases, and as the volumetric flow rate requirement increases the also the in order to produce more thrust you require to have more volumetric flow rate also. So, as the volumetric flow rate increases more energy has to be given out to convert it into gas, but that energy is no longer available. So, because we have increased the amount of fuel, which absorbs that energy, so therefore you do not have enough energy now to convert it to gas. So, of beyond a particular point as we keep on increasing the thrust, the conversion will stop rather the phase change will stop, and as the phase change stops this cycle is not going to operate, therefore this limited thrust will be produced by this. So, there exist a maximum engine size of approximately 300 kilo Newton of thrust beyond which there is no longer enough nozzle area to heat enough fuel to drag the turbines, and hence the fuel pumps. So, this is the problem with the expander cycle.

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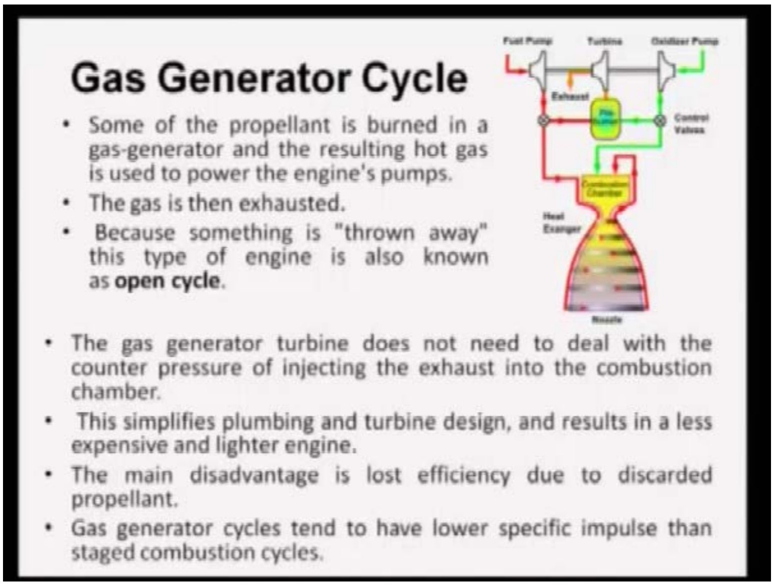

Next let us look at the third type of cycle, which is a gas generator cycle, it is very similar to expander cycle, only difference that we do not need it to gasify by heat transfer from cooling. Instead we have a separate burner a pre burner or combustor, which is called gas generator. So, some of the propellant as you can see here some of the propellant and oxidizer is taken here from the oxidizer and fuel and burned in a pre burner. Now the resulted hot gasses pre given burner and gas generator is used to run the turbine. And then this turbine runs the fuel pump for fuel and oxidizer pump. So, that fuel and oxidizer come into, and then they go into the chamber, the heating is used to cool it and then but it is into the chamber itself.

So, this heated thing is not used to run the turbine. So, you do not need to completely convert it into gas, it can still remain in the liquid phase. So, pre burner actually eliminates the requirement of this thrust limitation, we can go to higher thrust by having a pre burner which is a separate combustion system. However, the gasses after going through this turbine is exhausted directly into the ambient. So, that is where it is called an open cycle it is thrown away, this gas is thrown away. This is actually a combination of fuel and oxidizer. So, some of the it could have produced some of the thrust, but we are not utilizing that thrust. So, because of that the efficiency of the system is less than if you burn completely everything, since we are throwing out this which is not going through the nozzle, we are losing some of the efficiency. The gas generator turbine does not need to deal with the counter pressure of injecting the exhaust into the combustion chamber, because that require certain amount of pressure, this simplifies the plumbing and turbine design, and results in less expensive and lighter engine. The major disadvantage is the lost efficiency, because we are throwing out some of this gas outside. gas generator cycles tend to have lower specific impulse than stage combustion cycle. Next I will discuss stage combustion cycle primarily this is less, because this is the amount of propellant, which is not participating in thrust generation right, because of that the specific impulse is less.

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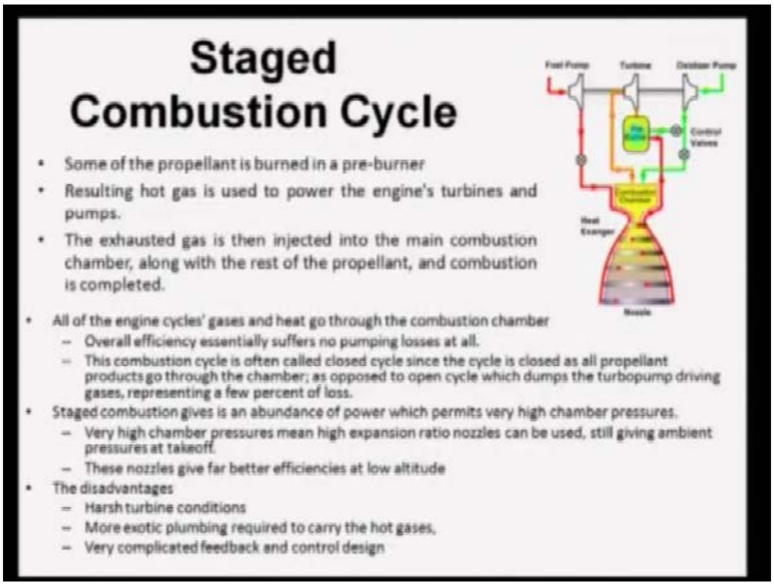

So, the forth type of cycle is the stage combustion cycle. In stage combustion cycle which is again actually its combination of both the gas generator cycle as well as the previous cycle we talked about the stage sorry, what was that expander cycle. This is a combination of expander and gas generator cycle. So, here is the schematic. The liquid fuel comes in goes around the combustion chamber gets heated up, but its fed into the pre burner, oxidizer directly comes in here part of the oxidizer is taken from the supply and put into the pre burner. Pre burner burns this fuel and complete all the fuel earlier in the gas generator it was all the fuel which was going to the pre burner. Here all the fuel goes to the pre burner. So, as you see you can see there is a fairly fuel reach combustion going on, and then it goes to the turbine, and then the entire product is fed into the combustor again.

