Introduction to Airbreathing Propulsion

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Lecture – 27
Performance/Cycle Analysis: Pulsejet (Contd.,) and Scramjet Engines

Okay so let us continue the discussion on ramjet so we are in the middle of the discussion of the ramjet cycle analysis and we have looked at both the ideal cycle and the actual cycle. So, there are couple of more things that I would like to discuss and then we will look at the scramjet analysis.

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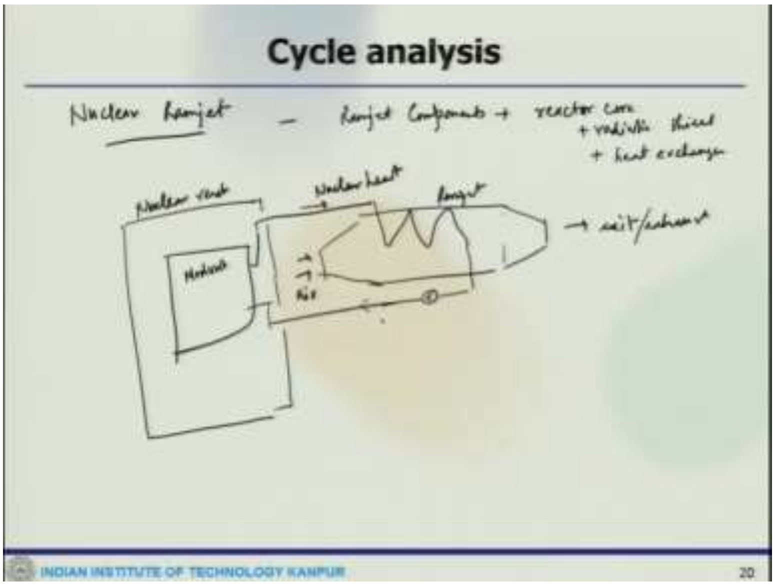

So one of the things that becomes is that also there is an application which is called nuclear ramjet okay. So, this is like the principle behind this nuclear ramjet it is relatively simple. So, there are the three basic components are the same but the nuclear ramjet is used to heat the air of burning fuel in a combustion chamber. So, this some additional components are used compared to ramjet okay and also like some ramjet components plus some additional component like reactor, core plus radiation, shield and heat exchanger.

So these are the some of the other extra component which are kind of used okay and so one can have a like an schematic like how it can look like that you have a sort of an moderator here and then the moderator from here it sort of goes back and then like you have this nuclear or reactor. This is the nuclear reactor and then it goes to like from here the things start and you have some piping here.

And this will be sort of enclosed and this is where your this is what you have the air inlet this is where the nuclear heat goes in and this portion is essentially your ramjet portion and this is your exhaust or exhaust. So this connection kind of connected with the pump and comes back so this is just an schematic how it looks like but will not go very much details of that.

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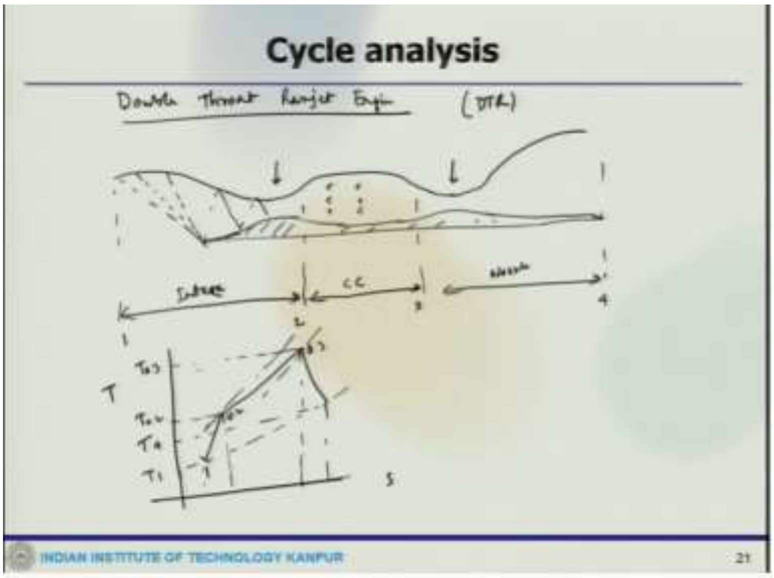

What we will be more interested to another important one which is called the Double throat ramjet engine. So Double throat ramjet engine will look at the schematic so this is a Double throat ramjet now just and it will look like this so this will go then maybe this will go up then second throat and then goes like this and if we just an have an basement here then this is the spike the so that takes into account and then kind of exiting out so you can have sort of different.

