Introduction to Airbreathing Propulsion

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Lecture – 38
Stationary Components: Nozzles, Industrial Gas Turbines

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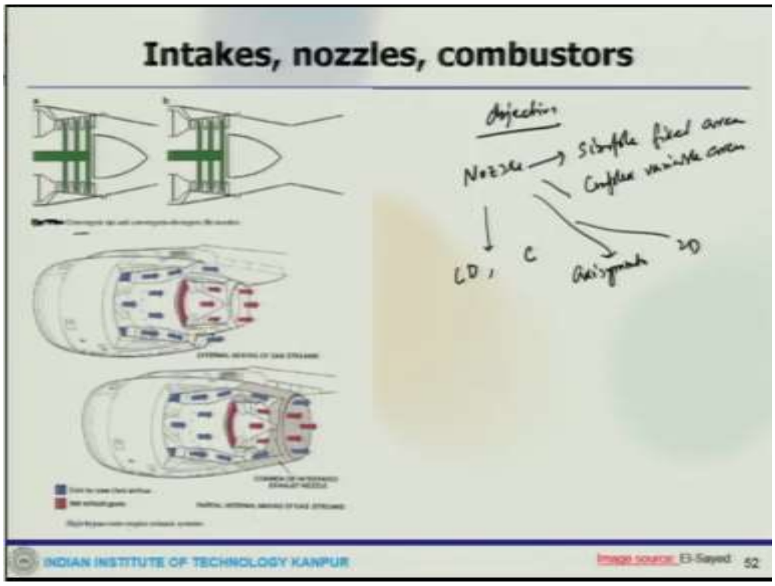

Okay, so we have looked at intake, we have looked at combustor, now we are going to look at the nozzle, so the nozzle is the another component which is going to basically, this is the third stationary module which to be examined because this actually produces the final and the nozzle could be different type like here you can see this is an convergent type of nozzle kind of convergent divergent nozzle, then this is an high bypass ratio nozzle which is there.

So, the main function of the nozzle is that they provide required throat area, so that is the objective, so provide required throat area to match the mass flow and exit conditions, then you can have efficiency to expand the high pressure provide require thrust in each flight phase with minimum installed drag provide the reverse thrust when needed, minimize noise, minimize infrared radiation, then provide the vector force for vertical take-off landing.

Now, the nozzle can be kind of classified in 2 things; simple area nozzle, simple area, simple fixed area like or it could be complex variable area or second classification could be convergent divergent type or convergent type only or also from geometry wise, it can be axisymmetric or 2D, so there are different kind of nozzle.

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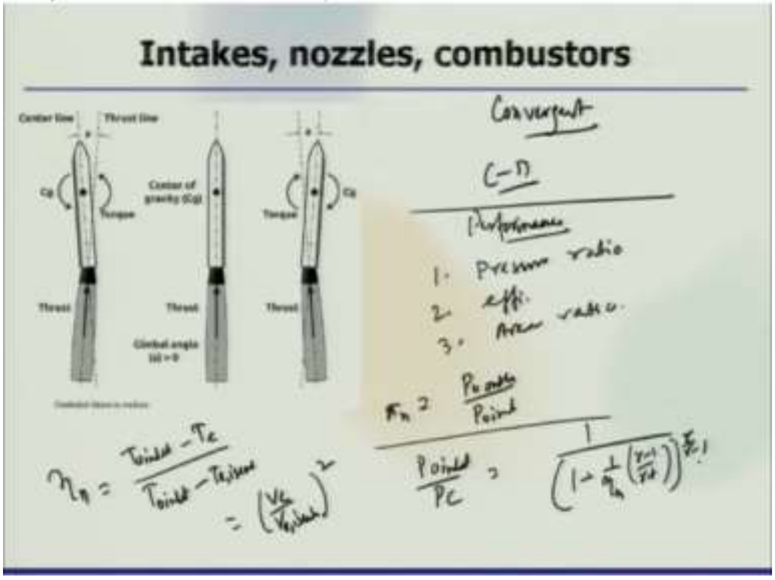

Now the rocket has also alternative options to use nozzles like they have used different kind of their possible nozzles which are used in rocket, the middle rocket shows a normal flight configurations, if the nozzle is deflected to the left then the thrust vector generates a torque about the centre and so on. So, now you have operation of nozzles let us say we start with the convergent type that is one category or we could have convergent divergent type nozzle.