So, nothing is lost and it is already a vapor phase now. So, your fuel is now coming as a vapor of product and fuel, because some of the product is created here. So, this is the stage combustion cycle, some of the propellant is burn in the pre burner and resulted hot gasses used to power the engines turbine, and the pumps. The exhausted gas is then injected into the main combustor along with the rest of the propellant and combustion is completed. So, all the cycle gasses are going through the combustion chamber, therefore overall efficiency does not suffer any loss.

So, we have fairly high combustion efficiency this combustion cycle is often called close cycle, because everything is going round. And the cycle is closed as propellant produce product goes to the chamber as oppose to the open cycle, where some of these were discarded right in the open circle some of gas generator cycle, some of it were discarded. Stage combustion gives an abundance of power, which permits very high chamber pressure, we can go to very high chamber pressure by this schematic, very high chamber pressure on the other hand means high expansion ratio nozzles are possible. and because of this high expansion ratio nozzle, we can get fairly good pressure at take of as well even at ambient pressure, we can get fairly high pressure in the combustion chamber to allow even take off, because it is possible to operate at very high pressures.

And this nozzle give far better efficiency at low altitude, because they are designed for high pressure operation, there are some disadvantages with the stage combustion cycle, first of all the turbine conditions are fairly harsh, because it is experiencing hot products coming from this combustion. So, turbine has to withstand these conditions. Secondly, the gasses, that is coming now to the combustion are hot gasses. So, require more exotic plumbing insulation and all to prevent heat from getting lost, and also from thermally insulated material. So, that it can withstand the high temperature. So, it is coming at high temperature right, so therefore the plumbing has to be more exotic. And first last and another most important thing is that you require a very complex feedback control for proper operation of all these devices, this is a major problem with this stage combustion, because everything has to be controlled in a proper way. So, that everything works in unison. So that is the stage combustion cycle. So, I have discussed all four cycles.

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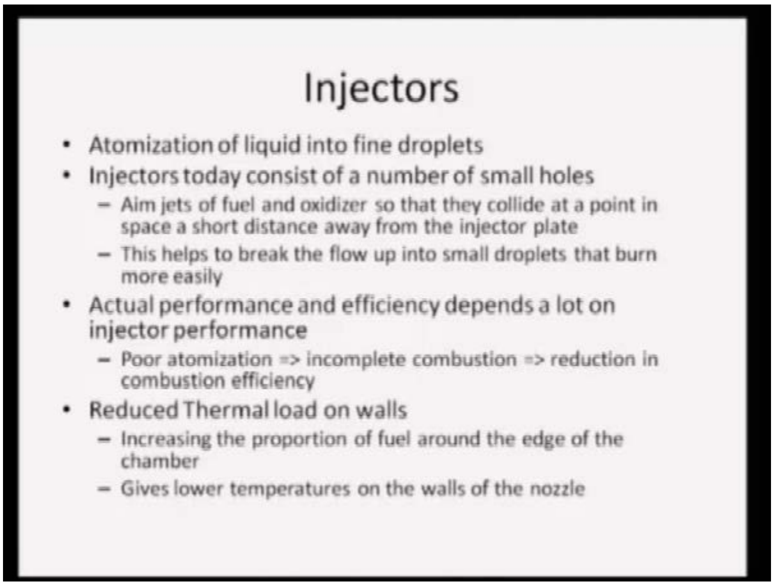

Now let us look at some other aspects of liquid combustion, liquid propellants. One of the most important component of liquid propellant is the injector, what are the injectors? The injectors actually atomize the liquid into the fine droplets. Today the injectors cost primarily of small number of number of small holes, lot of holes very small diameter they these small holes aim the jet of fuel and oxidizer in such a way. So, that they collide at a point in the space, the short distance away from the injector plate, and because of the collision the jets become study and then break into fine spray.

So, this helps to break the flow into small droplets which are then easy to burn they will evaporate faster, mix faster, and burn faster. Actual performance of a rocket and its efficiency depends a lot on injector performance, because if you have poor atomization, the droplets are big then combustion will be incomplete. Because then by the time the evaporation gets completed, it will be almost outside the thrust chamber. So, therefore, the combustion will be incomplete. So, poor atomization will lead to incomplete combustion and that essentially means reduction in combustion efficiency.

So, to have good atomization is very, very important or essential for good performance of a rocket liquid rocket. Secondly, the injectors work in as a secondary application in reducing the thermal loads on the walls. The injectors actually spray the fuel and oxidizer in such a way particularly close to the wall to create a small thin film on the wall. So, the providing increased proportion of fuel around the edge of the chamber, it reduces the chamber temperature, wall temperature of the chamber. So, that prevents the melting of the chamber material or the heat transfer out of the system losses out of the system, and then that can get evaporated and burn. So, therefore the wall the lower temperature on the walls of the nozzle can be obtained by essentially tailoring the spray in such a way. So, that we get a particular type of special distribution of temperature field. Injector can provide that.

