Introduction to Airbreathing Propulsion
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Lecture – 24
Performance/Cycle Analysis: Pulsejet

Okay, so far we have done the reciprocating engine and the discussion on propellers and all these, now we are going to look at the thermo dynamical analysis or aero thermodynamic analysis of other engines. So to begin with we will first look at the engines like pulse jet, ramjet kind of engine or the scramjet and then from there we will move to the turbo jet or turbofan kind of analysis.

The whole idea is that when we talk about this kind of engine like pulse jet or ramjet or scramjet this they do not have any rotating components, so they are like they do not have any compressor, they do not have any turbine, its geometric modifications are there or the geometric control is there, which actually takes care of the compression process and also that reduces the velocity before it enters to the combustion.

And then finally there would be nozzle which can actually provide the exit velocity to estimate for the thrust and all these, so we will move to the discussion now on this kind of engines which are having no rotating component.

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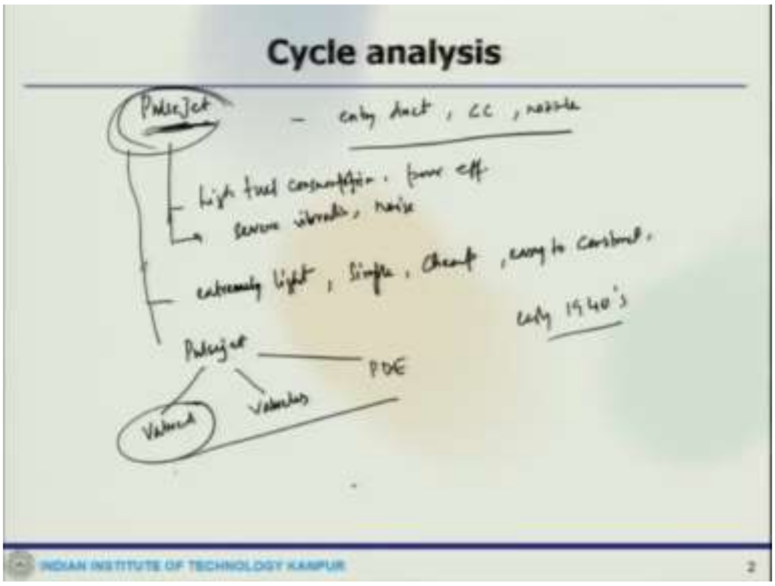

So, we will start with the engine is pulse jet, okay and then after that from pulse jet, we will move to ramjet and from ramjet, we will go to scramjet, so these are the different kind of engines where the RAM based cycles are there, so they do not have the major rotating components, so it has some sort of an entry duct and combustion chamber and nozzle, so it is that way geometrically, one can think about it they are quite simple.

Because this is a major problematic component like the rotating component are not there, so and now when you talk about the pulse jet, this has very limited applications because there is a great difficulties in integration into the manned aircraft but so the other disadvantage are very high fuel consumption, poor efficiency that is there, then severe vibration, noise, high noise and all these are there.

So but other way if you think about it, it is a very simple jet engine and which can be made with a few or no moving parts, so it has only a intake duct combustion chamber or and then the nozzle and all this. So, consequently the pulse jet engine is similar to piston engines in its intermittent combustion nature but at the same time, it is similar to all jet engines in generating thrust via reaction principle for propulsion.

Because so thus one can say that pulse jet engine resembles a traditional development between older piston engine and subsequent jet engine, so that is kind of a lies in between these 2. The advantage here with the pulse jet are extremely light that is there, then simple, cheap, easy to construct, so uses both atmospheric oxygen, cheap fuels capable of running statically.

So, these are the some of the advantage, so also pulse jet have 3 types, we have already seen, it could be valved or it could be valveless or it could be pulse detonation engine, so these are the different things and it started with, I think the in 1906 and 1907, when the initial work was started by the scientist Martin Wiberg that is in Sweden and then slowly there is a different kind of development which was carried under this kind of engine.