Now, so these are 2 different kind of nozzle, when you look at the performance parameter of the nozzle, so one is the pressure ratio that is their efficiency, third area ratio, now pressure ratio for the nozzle one can find out that

$$\pi_n = \frac{p_{0,outlet}}{p_{0,inlet}}$$

and the nozzle efficiency one can write

$$\eta_n = \frac{T_{0,inlet} - T_e}{T_{0,inlet} - T_{0,isentropic}} = \left(\frac{V_e}{V_{e,isentropic}}\right)^2$$

If the nozzle is choked, the choked nozzle is take by calculating the pressure ratio, critical pressure ratio

$$critical\ pressure\ ratio = \frac{p_{0,inlet}}{p_c} = \frac{1}{\left(1 - \frac{1}{\eta_n}\left(\frac{\gamma - 1}{\gamma + 1}\right)\right)^{\frac{\gamma}{\gamma - 1}}}$$

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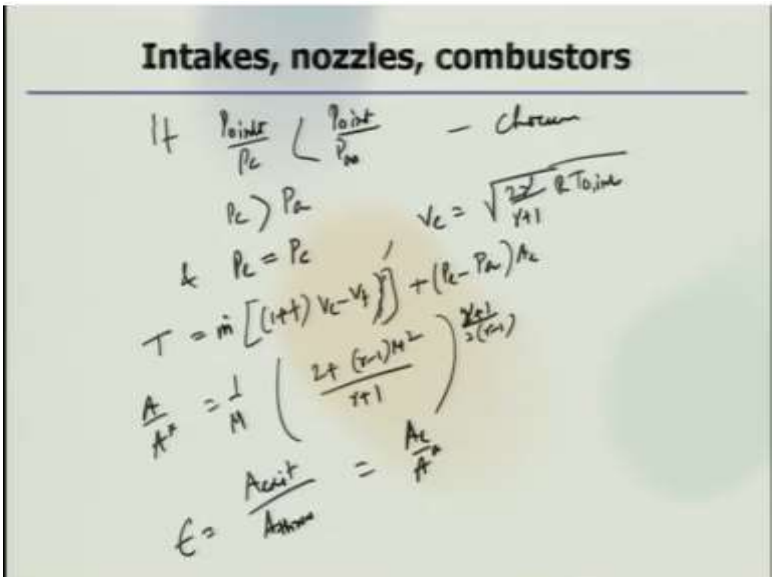

So, if

$$\frac{p_{0,inlet}}{p_c} < \frac{p_{0,inlet}}{p_{ambient}}$$

so this is choked, so

$$p_c > p_a$$

and

$$p_e = p_c$$

so and

$$V_e = \sqrt{\frac{2\gamma}{\gamma + 1} R T_{0,inlet}}$$

or thrust equation would be

$$T = \dot{m}\left[(1 + f)V_e - V_f\right] + (p_c - p_a)A_e$$

for isentropic relation and conservation of the mass in the both exit and interior section, one can write

$$\frac{A}{A^*} = \frac{1}{M}\left(\frac{2 + (\gamma - 1)M^2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

And expansion area ratio for nozzle design which is

$$\epsilon = \frac{A_{exit}}{A_{throat}} = \frac{A_e}{A^*}$$

so area ratio of convergent nozzle is unity while the convergent divergent nozzle is greater than unity for aircraft but for rocket and space vehicle, it could be as large as possible maybe 50 or more than that. So, the exhaust speed is obtained by nozzle area changing and this expansion through the nozzle.

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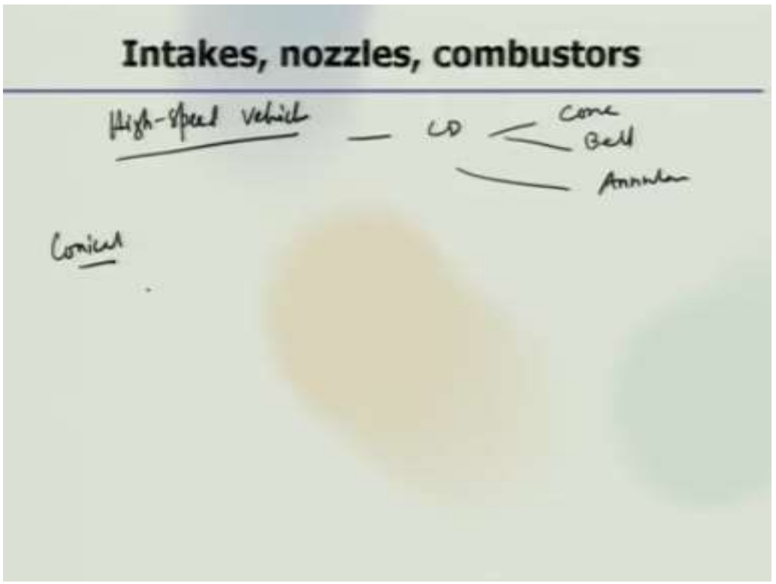