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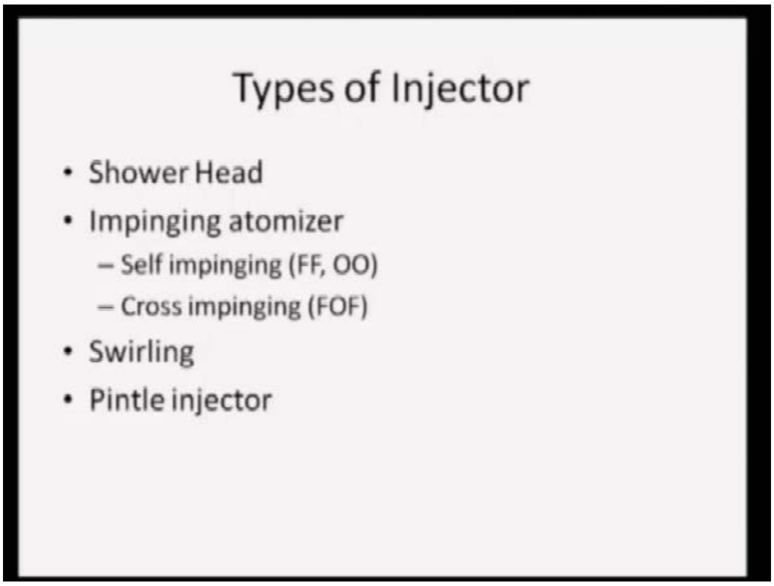

Now, what are the different types of injectors which are used, first is a shower head type of injector. I will discuss all of them in detail then an impinging injector, which can be self impinging either a fuel fuel or oxidizer oxidizer or cross impinging which is fuel oxidizer fuel, then we can have swirling injector or pintle injector; these are the different types of injectors used in rocket application.

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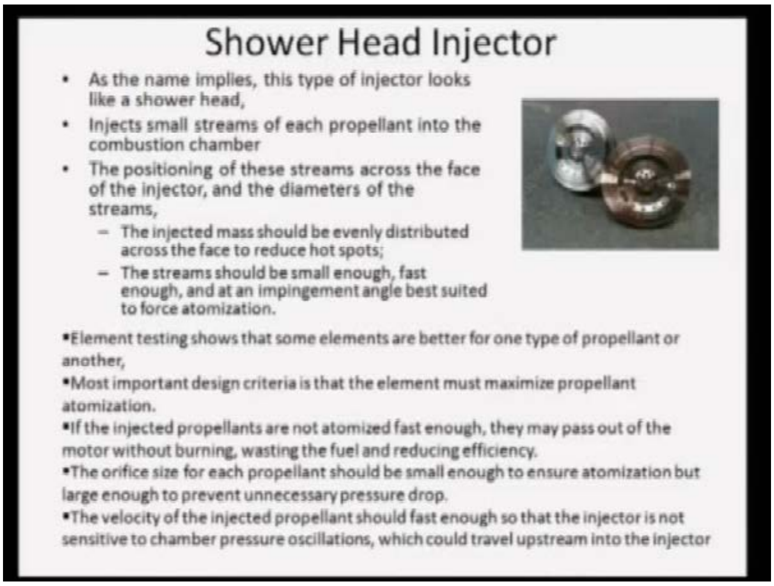

First let us look at a shower head injector. As the name implies this type of injector looks like a shower head, these are there are some of the pictures of shower head injector essentially it consists of various many, many small holes which are oriented in particular manner. This injects small streams of each propellant into the combustion chamber, the positioning of these streams across the face of the injector, and the diameter of the streams will be such that the injected mass should be evenly distributed across the face to reduce the hot spots.

And secondly the stream should be small enough fast enough, and at a particular angle best suited to force the atomization process. So, this whole design should take care of these two requirement, how we align and locate these holes. The element testing shows that these elements are better for one type of propellant or other, that has we cannot take one of this injector element, and use it for any type of propellant, because the atomization quality will depend on of the propellant or viscosity of the propellant or density of the propellant, right.

So, therefore, we cannot have a single shower head which will give best performance for all the propellants. So, therefore this diameters or rotation need to be changed for propellant to propellant. Most important design criteria is that the element must maximize the propellant atomization, this is the most important thing. If the injector propellants are not atomized fast enough, then that will reduce lead to incomplete combustion, wasting of fuel, and reduce efficiency, which we do not want. And the orifice size is another issue here that the orifice size that we provided for this propellant, we cannot have very large holes, then the atomization quality is going to be poor. At the same time we cannot have very small holes either, because in order to push the amount of flow rates through the small holes, then you require a very large pressure drop. Now the pressure is provided by your turbo pump. So, if you require a very high pressure drop you have to extract more power from the turbine right, which means that in your entire cycles efficiency is going to go down, right.

So, therefore we cannot have very small holes either although very small holes will give the better atomization, but at a cost. So, therefore, there must be a balance depending on the designers choice, there should be a balance between the size of the holes, it cannot be very small it cannot be very large, so this balance must be maintained. The velocity of the injector propellants should be fast enough. So, that the injector is not sensitive to chamber pressure oscillations. Now this is very important. The velocity at which or the delta p that is provided it should be such that the combustion chamber instability should not lead to feed line coupling, I will discuss this in detail again. So, when there is a chamber pressure oscillation there should not be transmitted back, and effect the fuel supply. So, that can be attained by having a high enough velocity of the flow of the fuel.