And now, what happens later on like 1940s or early 1940s, Lieutenant William Schubert of US Navy designed his valveless pulse jet engine called the resojet, so this is early 1940s, in between, there are other development which actually took place but it is 2 main advantage over other design was the combustor into a sudden expansion and produces had turbulence for thorough mixing of air and fuels.

And second one is that intake geometry was carefully designed, so that the exhaust gas does not escape before the pressure inside the chamber. Then, there are other development also took place later on and the other type which is; so now the when you talk about the valved pulsejet, it has an air scoop and say it one-way valve through which the incoming air process which we have already seen during the introductory lecture, the geometry and things like that.

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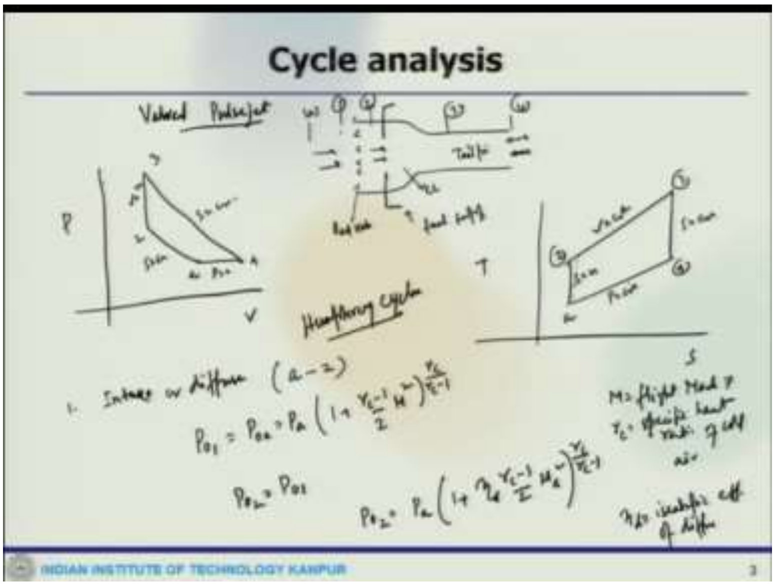

And now, if you look at that now, first we will start with the valved pulse jet and we put the simple construction of that, let us say this is how the geometry will look like, it is a simple construction where these are the; so let us say a, station number 1, this is 2, station number 3 and 4, so this is tail pipe, this is fuel supply, this is combustion chamber, so these are valve and the PV diagram would be like this is a, it goes here, then goes there, then goes there.

So, this is a, 2, 3, 4, this is s constant, this is volume constant, this is s constant, this is P constant, so at the same time if we put the TS diagram this goes like this, so a, 2, 3, this is V constant, this is pressure constant 4 and these are also s constant, this is also s constant. Now, simple thermo dynamical cycle, so this pulse jet actually operates on typical cycle called Humphrey cycle okay.

So, here the isentropic compression here, then here the isochoric heat addition, again isentropic expansion and this is isobaric heat rejection and so that it returns, so this a simple process, this is isentropic constant volume, constant pressure, constant isentropic, so it intake or diffuser, so this process occurs between state a to 2, from here to 2. So, air is sucked in and into the combustion chamber through a bank of spring loaded check valve.

So, a is fast stream while 1 is at the pulse jet inlet and 2 is the just aft of the check valve of stream of the combustion chamber. So, now there is a ramp effect which takes place and then we can get the pressure

$$p_{01} = p_{0a} = p_a \left(1 + \frac{\gamma_c - 1}{2} M^2\right)^{\frac{\gamma_c}{\gamma_c - 1}}$$

where M is the flight Mach number, γ_c is specific heat ratio of cold air. If it is assumed that the diffuser is an ideal one or isentropic process, then the total pressure temperature at state 2 is equal to those at state 1.