So, now the another one which is there is the high speed vehicle, so high speed vehicle like you have supersonic and hypersonic vehicle which uses CD type of nozzle and these also have different type, one could be cone type, one could be bell type, one could be annular type.

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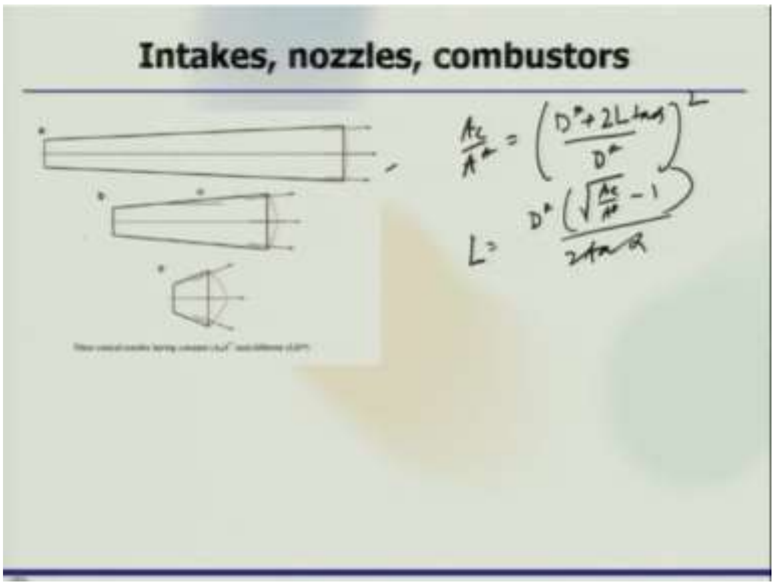

So, these are, now if you have conical nozzle, conical one, then the conical nozzle, you can see the structure of different conical nozzles here, so one can estimate the area ratio is

$$\frac{A_e}{A^*} = \left(\frac{D^* + 2Ltan\alpha}{D^*}\right)^2$$

and the L is expressed as

$$L = \frac{D^*\left(\sqrt{\frac{A_e}{A^*}} - 1\right)}{2tan\alpha}$$

So, length of the nozzle can be evaluated, throat diameter is D^* which is fixed by the combustion chamber condition and desired thrust.

So, here you can see that the longest nozzle is here which has nearly uniform axial outlet speed, second one has axial flow nozzle outlet, third one is the shortest nozzle whether the flow has a reasonable radial velocity.

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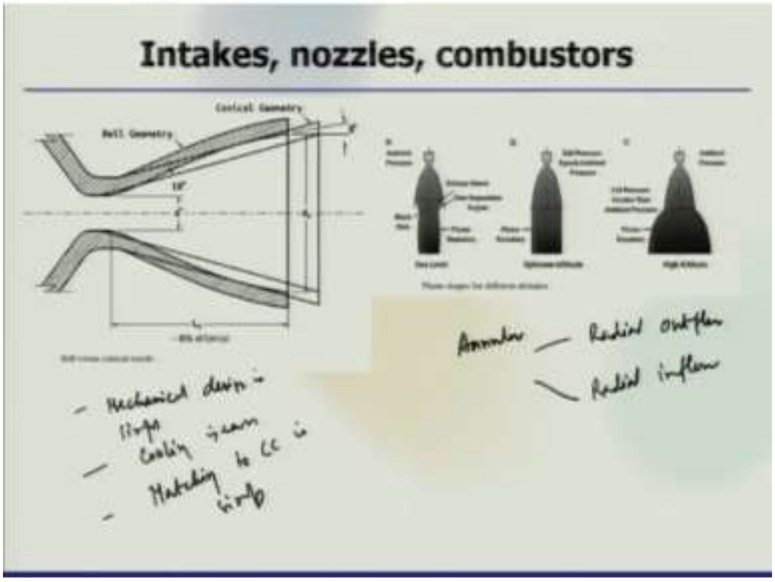

Now, the other type would be bell type and that you can see this is the bell type nozzle, so mostly using commonly used in nozzle shape, it offers significant advantage over conical nozzle, length is 10 to 25 percent shorter than conical nozzle, so it depends the performance depends of this nozzle on the flight altitude at optimum altitude, the gases are expanded ideally, and exhaust plume is a column shaped and so it depends on the pressure ratio that it operates.