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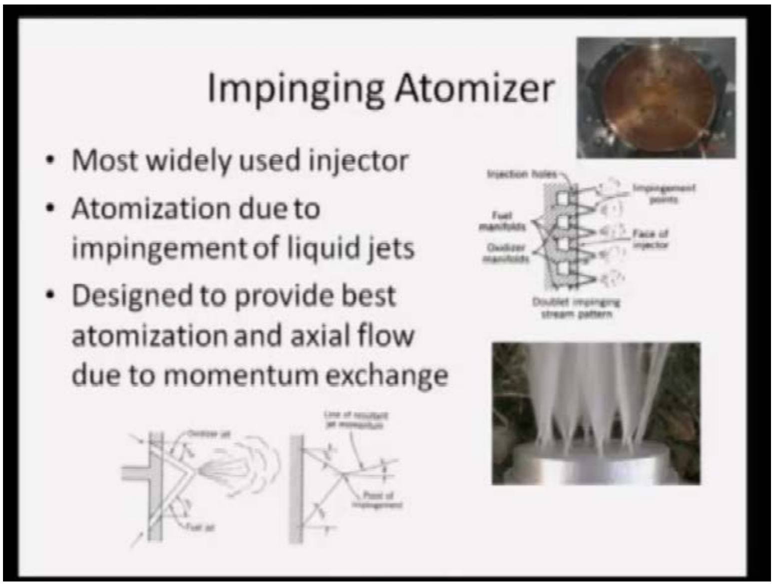

Next let us look at the impinging type of atomizer. This is a schematic of a impinging type of atomizer which is also called doublet atomizer in this one. As you can see there is a pair of holes here, 1 2 1 2 together you can see here; two holes are placed side by side, is a schematic here, these are the injection holes. So, this is the most widely used injector. Here the atomization is due to the impingement of liquid jets. So, the fuel and oxidizer jet as you can see here are set at an angle. So, that they strike in space and then because of this collision they break into fine droplets. So, this is designed to provide best atomization and once they collide, the resultants will flow is in this direction. So, it gives the axial flow also. So, it starts with angular flow then gets into the axial direction after the collision. So, this is the schematic diagram of that.

So, you can see there is a picture of doublet atomizer working, the two jets coming and colliding making the fine stray and then moving in the axial direction. So, this is the by far the most commonly used rocket injector, and the fuel and oxidizer are supplied through manifolds in the inside the plate and then they come out and create the spray.

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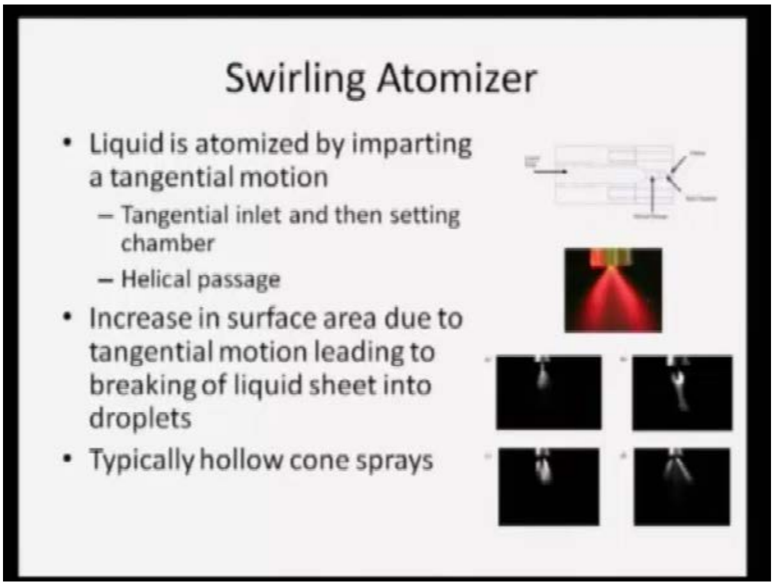

The third type of atomizer is a swirling atomizer. This in this atomizer liquid is atomized by tangential motion. So, the tangential motion can be impacted by either providing a tangential inlet and then a settling chamber. So, that the liquid gets a tangential motion or passing the liquid through a helical passage as it is done here in this atomizer, is a helical passage. So, the liquid passes through the helical passage gets a tangential velocity. So, when it comes out it has a tangential component of velocity, so it splits out like this. So, this is spray typically hollow cone spray is created. So, because of this spreading out of the liquid surface, there is a increase in surface area, and this leads to a breaking of liquid sheet into droplets. Typically hollow cone sprays are created, but this hollow cone spray is created after a particular pressure is given after a particular pressure is applied across the injector that you create a hollow cone spray, at lower pressure it the cone will not breakup you will not get fine spray. So, fairly high amount of pressure is required to produce this type of fine atomization from this type of atomizer. So, this is very similar to a pressure atomizer or pressure fuel atomizer.

