Aircraft Propulsion
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Lecture – 24
Thrust Augmentation and Engine Performance

Welcome to the class, today we are going to see about thrust augmentation and engine performance, here our topic of discussion is mainly focused upon there is a need of increment in thrust, so what are the ways by which we can increase the thrust of an engine and further, how the performance of an engine changes with different altitude or what are the governing parameters of engines performance.

So, these are the topics of discussion for this class, so first is thrust augmentation and then ways to increase the thrust. So, what are the ways by which we can increase the thrust of an engine?

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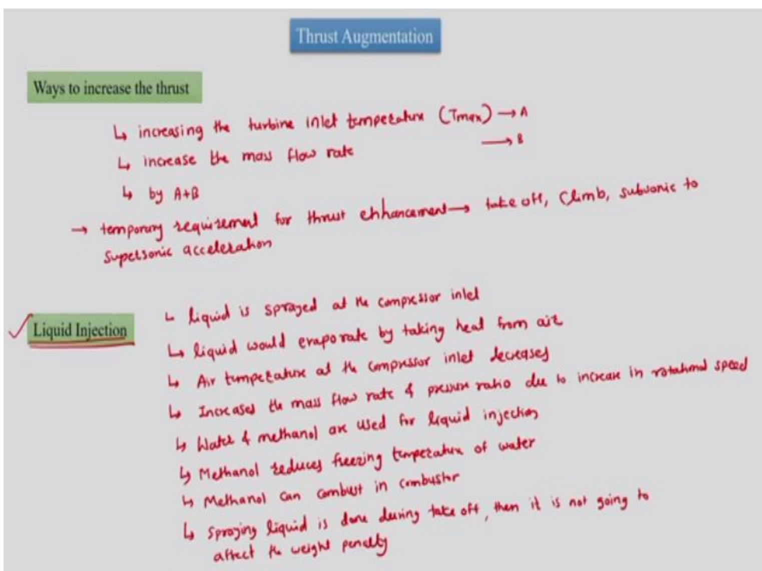

We can increase the thrust of an engine by increasing the turbine inlet temperature, we also call it as T max, if you can increase the T max, then we can increase the thrust, we can also increase the thrust, if we can increase the mass flow rate, so or third option is to increase the thrust by both methods, so this is A, this is B, so by A + B, so we can implement both methods and increase the thrust of an engine.

But these 2 methods need the alteration in the engine, so but there is some immediate requirement or temporary requirement for thrust enhancement; situations are like take off, climb, subsonic to supersonic expansion; supersonic acceleration, so these are the some special requirements in which we need the incremental thrust and as we said, we can increase the temperature at the inlet to the turbine or we can increase the mass flow rate.

But these are constitutional changes which we have to make in the engine design, so in such situations how to increase the thrust; so one way is liquid injection. In this method, liquid is sprayed at the compressor inlet, here liquid will be sprayed at the compressor inlet, mostly water or sometimes water plus methanol will be injected. This liquid injection technique is thrust augmentation technique which we are discussing for improvement of the thrust.

So, what will happen, once we inject the liquid, this liquid would evaporate by taking heat from air, thus air temperature at the compressor inlet decreases, this decrement in air temperature increases the mass flow rate and pressure ratio due to increase in rotational speed, here we practically mean that due to decrement in the temperature at the intake of the compressor, mass flow rate increases and then this ultimately, leads to increment in thrust.

Water and methanol are used for liquid injection, use of methanol basically, helps to reduce; methanol reduces freezing temperature of water, further methanol can combust in combustor and then it can also act as fuel, so these things help in improving the thrust, there is one more thing to be noted that if we exhaust or if we complete the liquid injection, so if spraying liquid is done during take-off or ascent, then it is not going to affect the weight penalty.

It means that we would have to carry liquid for its spraying and if we would have exhausted the liquid during the take-off, then the penalty of carrying the liquid will not be there and further we would have increased the mass flow rate and hence the thrust in the liquid injection method, so this is one of the thrust augmentation techniques. Next thrust augmentation technique is after burning and for that we have to first understand, how is the nozzle.