And so there are advantages, mechanical design is simple, so mechanical design is simple, cooling is easy as it is fabricated with walls of simple tubular construction, third; matching to combustion chamber is also simple, combustion chamber is simple, so these are some of the advantage but obviously, there are some disadvantage which are associated with this bell shaped nozzle that is like kind of over expansion case leads to both thrust loss and flow instability and as well as uncertainty and unsteadiness.

Generally, US nozzle design tend to have bell shapes and usually designed by method of characteristics, now another could be annular type and then annular nozzles also could have like there could be radial outflow nozzle or radial inflow nozzle.

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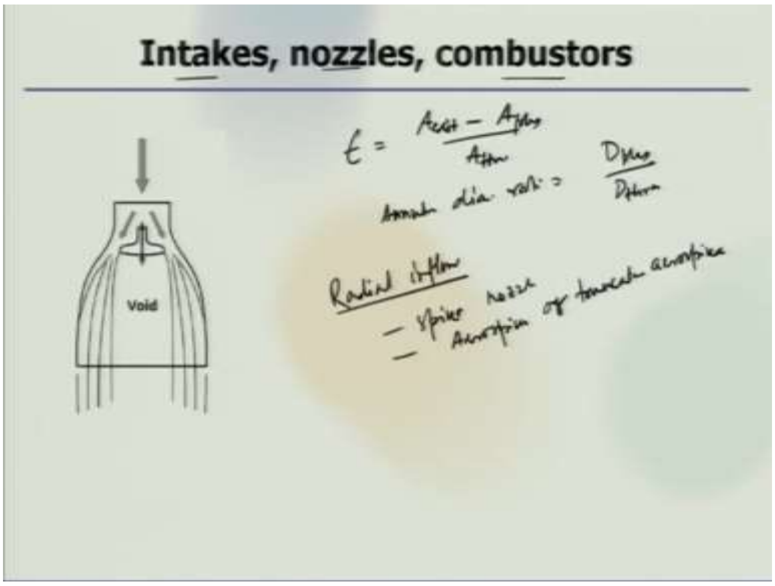

Now, radial inflow, outflow nozzle is; so this is what the radial outflow kind of nozzle, here the expansion ratio could be

$$\epsilon = \frac{A_{exit} - A_{plug}}{A_{throat}}$$

and annular dia ratio is

$$= \frac{D_{plug}}{D_{throat}}$$

these ratios used to measure the nozzle geometry for comparing with other plug nozzle or if it is radial inflow type, then there could be spike nozzles, aerospike or truncated aerospike like this.

So, these are the other category of nozzle, so the spike nozzle is named for prominent spikes inter body, it may be thought of as an burn bell inside out or aerospike or truncated aerospike which is generated by the moving pointed spike altogether replaced with a flat base, so these are the different kind of nozzle that we have and actually that is pretty much talks about the that the stationary component that we wanted to talk that is one is the intake nozzle and combustor.

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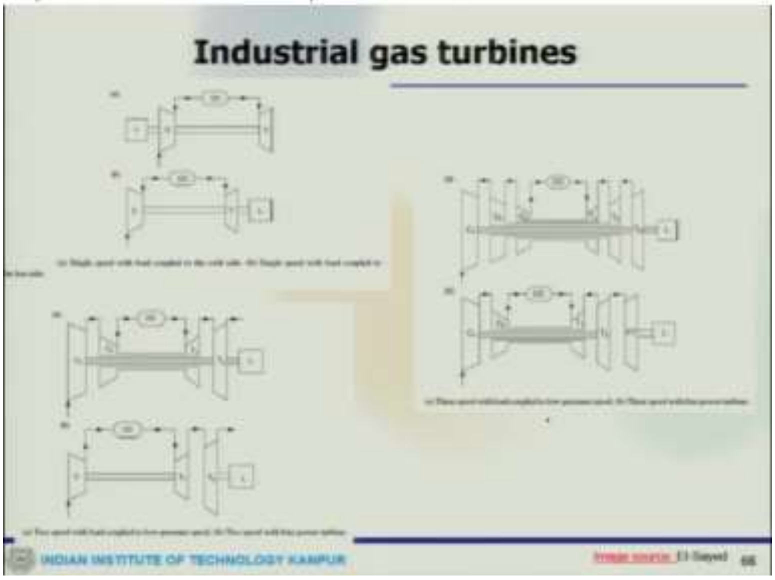