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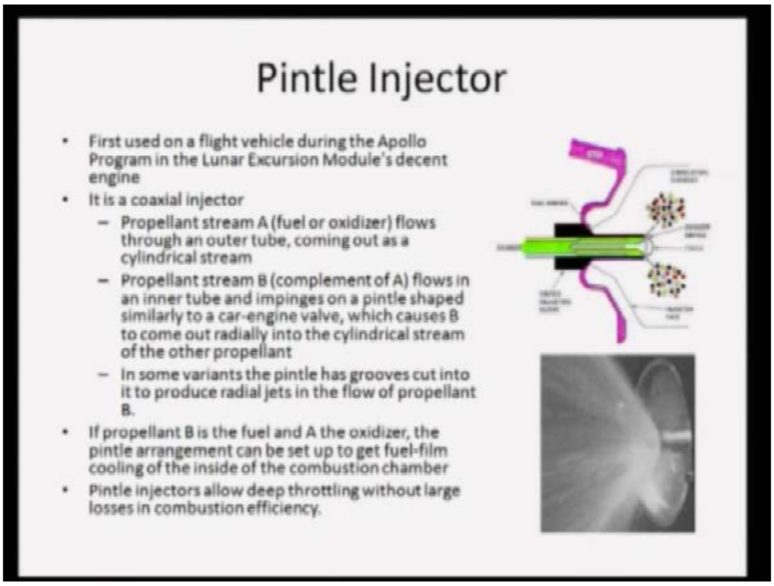

Then the other type of atomizer is a pintle injector or pintle atomizer, this was first used on a flight vehicle during the apollo program in lunar excursion module decent engine, it is coaxial injector as you can see here. the oxidizer comes here, this is the oxidizer passage we have a pintle or plug sitting here. Now this plug does not completely close the passage, but a small space is space remains, and then the oxidizer fed under pressure goes out through this passage. The fuel on the other hand as you can see here is fed through a small passage directly into this. So, the fuel and oxidizer interact or collide with each other at this surface, and because that the atomization takes place.

Both of them are coming at a fairly high pressure. So, therefore, they have a high momentum, so they break in collision. The flow rate can be controlled by moving this pintle up and down. Now if you have a pintle moved in the passage area decreases, that increases the that reduce it increase the velocity, so atomization become finer. If you take it out the passage area increases the velocity decreases, the atomization becomes course. So, you can have a control of the atomization property also. So, if the if the propellant is the b n propellant b is the fuel and a is the oxidizer, the pintle arrangement can be set up to get fuel film cooling of the chamber as well. We can design in such a way that it can use the fuel film cooling as well. The pintle atomizer the biggest advantage is allowing deep throttling, because we can just move the pintle and get different flow rate also.

So, it allows for deep throttling without large losses in combustion efficiency, this is the biggest advantage of these type of atomizer. So, this is the schematic and how it works? So, one component is the atomizer or injector.

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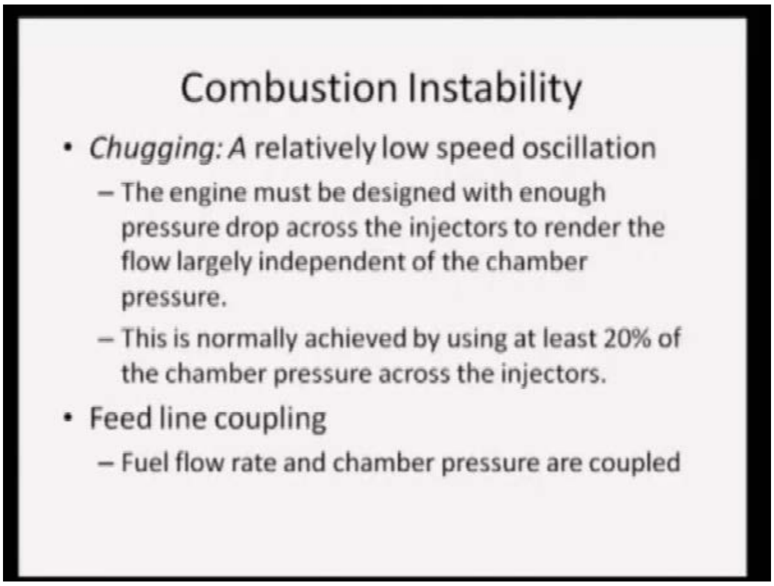

Now, let us look at some of the problems associated with liquid propellant rockets. What are the most recurring problem or very nagging problem is combustion instability; one type of combustion instability is chugging, this is a relatively low speed oscillation of the pressure in the combustion chamber. Now the engine must be designed with enough pressure drop across the injector to render the flow largely independent of the chamber pressure, because this chamber pressure oscillations always take place. So, normally it is achieved by using at least 20 percent of the chamber pressure across the injector. So, the pressure drop across the injector should be at least 20 percent of the chamber pressure, that is the basically rule of thumb. Now what happens here in combustion instability the due to the feedback between the pressure, and heat release the pressure starts to oscillate. As the chamber pressure starts to oscillate your turbo pump is feeding at a constant rate.

So, turbo pump is feeding at a constant rate, but a chamber pressure is increasing, because of that there is a decrease in flow rate. As the flow rate decreases then what happens that since the flow rate decreases your p c naught will decrease right. So, the more flow will go through the throat right, because it you have a throat rather less flow will go through the throat. So, there is a as the p c naught increases or chamber pressure increases sorry decreases. So, first chamber pressure was increasing, because of the increase in chamber pressure the flow rate decreases as the flow rate decreases the chamber pressure starts to decrease. So, again it will as the chamber pressure starts to decrease, the flow rate there is a because your throat is choked.

So, therefore the flow that will go through is increasing now, that will lead to again a decreasing the flow that will go through that will again lead to a rise in pressure. So, then the pressure will go to rise and fall rise, and fall periodically. So, that is called that is what the combustion instability is now what is the effect of that that the fuel flow rate then directly gets effected. Now, if it is a limit cycle oscillation is fine it will operate, but it may be possible that the feedback is such a way that the pressure rise flies away, it starts to increase and it starts to increase then the fuel flow rate will be more and more effected. And the point will time will come when the flow rate will be such that it goes beyond the flammability limit then the combustion will stop.