So, what will happen that $p_{02} = p_{01}$, however there are losses which will take place in the diffuser, so the pressure at state 2 is always at less than 1 but process in the diffuser is assumed to be adiabatic, so let us say having an isentropic efficiency. So, that means there is an ideal situation or there could be a non-ideal situation which could be like this. So, in a non-ideal situation what would be; the

$$p_{02} = p_a \left(1 + \eta_d \frac{\gamma_c - 1}{2} M_a^2\right)^{\frac{\gamma_c}{\gamma_c - 1}}$$

So, η_d is the isentropic efficiency of the diffuser, so isentropic efficiency of diffusor, so in all cases, I mean that is isentropic or adiabatic, the stagnation temperature for state a 1 and 2, they are equal.

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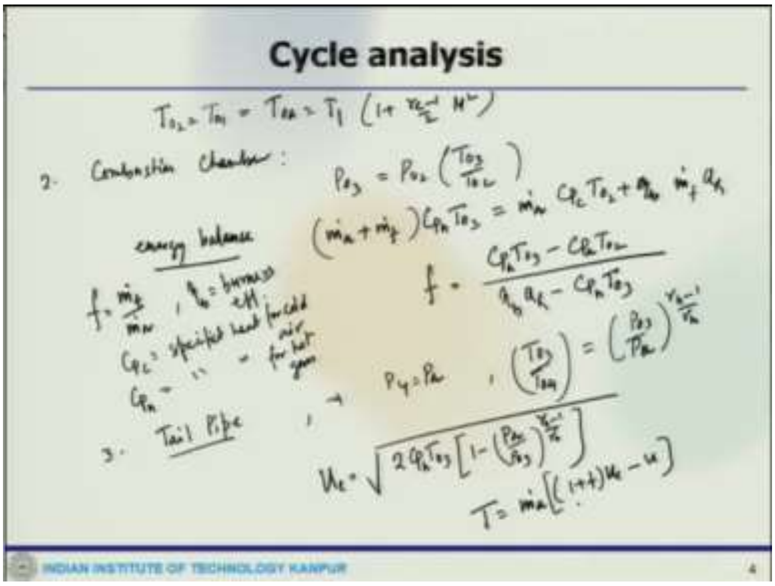

And so the temperature that could be written as $T_{02} = T_{01}$,

$$T_{02} = T_{01} = T_{0a} = T_a\left(1 + \frac{\gamma_c - 1}{2}M^2\right)$$

Now, coming back to the combustion chamber where we now here the fuel is added and the combustion chamber through several fuel injector, they are mounted there and the combustion takes place as a constant volume process, okay. So, what we can do to calculate that, so since this is a constant volume process, heat addition

$$p_{03} = p_{02}\left(\frac{T_{03}}{T_{02}}\right)$$

So, the actually, here the spark plug igniter is only needed for the initial start-up, once started the engine we will continue to operate on its own with hot residual combustion gases subsequently in cyclic manner igniting the incoming fresh fuel air mixture in a low high low passive pressure cycle and that combustion actually takes place in sort of an explosion fashion which digest the pressure in the chamber at high level and this.

So, the mass flow rate of the burn fuel can be calculated from the energy balance equation, so if we write the energy balance, where

$$(\dot{m}_a + \dot{m}_f)C_{p_h}T_{03} = \dot{m}_a C_{p_c}T_{02} + \eta_b \dot{m}_f Q_R$$

So, fuel air ratio is

$$f = \frac{\dot{m}_f}{\dot{m}_a}$$

η_b is burner efficiency and C_{p_c} is specific heat for cold air, C_{p_h} is specific heat for hot gases, okay. Now, from here we can find out the fuel air ratio which would be

$$f = \frac{C_{p_h}T_{03} - C_{p_c}T_{02}}{\eta_b Q_R - C_{p_h}T_{03}}$$

So, find out the fuel air ratio.