So, now before moving to the rotating component like turbo machine component like compressor and all these, so we can just quickly discuss some of these industrial gas turbine like that is some just quickly glance through some of the issues that industrial gas turbine has some major advantage. So, one of the biggest advantage for industrial gas turbine is that its compactness, so one is that compactness.

Then, low vibration, reliable, then low cost per kg at larger size, low emission that is very, very important, then change over to fuel or fuel flexibility, change over from one fuel to another, transportation so and one side maintenance, so these are very, very important features or advantage but obviously, like some special applications like when you have units which using generating electricity, have the ability to produce full power.

Then, we can have gas turbines may be installed on mobile trailer or something, engines used in naval application are of compact size and a high power density, less noise electrical power, obviously the disadvantage are be there; lower thermal efficiency, relatively poor performance, now there could be different kind of gas turbines as you can see there are heavy duty gas turbine, there are aircraft derivative gas turbines or aero derivatives like as the name indicates the power generation units are originally aircraft engines which were later adopted in electrical generation also.

Then there are industrial type gas turbines, these are vary in range from 2.5 to 15 megawatt, these are extensively in for petrochemical plants for compressor, trans effectiveness are very less, small gas turbines which are of the power output of 0.5 to 2.5 megawatt micro turbines, these are used in a range has a dramatic growth since the late 1990s. So, now the industrial gas turbine also has different type like single shaft or multi shaft, like this is a single spool with load coupled with the pole side and load coupled with the other side.

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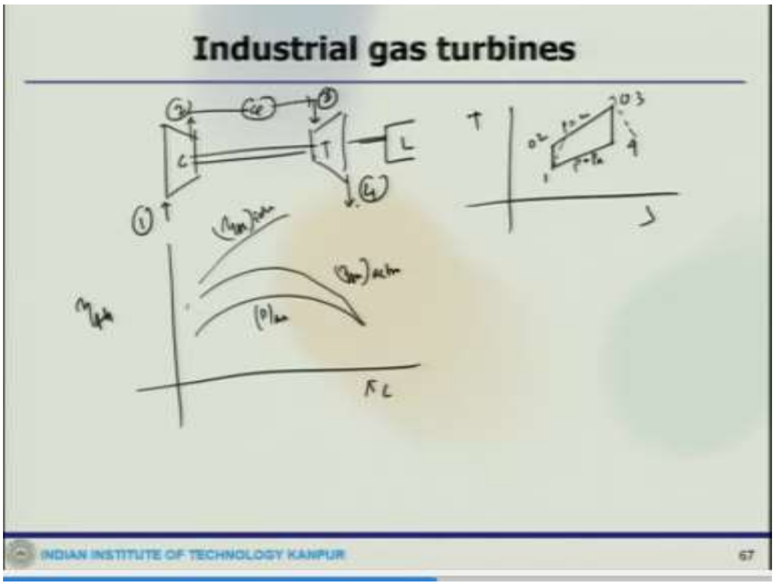

Then, this is 2 spool where you can see this is coupled and then this is 3 spool configuration, now single shaft unit one can think about like, this is the compressor, then this is connected with turbine, then here is the combustion chamber, so like and this is the load. So, something comes in here, 2, 3, 4, so typical single spool 1 and if you draw the TS diagram, so this is ideal cycle; 1, 02, 03, 4, here P constant, here also P equals to Pa, so this is an ideal situation.

So, another could be single compressor and turbine unit where you can have the, this is what you call the single shaft single compressor and turbine unit and then here you can do the simple thermodynamic analysis but that we are not going into the details because we have been talking about these things, so details with all this like gas turbine respect to gas turbine engine, so there is no point going into that.