So, therefore the feed line coupling can lead to the combustion being stopped, therefore combustion instability is a dangerous phenomenon to occur in gas turbines sorry, rockets and it is a fairly common phenomenon in liquid propellant rockets. So, that is why I mentioned in the previous case also that the injectors should be such that they are kind of isolated from this oscillations, which will be possible if you provide high enough pressure drop. So, that the pressure does not get effected. So, this is one of the major problems with liquid propellants.

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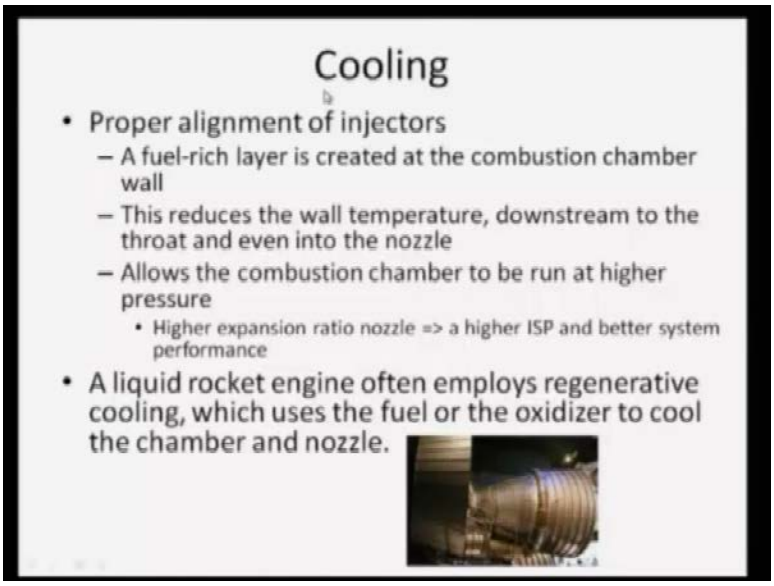

Now, next let us look at the another issue associated with liquid combustion is the cooling. Proper alignment of injector is required to provide proper cooling, a fuel reach layer is created in the combustion chamber wall; otherwise the combustion chamber gets heated up. So, fuel reach layer is created in the combustion chamber wall this reduces the wall temperature downstream to the throat and even into the nozzle, because of that it allows the combustion chamber to run at higher pressure.

And because of that higher expansion ratio nozzles can be fitted, which will give us higher specific impulse and better system performance. So, if you can get proper cooling of the combustion chamber wall, we can get higher specific impulse, and better efficiency of the system. Liquid rockets apart from this cooling also often employs regenerative cooling, which uses the fuel, and oxidizer to cool the chamber, and the nozzle like in the expander cycle we mentioned that goes all along the liquid flow channels are made all along the chamber. So, that continuously keep on cooling maintaining the temperature to a lower value, so that you can operate at higher pressure. So, cooling is the major requirement for this entire system, but again this cooling or heat transfer has to be done in a proper way, because your fuel is supplying passing through this and many times we have hydro carbon based fuels.

So, if the heating rate is very high, it will form ((Refer Time: 38:21)) coking it will coke, and then that will block the passages, and that can be disasters if the passages are blocked you do not get enough fuel and rockets will fail. So, therefore, it has to be done in a proper way this is a again one of the major engineering problem to get proper heat transfer in cooling the chamber.

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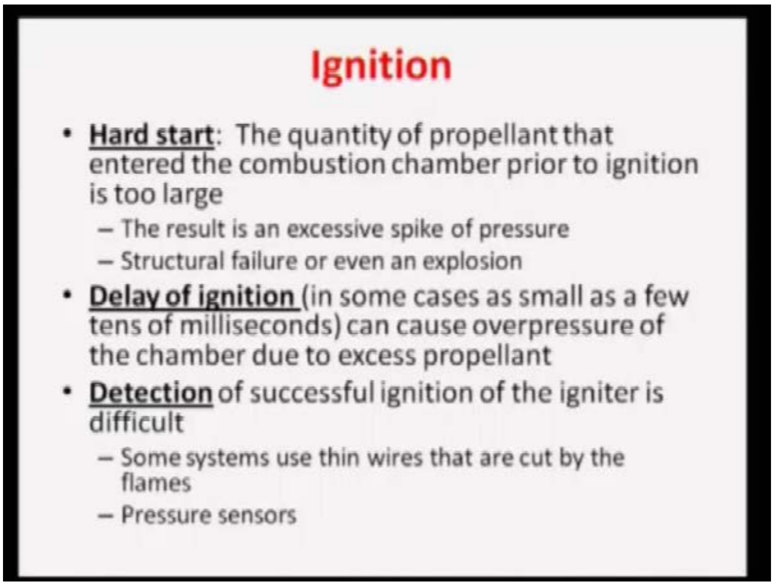

Then another issue is the ignition. Now ignition here for the liquid propellant, there are of course, the ignition system are going to be similar to that on the solid propellant which we have already discussed. The three major issues involved in the ignition part. First is the hard start, what is hard start typically when we start the process the quantity of propellant that enter the combustion chamber at prior to ignition may be very high or large; large amount of propellant come in. Now if that is the case, then we can have an excessive spike in pressure, the pressure can increase very high to a very large amount, and because of this high spike or increased pressure, it can lead to a structural failure or even an explosion. So, this is typically a problem when the start the engine, where lot of unburned propellant, and fuel and oxidizer come in.