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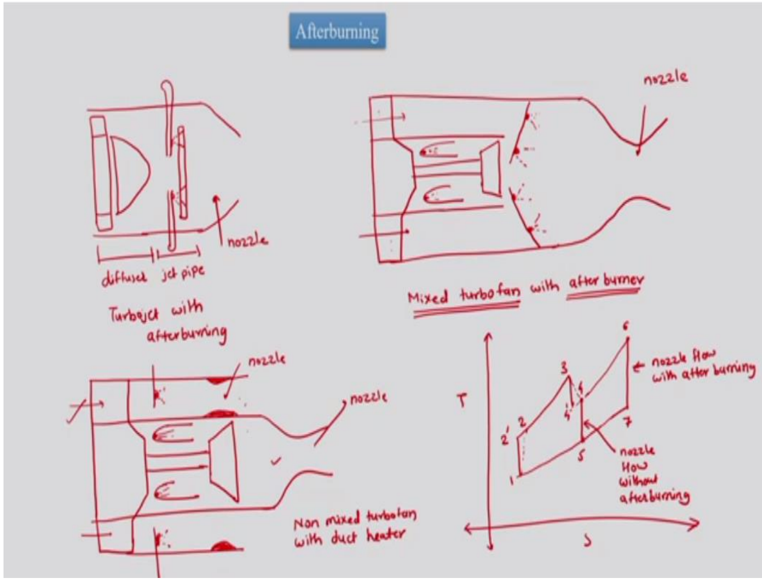

So, nozzle as we said is also called as propelling nozzle, since the nozzle components also exist in turbine, so as to have different title, it is also called as propelling nozzle, so we are trying to draw a propelling nozzle and this is a typical propelling nozzle. In this propelling nozzle, this is a diffuser, this is called a jet pipe, and this is nozzle, so in general this diffuser is added, so that the annular part afterburning would have connectivity circular duct, this also reduces the pressure loss which is going to happen in this process by reducing the velocity.

In this after burning case, we would have to implement and after burner or fuel injector which would inject the fuel in the jet pipe, so there will be fuel injection in the jet pipe and this fuel is going to interact with the hot gases which are coming out of the turbine exhaust and it would burn with those gases and generate the additional kinetic energy and that additional kinetic energy would helpful; would be helpful in heating the more thrust.

So, this is the idea of having after burning; after burning is similar to reheating but in case of reheating, once reheated, the gas will further expand it into the next turbine but here we are going to expand it into the nozzle. Thermodynamically, this addition of heat would again be treated as concentration, heat addition where we are adding the heat in a duct, so if we try to see how would be the case for the turbo jet engine, then this case whatever we refer here as a diagram drawn for after burner is for a turbo jet with after burner or with after burning.

Now, let us plot turbofan and in case of after burning, so let us draw the diagram, so we are trying to draw a turbo fan engine where the front portion is fan, this is compressor and then we have compressor connected with a turbine and in between we have combustion chamber in the schematic, so which will inject the fuel and provide the necessary combustion, so this is the fan which will pass the air.

And then here, in case of turbofan we are trying to plot mixed turbofan with after burner, we know that in case of mixed kind of turbofan, there will be hot and cold gases which will be mixed together and those mixed gases will be further expanded in the nozzle. So, before expansion there in digit pipe, we would have injection of fuel for the cold gas and also for the hot gas, so this cold and hot gas will further be heated due to injection of fuel in the after burner.

So, this is a typical sketch for mixed turbofan with after burning, now I am trying to plot second case where we have turbofan which is unmixed on non-mixed turbofan with after burner but in that case it is not called as after burner, it is called as duct heater, if we are going to heat only the combusted or the cold gas or cold air, so here as well first we will have compressor and from the compressor air will go which would have passed from the fan, it would go into the compressor.

And then it will go into the combustion chamber, turbine and then it would be expanded in the nozzle, so this is hot gas nozzle and in this case, there will be fuel injection into the duct and this fuel injection would heat the cold air and then this cold air would then passed into the nozzle after heating using the duct heating, so this is non-mixed turbofan with duct heater, this process of duct heating is same as that of after burner where we are heating the air using the fuel injection.

Now, we will plot the thermodynamic TS diagram for this pattern cycle with the after burner, so we know it is first compression process, then we have heat addition, then we have expansion in the turbine, so it at all we have certain efficiencies of compressor and turbine, we would reach points like this and then if we are here at station 4, then expansion from station 4 to station 5 is going to give a certain thrust, if we would not have any after burning.