And obviously this is an ideal cycle but when there would be actual cycle, there would be deviation like this, then there could be special laws, so this could come here and this deviation would occur because of the irreversibilities and that one has to take into account and obviously, if you look at the thermal efficiency with the compressor ratio, this is actually this guy could be eta thermal actual, this is power actual and this is how the eta thermal ideal.

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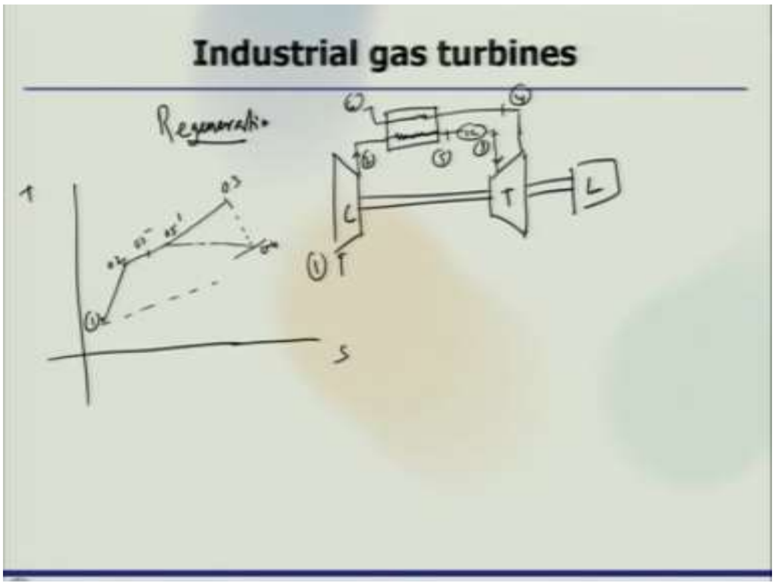

So, now the other interesting thing is that which is important in these applications of industrial gas turbine is the regeneration, so the temperature of the exhaust gas leaving the last turbine is often considerably higher than the temperature of the air leaving the compressor, so the high temperature here leaving the compressor can be heated by transferring heat something from there.

It is just like if you see this is a compressor unit connected with a turbine unit, now this is what the load is, then when it goes there it passed through like, so this comes here combustion chamber and then comes here and this guy goes back and comes here, it goes out, so something comes at 1, this is 2, this is 5, this is 3, 4, this is 6. So, if you put in the TS diagram 1 goes to 2, 5, 05, 03, this is 1, this is what, 04 and this is 05 prime, so that is the single spool configuration.

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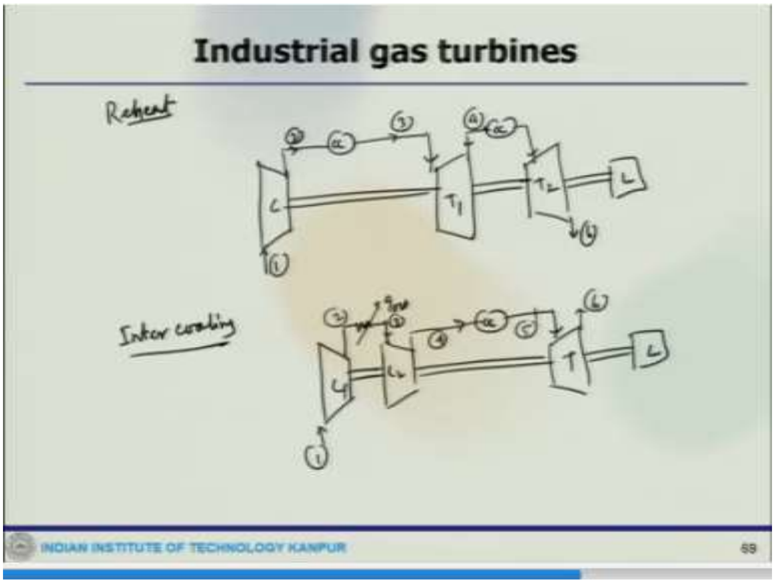

Again, this is one turbine one compressor unit, so you regenerate the things, so if it is a now this is one way that you can use the exhaust gas, then another option is that you can do some sort of an do that thing is that this is called regeneration, you could do reheating also like in that case, the compressor and the first combustion chamber where you can see this is the compressor connected with turbine, this is again single spool connected with, second turbine connected with load.