So, like cross shock interaction then so from this portion up to this this is intake and then this is the portion which is combustion chamber. So, we can have the burners here let us say 1, 2, 3 and then this portion is nozzle. So that is 4 so it has 2 throats the first one is to decelerate the flow to subsonic before combustion chamber and second one is to accelerate the flow to again supersonic.

So, this guy supposed to decelerate before it comes to the combustion chamber and these throats is supposed to accelerate so that you get so DTR this double throat ramjet it has a supersonic subsonic intake followed by a subsonic combustion chamber then a subsonic supersonic nozzle. So, the flow is decelerated supersonic flow so it enters combustion chamber then again it actually the exhaust it actually again increases to supersonic flow.

And the typical TS diagram that one can have is that you go to 1 then 1 to 3, 3 to 4 so this is 1 this is 02 then 03 so that is T_{03} this is T_{02} then T_4, T_1 so that is how the diagram would look like now that is a double throat ramjet.

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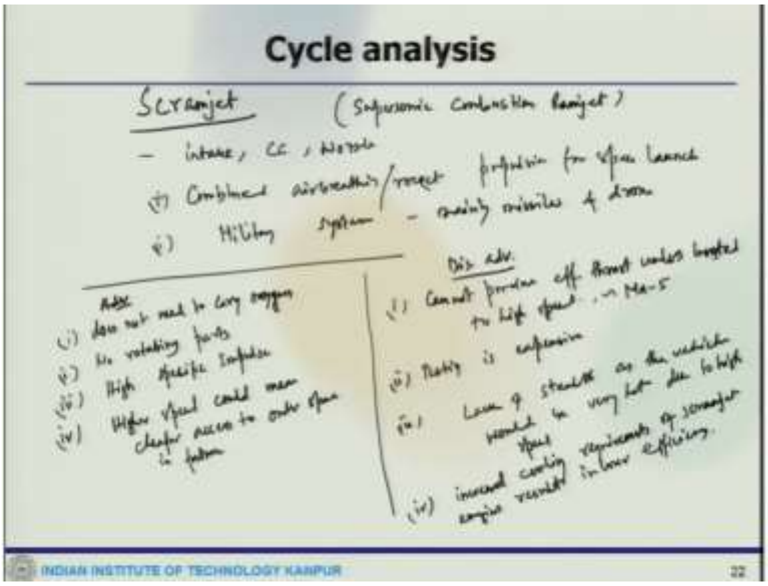

Now then we will move to the scramjet so it is called the supersonic combustion ramjet that is what the name stands for. So experimental scram jet powered is that Boeing x51 a the test craft was lifted to flight altitude by a Boeing b-52 Stratofortress before being released and accelerated by a detachable rocket to near Mach 5.1. So, this was tested in 2013 so it also has three basic components like intake, combustion chamber, nozzle while this is also conceptually very simple.

But actual implementation is very limited and because of the technological challenges. Now only limited testing can be performed in ground facilities long-duration full-scale testing requires flight test speed above Mach 6. Now also the hypersonic flight within the atmosphere generates immense drag temperatures found on the aircraft within that engine and then also maintaining combustion in supersonic as the fuel must be injected mixed and ignited so that is a challenge so within a few milliseconds.

So these are the some of the challenges that there are two families of operational application can be seen for this high-speed propulsion one is let us say combined air breathing or rocket propulsion for space launcher and second one could be the military system mainly missiles mainly missiles and drone like that and the evaluation. So first in 1940 in the R and D started in USA and Canada so then later on there are different development which took place.