And then once the ignition stabilizes then we get the proper flow rate, but initially still the ignition is process is started we keep on feeding and that gets accumulated and suddenly ignition starts we have a lot of propellant sitting there, lot of fuel and oxidizer. So, when the combustion occurs it may lead to a mass flow rate, which is more than the nozzle can handle, nozzle throat can handle. And so if the nozzle throat cannot handle the entire mass flow rate, the chamber pressure is going to be higher. So, chamber pressure increases beyond our design limit, it may lead to structural failure. So, this is one of the major problem that how much time it takes to ignite the process. So, that we do not get into this problem, we have to have the ignition as soon as possible. So, that even before the pressure goes to this high value, the ignition is started and then it is burning and flowing with the required flow rate.

So, that brings us to the next point, so delay in ignition. In some cases as small as a few tens of milliseconds is required or even the small delay can cause over pressure of the chamber due to excess propellant. So, therefore this ignition timing is very critical, if the ignition is not timed properly we can have catastrophic failure in rocket. So, that is why in the starting that combustion process, once you have the say countdown is complete, you have to keep your fingers crossed till you have proper ignition, because that is where most catastrophic accidents can happen on the launch pad itself. If we have this hard start problem, another problem associated with this is that see what happens is that you keep on throttling till you have the ignition.

But how do you know this is successful ignition, when to stop you do not know right. So, detection of the successful ignition of the igniter is very difficult, some systems use thin wires that are cut by the flames when you have the flames; these wires are cut. So, we know there is ignition and then we give the throttling and the system works on its own or we use special sensors to see that the chamber pressure is rising. So, that can be used as detection, but it is very difficult to detect also. So, therefore, these are the problems associated with ignition in liquid propellant rocket, it needs to addressed what are the different methods of ignition.

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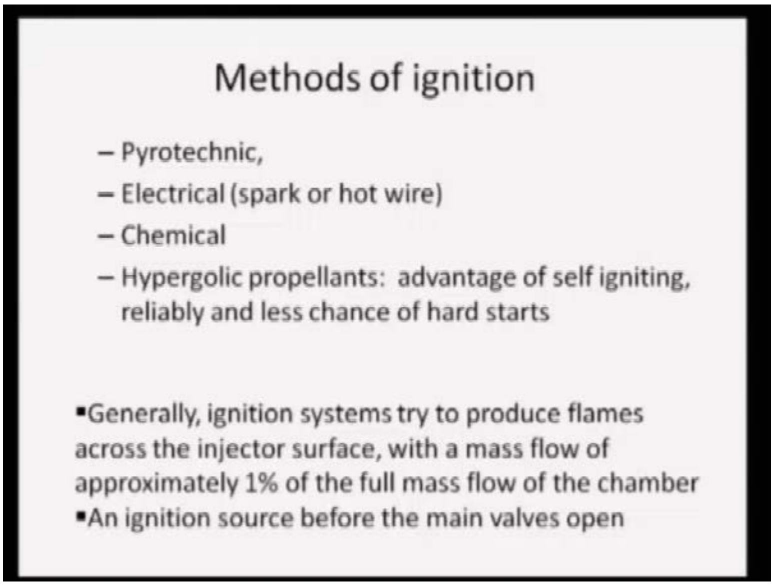

We have discussed in solid propellants, similar methods are used pyrotechnic or we have electrical ignition like spark or hot wire, we can have chemical ignition or a pilot flame, we can use hypergolic propellants which has an advantage of self igniting, reliable, and less chance of hard start, because it is hypergolic propellant. Generally ignition systems try to produce flames across the injector surface with a mass flow rate of approximately one percent of the full mass flow of the chamber an ignitions this then provides an ignition source before the main valves open. So, it is like a pilot flame. So, we have a pilot flame in the system before the main valves open, hoping that as soon as the fuel and oxidizer come in, because of the presence of this flame that will catch fire and the combustion will proceed without any problem. So, we have enough energy density sitting inside the rocket from the from this pilot flame. Now, let us look at some practical issues associated with liquid combustion sorry, liquid propellant rockets.

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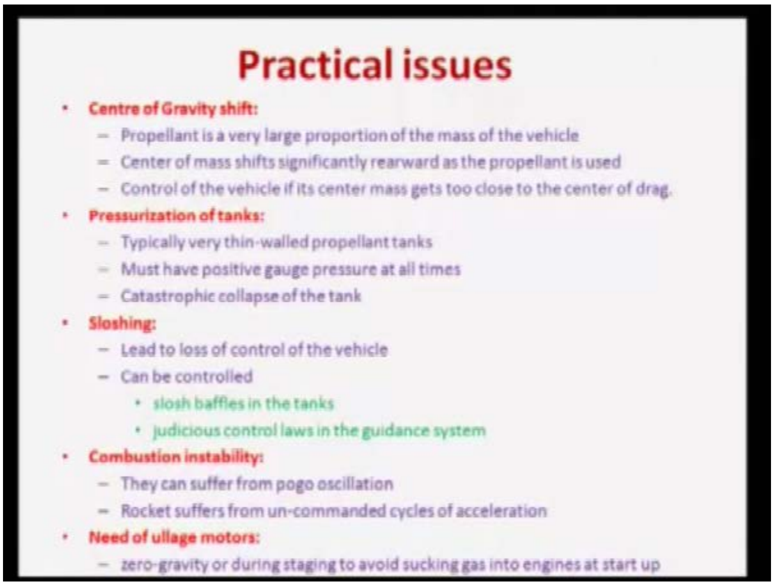

First of all the shift in center of gravity, here the propellant is carried in large tanks and propellant is a very large portion of the mass of the vehicle. Now as a propellant get used up the center of mass shift significantly rearward as the propellant is gets used up. And it is because difficult then to control the vehicle if the center of mass goes very close to the center of drag. So, this is one issue, that as a how long we are use we are going to use it.