So, this combustion chamber which is comes here, comes down, so you can think about these things so far we have done so much of discussion on gas turbine, this is nothing but talking about some sort of an, see after in between 2 turbine there is one another heat addition but this is some similarity you can find which you call it like using an afterburner in the military applications.

So, similarly one can have intercooling capability, so the inter cooling capability is that you may add some intercooler, now in a single shaft gas turbine is now composed of 2 compressor, so and then you can find out the essentially some intercooler in between let us say there is a one compressor here, then you connect there another compressor, let us say C1, C2, in between that you add some intercooler, so here the q out goes out.

And then it connects with the turbine where it goes out, combustion chamber comes here connected to the load, so this is 1, 2, 3, 4, 5, 6, so that is how you get an inter cooling capability, so you can keep an intercooler there.

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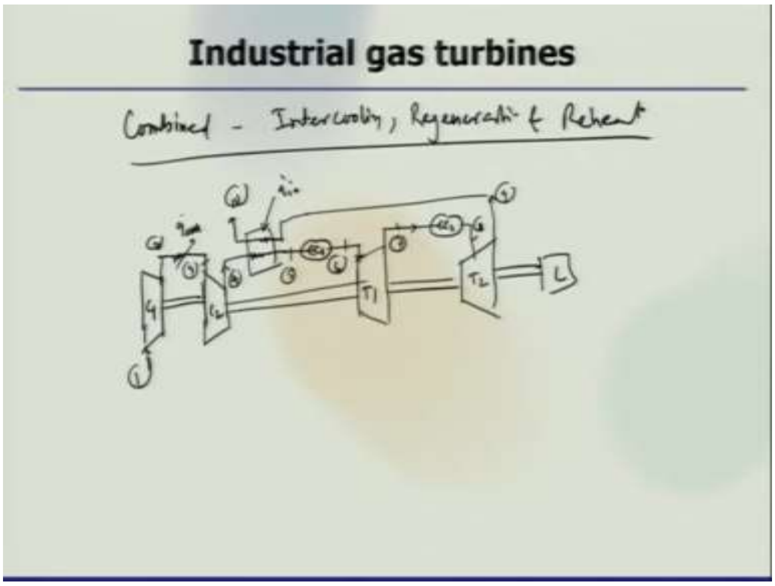

Now, or one can have in sort of a combined inter; you can have an unit with combined intercooling regeneration and reheat. So, how does it look like; you have a compressor C1 connected with compressor C2, in between there would be intercooler, so this is q out, now C2 connected with turbine T1, now this guy comes out goes to CC1 comes here and then this guy goes out, CC2 comes to second turbine which is connected to load.

And this one goes out and have intercooling, intercooler here, so this is q dot in, so you can just mark the, this is 2, this is 3, this is 4, this could be 5, 6, this could be 7, 8, 9 and this could be 10, so you can have this kind of configuration also whether you have intercooler regenerative and these are used in different kind of applications. Now, similarly you can have double shaft engine also where you can have a free turbine which is like and similar to what we have seen.

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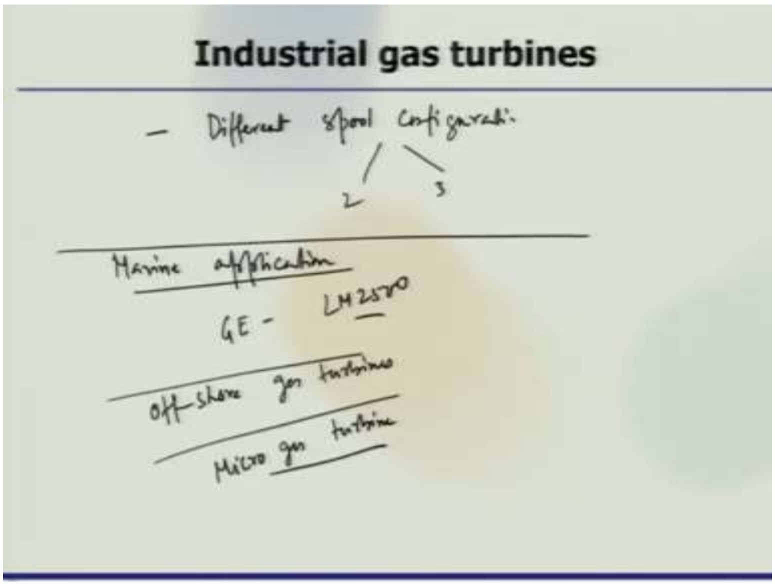

Then we can have a different spools configuration like, so different spool configuration like 2 spool, 3 spool, so that is another that you can have, so that is but these things are all which are you can see these are all, I am just giving trying to give you an idea about and we are not going into the all the detail analysis of different spool configuration or multiple shaft because we have done enough detail analysis in the context of turbine based cycles where we have considered all these different possibilities and all these.