And the latest one is that now there are different countries which are involved at present now or like hypersonic program in Germany, India, Brazil they are also all are in this these things so advantage and disadvantage of this can be reached. So, if we put some advantage and at the same time some disadvantage like one of the biggest thing is that it does not need to carry oxygen second no rotating parts which makes it easier to manufacture a high specific impulse.

So that is another beauty of that fourth higher speed would mean cheaper access to outer space in future. Then disadvantages it cannot produce efficient thrust unless boosted to high speed. Let us say around Mach 5 for a horizontal take-off scramjet would need neither a rocket or a combined propulsion system like turbojet or turbofan to boost it to some Mach 2 to 3 followed by another propulsion method like ramjet or rockets so that is a problem.

Then testing is expensive. So, any prototype design also are extremely expensive hypersonic test chamber or large vehicle because not only high instrumentation cost also other factors which are involved. Lack of stealth as the vehicle would be vehicle would be very hot due to high speed within the atmosphere and it would be easy to be detected with infrared sensor the increased cooling requirement. So increased cooling requirement of scramjet engines result in lower efficiency. So, these are some of this thing so now we can draw a schematic of the engine.

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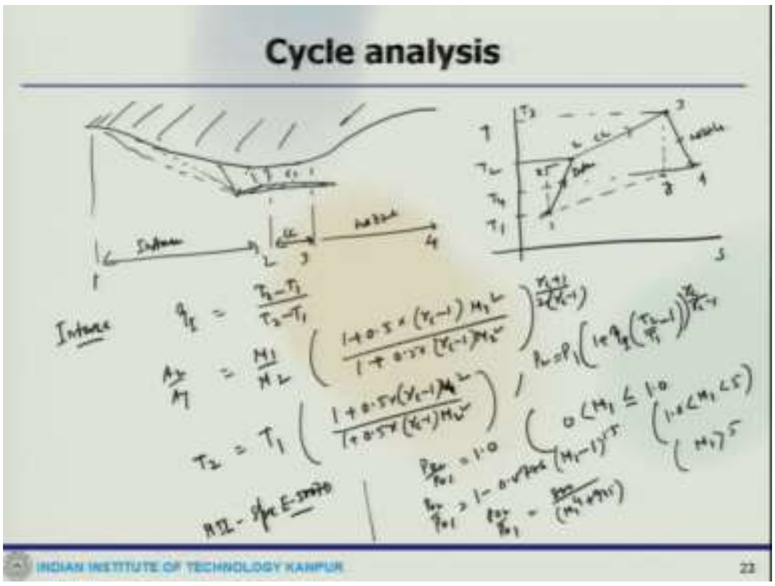

Let us say like this we could so this portion is the sort of intake then this is combustion chamber and this is nozzle so 1, 2, 3, 4 here you will have all these the shock like this and if I put the TS diagram so this 1 to 2 3 so that is 4, 1, 2 T_4 T_1, T_2, T_3 so this is combustion chamber this is intake this is nozzle okay. Let us say this point is somewhere y this point is x. So station 1 it is the represent the intake inlet of the intake which is also beginning of the compression process.

Since the hypersonic shock wave angles are small the ram or spikes are long and so then station 2 it starts the combustion entrance of the combustion chamber and it is a in a fixed geometry scramjet the pressure at the combustion chamber varies 3 it is the exit of the combustion chamber and entry to the nozzle and the station 4 it exit of the nozzle. Now we look at the intake first and intake module so what will happen because of the shock there are losses so intake isentropic efficiency would be

$$\eta_I = \frac{T_x - T_1}{T_2 - T_1}$$

So the area ratio should be

$$\frac{A_2}{A_1} = \frac{M_1}{M_2}\left(\frac{1 + 0.5(\gamma_c - 1)M_1^2}{1 + 0.5(\gamma_c - 1)M_2^2}\right)^{\frac{\gamma_c+1}{2(\gamma_c-1)}}$$