But in the case of after burning, we can go to high temperatures and then we have 0.6 and then we will expand from 6 to 7, so it is evident over here that the enthalpy draw from 6 to 7 is more than the enthalpy drop from 4 to 5 and hence we would have more thrust in case of after burning. So, now we are going to see here that this is nozzle flow where we do not have after burning, so this is nozzle expansion with after burning.

It should be noted here that these 2 gases in case of turbo fan engine when they are separately going to expand in 2 nozzles as these cold nozzle and as this hot nozzle, then we would have to maintain the barricade between cold and hot gas and this barricade becomes complicated since it needs to maintain the 2 temperatures separately, so there is a complex cooling mechanism which needs to be implemented.

Hence to avoid these separate cold and hot gas nozzles generally, in case of afterburners, mixed types of turbofans are used, so mixed type of turbofans would not need the separation or barricade between the cold and hot gases, they would mix with each other and then after burning would be taking place for that mixture, so turbofans when they are used with afterburner in general, they will be mixed type of turbofan.

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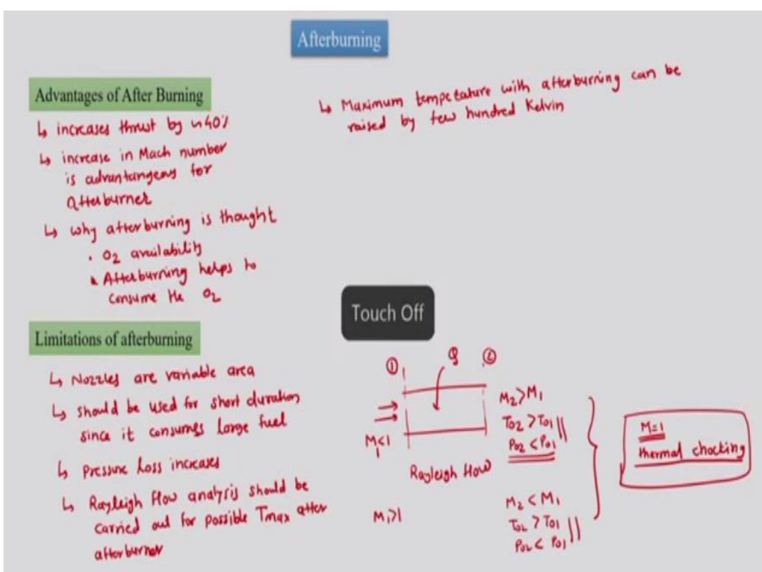

So, advantages of after burning; after burning increases thrust by around 40% however, this increment would further increase with increase in Mach number is advantageous for after burner.

Why do we go for after burning, why after burning is thought; we are need of increment in thrust but why after burning process is thought? The major reason is oxygen availability, we would have seen in the examples that air fuel ratio is very large.

So, amount of fuel is always small, when it is burnt in a combustor, so there is large amount of oxygen which is left out after the process of combustion in the combustor, so we have lot of oxygen available in the inlet of the nozzle or in the jet pipe further, in case of turbofan engine when we are having cold expansion, there is complete air available for heating, so if we put fuel in those cases and that would be more helpful to combust the complete oxygen.

So, oxygen is available and after burning, helps to consume the oxygen, further the advantage of after burning is that the maximum temperature with after burning can be raised by few hundred kelvin, here we are knowing that in case of turbo jet or turboprop engine or maybe with brayton cycle, maximum temperature has limitation due to the turbine inlet conditions, since the inlet of the turbine would be facing high temperature gas, so there is a material constraint due to which we cannot go for very high temperatures and then turbine inlet.

So, maximum temperature for brayton cycle or turbojet engine is having limitation due to rotary parts however in case of after burning, during the process of expansion in the nozzle, there is no such rotary part encountered by the gases. So, we can go to very high temperatures in the after burning process which is practically higher than the temperature at the inlet to the turbine. So, this is the advantage with the after burning process.

Now, we know that after burning increases the thrust, it is; it consumes the oxygen, it is going to increase the maximum temperature and it is more advantageous with higher Mach number, so we will see now limitations of after burning. So, first limitation is that we have to use nozzles, this is not necessarily the limitation but this is the adaptability which we have to consider with the afterburning that nozzles are variable area.