Now, other important thing is that there could be marine application, so this is now; so marine application like the most of the engine used for marine propulsion use an adaptation of a machine that was originally developed for other purposes, so like aero derivative gas turbine is a prominent example where aircraft derivative gas turbine engines are used for both main propulsion and ship service electric power.

So, wide range of brush seals is powered by marine gas turbine engines ranging from modest sized requiring several 100 to now; advantage of that gas turbine plant as compared to steam plant would be there. Now, when you talk about the marine applications, there would be some other things like some of this engines example like General electric LM 2500 which is used for, it has natural gas power fuel.

So, it also has compressor, combustor, HPT, then you can have offshore gas turbines, so this offshore gas turbines are widely used for used offshore for a variety of purposes including power generation, gas and water injection, pumping, gas lift, water flooding, export compression, so these are adapted in place of diesel generation system on significant number but they are also lightweight and compact in size.

So, typically if you look at the gas turbine and diesel engine used in marine application, their power range varies from 5 to 40 and then that is the where it, then one can have also micro gas turbine, you can now connect these things the discussion we had in the context of turbojet, so these are small gas turbines.

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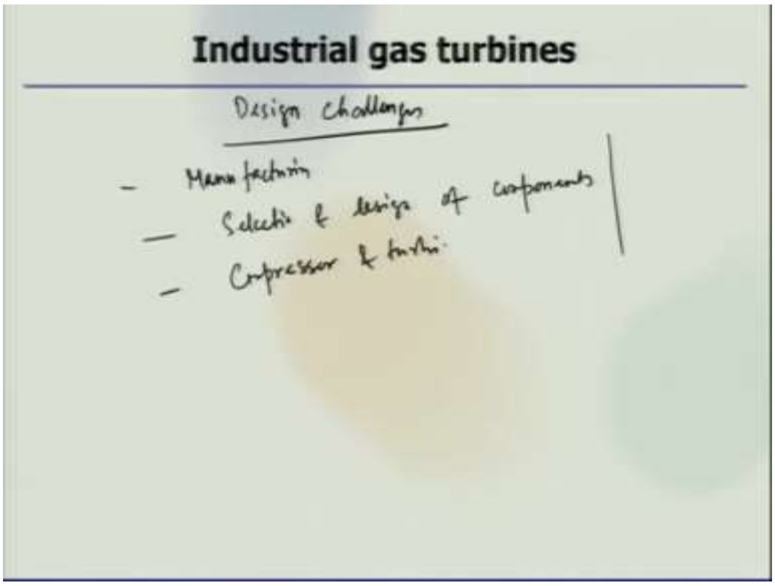

And but there are obviously, when you talk about all these gas turbine, there are different design challenges which are associated obviously, important one is the manufacturing, then selection and design of components. So, then compressor and turbine, so these are different things that you have and there are different challenges, obviously these are only few to be listed, it is not all but it just give you an idea what are the requirement for industrial gas turbine and all these things.

So, having said that I mean, if you look at the situation of the discussion, so we started with all basic fluid dynamics and thermodynamics and then compressible flow and from there, we moved to the performance parameters, efficiencies and all these calculations and after doing that we have done the detailed discussion on the cycle analysis and performance analysis of both RAM based cycle and turbine based cycle and then the hybrid cycle also.

And once we did that then we looked at some of the stationary components like intake, compressor and nozzles because these are stationary, they are not moveable and then just touched upon some of the issues related to industrial gas turbine. Now, our focus would be shifted to more into the turbo machinery part or we will start our discussion on turbo machinery part which are the rotating components or rather non-stationary component.

So, started with simple aero thermodynamic analysis moving to the stationary parts and their component wise discussion, now we are going to the; now the rotating part and their detail discussion where we will be talking about axial flow compressor, radial compressor, axial and radial turbine and so on and that would pretty much complete the all theoretical discussion related to this particular course. So, we will start our turbo machinery in the next class.