Similarly, we get

$$T_2 = T_1\left(\frac{1 + 0.5(\gamma_c - 1)M_1^2}{1 + 0.5(\gamma_c - 1)M_2^2}\right)$$

$$p_2 = p_1\left(1 + \eta_I\left(\frac{T_2}{T_1} - 1\right)\right)^{\frac{\gamma_c}{(\gamma_c-1)}}$$

So the inlet total pressure recoveries is modelled with MIL so it is modelled with MIL space E 5007 D which can provide some correlations this correlations are like

$$\frac{p_{02}}{p_{01}} = 1; \quad 0 < M_1 < 1$$

$$\frac{p_{02}}{p_{01}} = 1 - 0.776(M_1 - 1)^{1.5}; \quad 1 < M_1 < 5$$

$$\frac{p_{02}}{p_{01}} = \frac{800}{M_1^4 + 935}; \quad M_1 > 5$$

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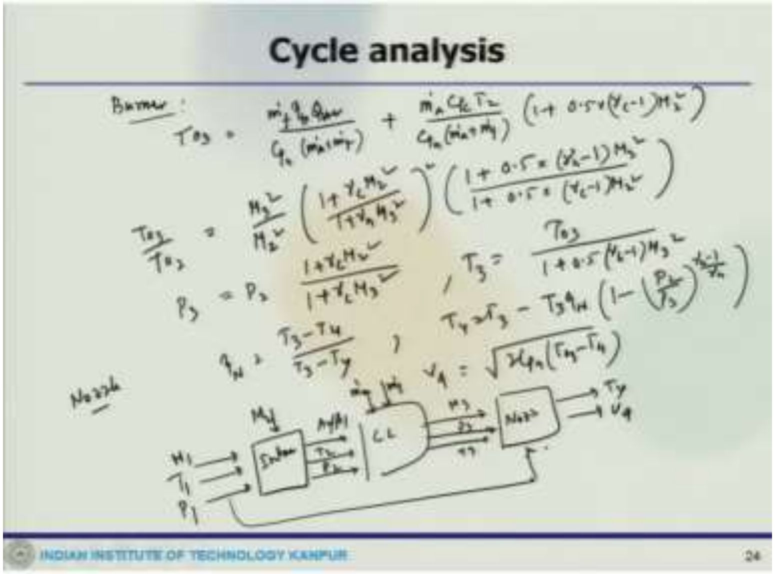

So then we go to the burner and once we go to the burner then we again do the analysis so what we get

$$T_{03} = \frac{\dot{m}_f \eta_b Q_{HV}}{C_{Ph}(\dot{m}_a + \dot{m}_f)} + \frac{\dot{m}_a C_{Pc} T_2}{C_{Ph}(\dot{m}_a + \dot{m}_f)}(1 + 0.5(\gamma_c - 1)M_2^2)$$

So

$$\frac{T_{03}}{T_{02}} = \frac{M_3^2}{M_2^2}\left(\frac{1 + \gamma_c M_2^2}{1 + \gamma_h M_3^2}\right)^2 \left(\frac{1 + 0.5(\gamma_h - 1)M_3^2}{1 + 0.5(\gamma_c - 1)M_2^2}\right)$$

And

$$p_3 = p_2 \frac{1 + \gamma_c M_2^2}{1 + \gamma_c M_3^2}$$

and

$$T_3 = \frac{T_{03}}{1 + 0.5(\gamma_h - 1)M_3^2}$$

and similarly nozzle will get the nozzle efficiency

$$\eta_N = \frac{T_3 - T_4}{T_3 - T_y}$$

So

$$T_4 = T_3 - T_3 \eta_N \left(1 - \left(\frac{p_2}{p_3}\right)^{\frac{\gamma_n - 1}{\gamma_n}}\right)$$

And

$$V_4 = \sqrt{2C_{Ph}(T_{03} - T_4)}$$

So if we put the block diagram it looks like we have a block diagram here this is intake so you have M_1, T_1, P_1 this is where M_2 then combustion chamber this is A_2/A_1 from here it goes T_2, P_2 $\dot{m}_a$, $\dot{m}_f$ then we get to nozzle where M_3, P_3, T_3 and then finally at T_4, V_4 and this goes here.