In case of turbojet engines, we would have suppose, fixed area nozzle which cannot change its geometry but having the heat added further; would further decrease the density in case of after burning, so have to to maintain the steady flow system such that same mass flow rate of air should again go out which would have lower density, so as to accommodate this, we have to increase the area of the nozzle, so for that we have to use variable area nozzles with afterburning.

Secondly, it should be used for short duration, since it consumes large fuel, so after burning consumes large amount of fuel, so specific fuel consumption actually is going to increase with increasing after burning; degree of after burning, so we have to use it for the small amount of time. Pressure loss increases basically, process of heat addition increases the pressure loss and pressure loss in general, is due to 2 reasons.

First reason is having friction and second reason is momentum change due to the heat addition process, so in the burner although both the processes are there for the pressure loss, prominent process is frictional however, in the afterburner frictional losses are less but pressure losses mainly due to the momentum change due to process of heat addition and then that is why a Rayleigh flow analysis should be carried out for possible T max after burner.

If let us consider a duct in which we are adding heat Q and let us say that this is some flow which is coming with Mach number subsonic, we are trying to understand a Rayleigh flow; Rayleigh flows are the flows with heat addition, so flows with heat addition are called as Rayleigh flow. So, now if we are adding heat into the subsonic flow then this is station 1, so it is M1, and this is station 2, so M2 would be more than some M1.

So, Mach number of the flow increases, total temperature of the fuel also increases but there is loss of total pressure, so this is what we are talking about but now if we have Mach number more than 1, then the Mach number M2 decreases with heat addition, further T02 increases invariantly and P02 decreases, rest 2 things would have similar variation but Mach number has different variation for subsonic and supersonic flows.

So, there is a limitation for heat addition or amount of heat added, since both supersonic Mach numbers or subsonic Mach numbers will try to become sonic with heat addition, so these are maximum amount of heat to be added into the gas such that it will go to the sonic condition and then this is called as thermal choking, we have understood what do we mean by choking in case of nozzle where that is the area based choking, so for a particular area variation in the nozzle, we would have maximum mass flow rate.

And there will not be change in mass flow rate with further decrement in exit pressure, so similarly, there as well we would have seen that or we had seen that the minimum cross section reaches Mach number 1, here as well the flow reaches Mach number 1 and then we for not further have heat addition into the gas, so both supersonic and subsonic Mach numbers would try to reach Mach 1 or sonic state in the process of heat addition.

And that gives us limitation on the after burning process and then this is related with the momentum loss and this momentum loss defines the amount of pressure loss in the after burning process and this we have to analyse.

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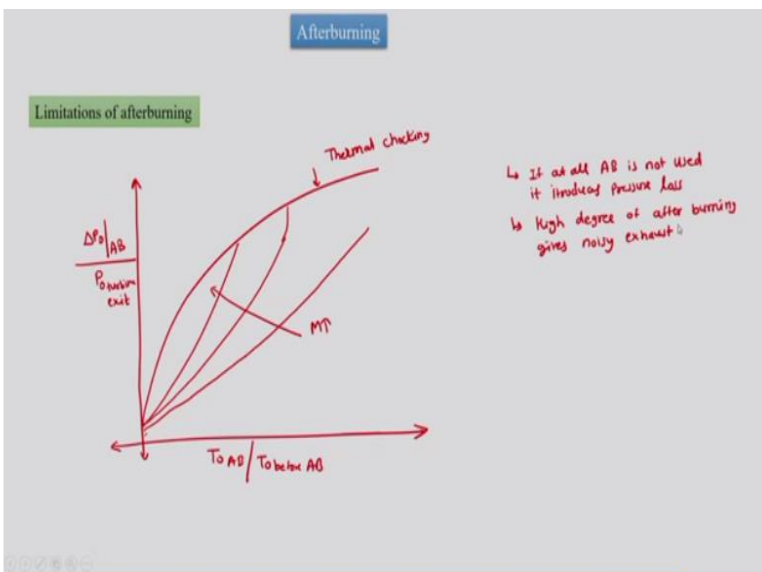

So, if we try to plot the pressure loss, delta p0 into the afterburner divided by p0 at the turbine exit on y axis and if we have T0 after the after burner divided by T0 before the afterburner, then the plot would be like this where we will have this is thermal choking limit for a one Mach number, for lower Mach number, the curve would go like this, for higher Mach number, we will attain the thermal choking early, so Mach number increases in this direction.