Now, the third is tailpipe okay, so when you go to tailpipe, now the resultant high pressure and temperature, forces the gas to flow out of the tailpipe with high velocity, so if the gases are assumed to expand isentropically in tailpipe to the ambient pressure, so in that case

$$p_4 = p_a$$

and that temperature of the exhaust gases can be obtained through this relation,

$$\frac{T_{03}}{T_{04}} = \left(\frac{p_{03}}{p_a}\right)^{\frac{\gamma_h - 1}{\gamma_h}}$$

So, exhaust velocity can be now estimated which is

$$u_e = \sqrt{2C_{p_h}T_{03}\left[1-\left(\frac{p_a}{p_{03}}\right)^{\frac{\gamma_h}{\gamma_h-1}}\right]}$$

and at the same time, we can calculate the thrust which is

$$T = \dot{m}_a[(1+f)u_e - u]$$

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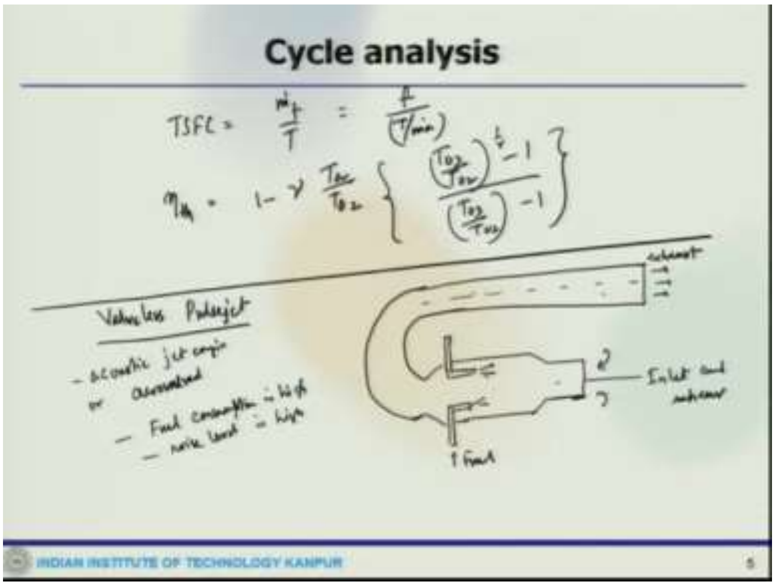

And the other term like TSFC which is the thrust specific fuel consumption which is

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

and the thermal efficiency of the system is

$$\eta_{th} = 1 - \gamma\frac{T_a}{T_{02}}\left\{\frac{\left(\frac{T_{03}}{T_{02}}\right)^{\frac{1}{\gamma}} - 1}{\left(\frac{T_{03}}{T_{02}}\right) - 1}\right\}$$

So, here essentially the process is following an, a, 3, 4, 1 in that cycle, so this is how you can obtain this details of the pulse jet engine.

Now, second one that we can talk about is the valveless pulse jet that is pulse jet and we have already seen this simple design which could be like, it could be having a design like that, so like this, this is where the valve is, then we have these and from here it goes round and goes like this, here it goes like that and goes like that, so this is where the exhaust, this is where fuel comes in, this is the inlet and exhaust too.

So, that is a simple design that we have already seen this valveless engine, this is simplistic jet engine in the valves, as it has no mechanical valve but it does have aerodynamic valve which for the most part restricts the flow of the gases to a single direction, valveless pulse jet engine is sometimes identify as acoustic jet engine or sometimes called acoustics jet engine or aerovalved and or also intermittent ramjet something like that.

So, this has no moving parts which means no where it is similar to a ramjet in that respect, so it is designed to where issues of valves in valved type and they have all the advantage and most advantage of conventional valved pulsejet. Fuel consumption is extremely high, noise level is also, so fuel consumption is high, noise level is high, however they do have the troublesome reed valves that need frequent replacements.

So, they can operate for their own inter useful life with practically zero maintenance, so these have been used to power model aircraft like experimental go-karts and even sometimes unmanned military aircraft like this, so this u shaped tailpipe which is sort of a U shaped bend is there. In this type of pulse jet, the combustion generates 2 shockwave fronts, one travels down each tube by, so one goes this side, one goes that side.