So, the timing of a liquid propellant rocket is set by this beyond that the control becomes difficult, so we do not want to use it for more than that time. Then pressurization of tank itself is a problem typically a very thin walled propellant tanks are used, and must have positive gauge pressure in all times otherwise they are going to collapse, right. So, if the propellant tank is at a pressure less than the atmospheric pressure is going to collapse, and this collapsing tanks then can have severe implications. Then sloshing the propellant that is stored in the tanks as they move it may slosh, and because of that sloshing the fuel head is changing, pressure difference or head is changing that may have a negative impact, it can loss lead to loss of control of the vehicle. This can be controlled however we can have slosh, slosh vessels in the tank or judicious control law in the guidance system can be provide to prevent the sloshing. Then as I mentioned previously we have combustion instability, they can suffer from pogo oscillation, rocket suffers from uncommand un commanded cycles of acceleration, because of the combustion instability, because as the instability sets in the thrust then ((Refer Time: 44:35)), and that will lead to ah periodic acceleration field or acceleration change, which is something that is not? I would say advisable for rocket operation. And in the particularly in the case of ullage motors zero gravity or during stages, it have to avoid sucking of gas into the engine during start up. So, this is something very important that the gasses should not be sucked into the engine, because then you create an environment, which is different from what you design for, because your propellant has to come from your system suddenly you have additional gasses sitting there which will not burn right. It has to be pushed out then that will delay the ignition process.

So, therefore this problem that sucking of burned gasses into the engine itself should be avoided as much as possible. Then vortexing within the tank particularly towards the end of the burn vortices are formed in the tank, and that can result in gas being sucked in the engine or pump, and that will stop the operation; the gas being sucked will stop the operation of the engine.

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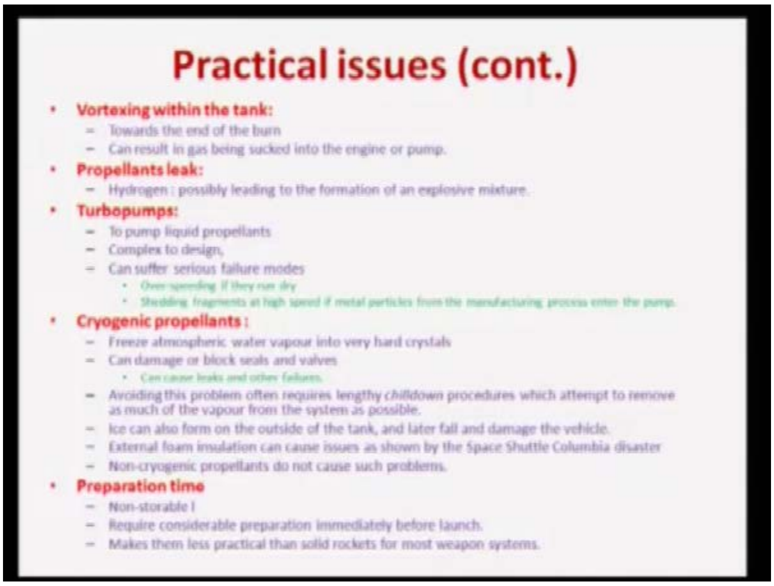

Then the propellant leak particularly if I use a hydrogen as a propellant is can lead to possible formation of a explosive mixture which is very dangerous, then the turbo pumps which we are using they are used to pump the liquid propellant, they are very fairly complex in design and can suffer from serious failure modes. Particularly if you are going for if you run dry, it may go to over speeding and that may completely destroy the blades or shading fragments at high speed if metal particles from the manufacturing process enter the pump. We have some bolt or something left, somewhere or small pieces if it goes into the pump it will shed all the blades. So, therefore, that is a very dangerous mode of failure. So, therefore, this turbo pump itself is a very significant issue and particularly these pumps have to come into full life within a very short time, because the rockets the maximum operation time is about 40 seconds, ignition should start in few micro seconds. So, in this sorry few milli seconds, in that time it has to go from zero flow to full flow right. So, the pump have to be have very fast response.

And that is what makes it more complex special materials are required, because the loads are more then when we are dealing with cryogenic propellants; propellants are, but the atmospheric water vapor may freeze into very hard crystals. And this water vapor may damage or or block seals and valves, because water vapors are present which may create problems. And to avoid this problem one often requires lengthy chilled down periods, where we once we drain the system we have to give a chilled down for a long period. So, that all these water vapors and all are removed. And then ice can also form on outside of the tank which may fall and damage the vehicle, then the external foam insulation can cause problem as happened in the space shuttle Columbia then non cryogenic propellant do not cause such problems, but cryogenic propellant propellants may be safe, but the water vapor around it will freeze on them and create problems for you. So, therefore, those needs to be taken care of.

The biggest problem with the liquid propellants is the preparation time, most of them are non storable particularly cryogenic propellants are not storable at all. So, they cannot be stored for long duration and they require considerable preparation immediately before the launch. So, therefore they cannot be kept ready you have to prepare it for launch, and that makes them less practical than solid rockets for most weapon systems, but they are good as say rocket or space vehicles, because once you prepare you can fire. And then it goes out, but if mission is aborted then you have to go through this process to make it safe. So, this is what? I wanted to discuss on the liquid propellant rockets. So, we will that brings us to an end of our discussion in chemical rockets. So, in the next class we will talk about the electric propulsion systems.

Thank you.