So, this is what the pressure loss we have to account while increasing the temperature in the after burner. There is one more limitation of the after burner that we have put the afterburner in the jet pipe, so if at all after burner is not used, it introduces loss; pressure loss further, high degree of after burning gives noisy exhaust, so this is one more problem of after burning. So, this is how we can increase the thrust of an engine by thrust augmentation techniques.

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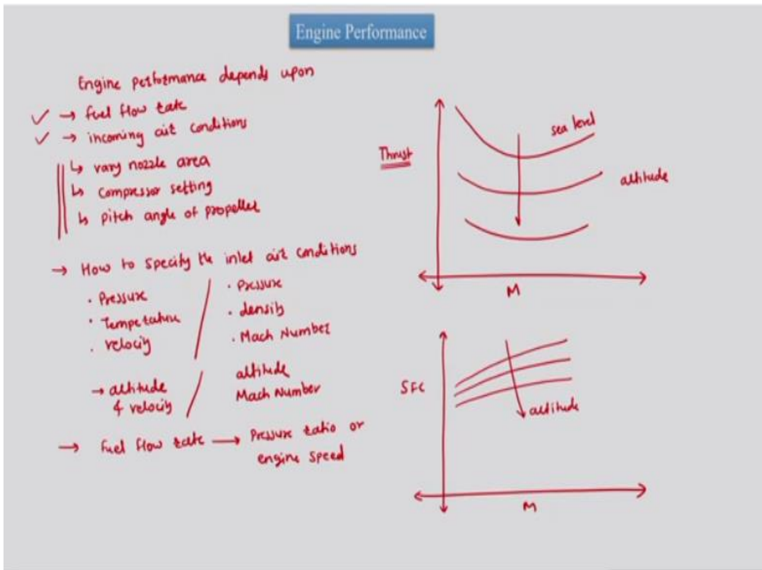

But then, there are certain limitations or certain constraints on increment of the thrust now, we will see engine performance, we have seen till time that propulsive efficiency or cycle efficiency or combustion efficiency overall efficiency, this efficiencies were used by us for the engine performance, here we are trying to see how engine performance is going to alter, which are the parameters governing that and then how it is going to vary with altitude.

First engine performance depends upon fuel flow rate and incoming air conditions, these are the conditions which are for a given engine, for a given engine, if we alter the fuel flow rate or incoming condition then performance will alter but there are certain possibilities that we can make geometrical changes in the engine, something like we can vary nozzle area, we can have variation of compressor settings, we might vary pitch angle of the propeller.

So, these geometrical variations would also be thought for if we are considering the engine performance however, for a given engine, we would have these 2 fuel flow rate and incoming air conditions as the basic parameters or for given settings, these 2 are the basic parameters. So, how to specify the inlet air conditions; we can consider pressure, temperature and velocity or we can consider pressure, density and Mach number.

These 2 combinations can completely specify the inlet air conditions here, we can see that we need 3 parameters to specify the inlet air condition was as the engine performance but instead of these 2, we can specify altitude and velocity or altitude and Mach, there is a given database for the altitude variation and an corresponding pressure temperature or pressure and density, so if we can use that database, then we do not have to specify pressure and temperature or pressure and density, we can just specify altitude and velocity or altitude and Mach number.

Further, we have said that fuel flow rate but fuel flow rate can be replaced by pressure ratio or engine speed or shaft speed, so these 2 things can vary the engine performance, so mutually exclusive data of among these are equivalent of these should be used for engine performance analysis. So, now if we plot thrust versus Mach number M, for an engine say turbojet engine, so this is for sea level and then this is with increase in altitude.

So, we can see here that with increase in altitude, thrust decreases similarly, for specific fuel consumption with Mach number, there is rather good news that specific fuel consumptions, this is variation of specific fuel consumption with altitude and specific fuel consumption decreases with increase in altitude, so this is what the engine performance parameters which are governing the engine and how the engine performance will vary with the altitude. So, with this we end with the topic of discussion for thrust augmentation and engine performance analysis, thank you.