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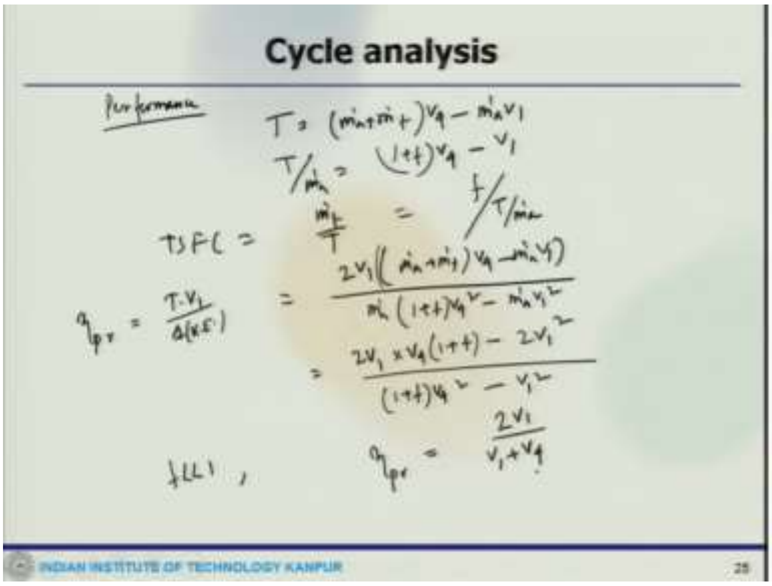

So now we just look at the performance analysis and when you do that so that thrust would be

$$T = (\dot{m}_a + \dot{m}_f)V_4 - \dot{m}_a V_1$$

$$\frac{T}{\dot{m}_a} = (1 + f)V_4 - V_1$$

so TSFC would be

$$TSFC = \frac{\dot{m}_f}{T} = \frac{f}{T/\dot{m}_a}$$

and then propulsive efficiency which is

$$\eta_P = \frac{TV_1}{\Delta KE}$$

so that means it could be written as

$$\eta_P = \frac{2V_1V_4(1 + f) - \dot{m}_a V_1}{\dot{m}_a(1 + f)V_4^2 - V_1^2}$$

So this is what we can write is

$$\eta_P = \frac{2V_1(\dot{m}_a + \dot{m}_f)V_4 - 2V_1^2}{(1 + f)V_4^2 - V_1^2}$$

So if f is small then it appear this propulsive efficiency is

$$\eta_P = \frac{2V_1}{V_1 + V_4}$$

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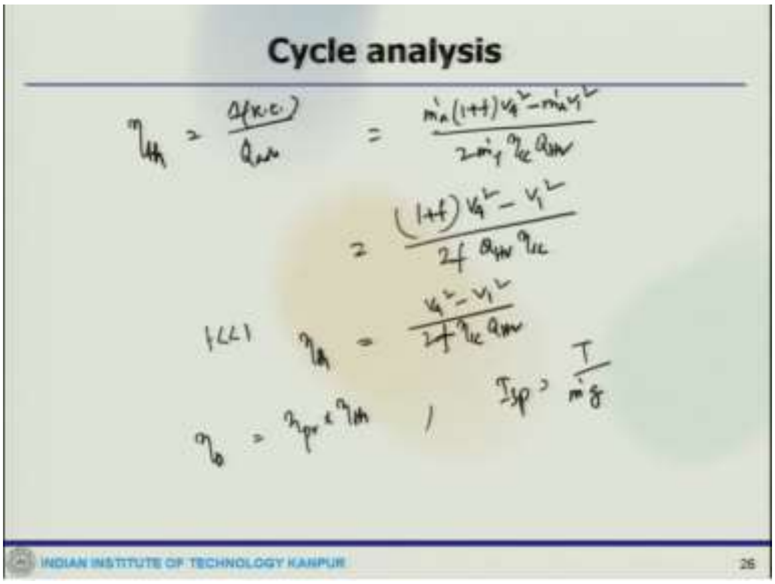