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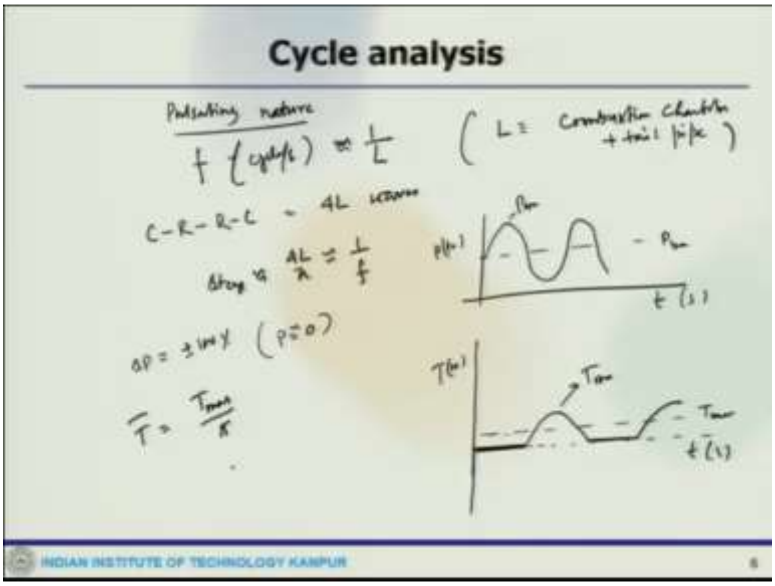

So, this can be built in many different sizes and other things and during start up, some sort of an ignition is required and for pulsating nature of the flow parameter in pulse jet engine, so what pulsating nature; so several researchers were I mean, some they have performed tests and to examine the fluctuating nature of the flow, so the fundamental operating frequency for the pulse jet f which is sort of a cycles per second is kind of related to the length of the pulse jet which is this L is sort of an combustion and tailpipe, length of combustion chamber and tail pipe together.

So that is the typically length of that, so in acoustic terminology a conventional pulse jet operate on four length wave system that is to say, its creates 4 pressure waves which is compression, refraction, refraction, compression, so this is 4L waves pattern. So, what happens these 4 pressure waves moving at or slightly above the local gas sound speed sequentially traverse the duct system that is combustor and the tail pipe.

So that is the operational period of one cycle is t cycle would be 4L by a, which is 1 by f, so various parameters in pulsejets like air mass flow rate, pressure, temperature, Mach number, thrust force are pulsating in nature, so people also do like if you look at the with time, if this is the mean, this goes like these kind of things, so the P base pressure, pressure at Pascal this is the P max.

Similarly, the thrust also goes with time, this is second, this is thrust in Newton, so this goes like first this segment, then goes like that, then again and then we have, this is T mean and this is the T max, so this shows an idealized sinusoidal fluctuation of pressure in the combustion chamber and this is the thrust, see then now upper and lower absolute pressure limits and there is an idealized basement.

Since they are nearly equal in magnitude; so the delta P would be plus minus 100% for a symmetrical cycle, where vacuum limit or P is almost 0 as the most negative trap point possible in the idealised sinusoidal cycle here. So, analogous to idealize combustor pressure time cycle, so this is what the thrust time profile would be there. So, if you assume there is no appreciable negative thrust resulting from back flow during the induction phase of the operational cycle, the remaining positive components of the cycle thrust profile would produce a net mean thrust.

So, the net mean thrust would be T max by pi, so it is worthy to mention here that the people have been also investigating this kind of pulse jet or rather pulsating engine through different kind of numerical analysis because this testing is also required to be done in a very safety environment and that is why it requires because as we said that the ignition and the combustion process actually takes like in sort of an explosive process like an explosion.

And then there is a huge wave propagation both in this direction and that direction, so this is what we can have in the valved and valveless pulsejet, the other one that can be there is the pulse detonation engine, so that one we will discuss in the next session.