And similarly, we can find out thermal efficiency it is

$$\eta_{th} = \frac{\Delta KE}{Q_{added}}$$

so this would be

$$\eta_{th} = \frac{\dot{m}_a(1+f)V_4^2 - V_1^2}{2\dot{m}_f \eta_{cc} Q_{HV}}$$

so which is written as

$$\eta_{th} = \frac{(1+f)V_4^2 - V_1^2}{2f \eta_{cc} Q_{HV}}$$

So again, if f is small this will going down to like

$$\eta_{th} = \frac{V_4^2 - V_1^2}{2f \eta_{cc} Q_{HV}}$$

and overall efficiency which would be

$$\eta_o = \eta_{Pr} * \eta_{th}$$

and is

$$I_{sp} = \frac{T}{\dot{m}_g}$$

So, these are all the performance parameter that one can calculate and look at so there could be another one which could be looked at is that.

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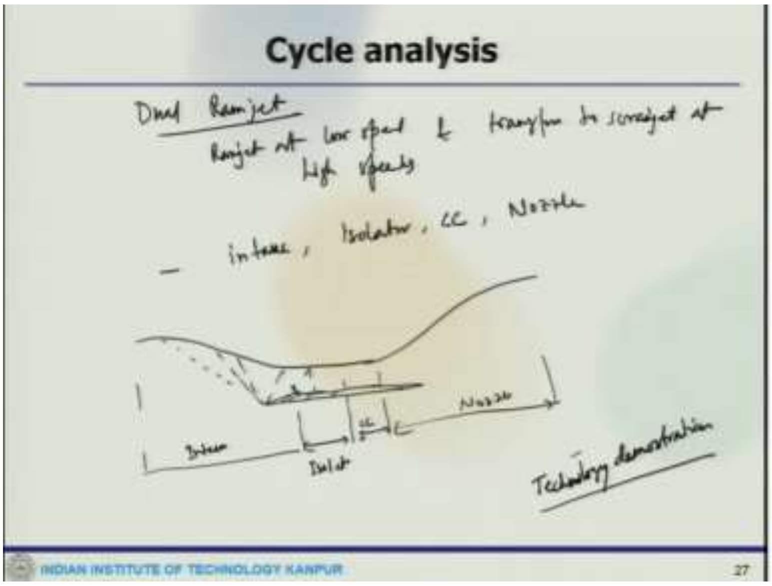

So, which is called dual ramjet so this is dual ramjet is also a dual mode ramjet. So, where the ramjet at low speed and transform to scramjet at high speeds okay. So that is how it is called dual mode. So now I mean basically this is another advancement where one can also look at these things and can do the thermo dynamical analysis that so this will also have a similar component like intake or inlet.

Then I mean it will have let us say component like intake then there would be isolator then there is combustion chamber then there would be nozzle. So, these are the some of the component is just like if somebody draw a schematic like that and if that is the spike. So, these are the pattern of the shock. So now this portion is essentially this is the intake then there would be this portion which is called the isolator.

Then this portion which is combustion chamber and this is nozzle and also I mean if you draw the TS diagram then you can always do this aero thermodynamic analysis so that can be also done. So essentially these are also some of that one meant in the scramjet application that where people can use all these. But eventually it is important to note that the scramjet things are still at the experimental mode I mean none of the flight I mean only the flight which was given some tests by US.

But others; all other countries they are in this scramjet hypersonic program they have different program in hypersonic zone where they are about to build some prototype and then basically demonstrate the technology. So mostly I would say these are all at the level of technology demonstration so that sort different context what they have this program these different vehicles they are into or the kind of things they are trying to develop these are called technology demonstrator vehicle hypersonic technology demonstrator vehicle.

And they have pretty much the; I mean outer configuration or the from apparently they look probably similar but because they built on the same principle similar kind of things but this is fairly a challenge. So, we will close the discussion on scramjet here or rather stop the discussion on scramjet here and we will move to the next set of engine for discussion in the next class.