# Jet Aircraft Propulsion

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## Lecture No. # 38

## Thermodynamic Cycle and Performance Parameters

Hello and welcome to lecture number thirty eight of this lecture series on jet aircraft propulsion. You have in the last couple of lectures being introduced to the sub concept of ram jets and pulse jets, that is a very interesting concept all together. Ram jets and pulse jets are very simple forms of aircraft engines, and they are simple in the sense that none of these engines have any rotating components; that makes them extremely simple to construct and design. And the reason why they do not have any turbo machinery like compressors, and therefore turbines is the fact that some of these engines; can in fact generate so much pressure ratio, because of the ram effect which is what happens in a ram jet. That you do not really need a compressor, and since you do not need a compressor, you also do not need a turbine.

So, that that makes the whole engine very simple, because you do not have rotating machines, and that makes construction of a ram jet very easy, and to some extent the pulse jets are also simple which we will see a little later. And the whole aspect of making a very an engine simple is something that every engineer would dream off that, if you have an engine which is very simple and can deliver the required thrust that is perhaps the best thing that could happen. Unfortunately of course there are certain limitations to some of these engine concepts like ram jets and pulse jets. The basic aspect is that some of these engines cannot generate any static thrust, that is you cannot really take off with either of these types of engines, because they require a certain velocity, and therefore a certain ram effect before which they can start generating thrust.

And very soon you are going to see that ram jets have a certain performance curve, which peaks at about Mach around Mach number of Mach 3, and again after a certain Mach number after that number the performance drops drastically, which means that ram jets have a very fixed or certain desire range of operation in terms of Mach number during which it of course, performs very well. And Of course, ram jets and pulse jets have been used extensively not for civil aviation purposes, but they have been used for missiles. Pulse jets were In fact, used by the Germans way back in 1940, when they had one of their bombers which was very successful.

And the allied forces were very, very much affected by the German use of pulse jet based bombers like the V-1 bomber and so on… These aircraft which were operational 50 years back were very successful in those days, but they have lot of other issues which have not which needs to be resolved before which these engines concepts can actually be used for civil aviation purposes. Ram jets have been used for a long time for missile applications. And in fact, some of the missiles which even India, have uses ram jets and the ram and some of the long range missiles would want to use ram jets, because they are air breathing propulsion systems and because of which you do not need to carry an oxidizer.

The only requirement is that these ram jets will have to be first flown to a desired speed before which the ram jets can actually start operation operating, which means typical missile configuration would have rocket system; which takes the ram jet the whole engine to a certain speed and then once the rocket has once the missile has attained a certain Mach number at which the ram jets can begin to generate thrust. The ram jets can take over and then continue to operate like a pure ram jet missile system. So, the advantage is that it gives you very long range because you can carry extra fuel in the missile and you do not need to carry an oxidizer unlike rocket based propulsion system, where you also have to carry an oxidizer that puts a lot of restriction on the amount of fuel; that can be carried as well as the amount of pay load; that can be carried.

So, these are some of the advantages that ram jets have pulse jets also have certain inherited advantages at the same time they also have disadvantages basically because pulse jets make use of certain valves if it is in the valved configuration there also valve less pulse jet configuration which we will take up for more discussion in the next class. So, in valved pulse jets have been popularly used there are certain valves which operate and as a result of valves, which are mechanical devices there are lot of issues associated with valves the operation of valves and synchronization of the valves with the whole engine cycle and so on…

Therefore, the efficiency actually comes down as a result of these mechanical issues. So, what we are going to discuss in today’s class are basically the thermodynamics of these two engine concepts: the well, they are not really concepts any more they have actually been demonstrated and they are operational. The basic thermodynamic cycle of the ram jets and the pulse jets and also we will look at the cycle analysis of two of these engine types the ram jets and the pulse jets both the ideal cycle as well as we will look at the real cycle analysis in some detail. So, this is what we are going to discuss in today's class and subsequently in the next class we will take up little more details of the components that constitute these engines like the ram jets and the pulse jets.

So, today's class is going to be basically a discussion on the thermodynamics and also the performance parameters of ram jets and pulse jets. So, we will look at the thermodynamic analysis and the thermodynamic cycle in today's class. We will begin with the ram jets first and. So, just to give you some brief introduction, which you I am sure you would already have had in the last lecture when you were exposed to the ram jets and how ram jets operate and how pulse jets operate.

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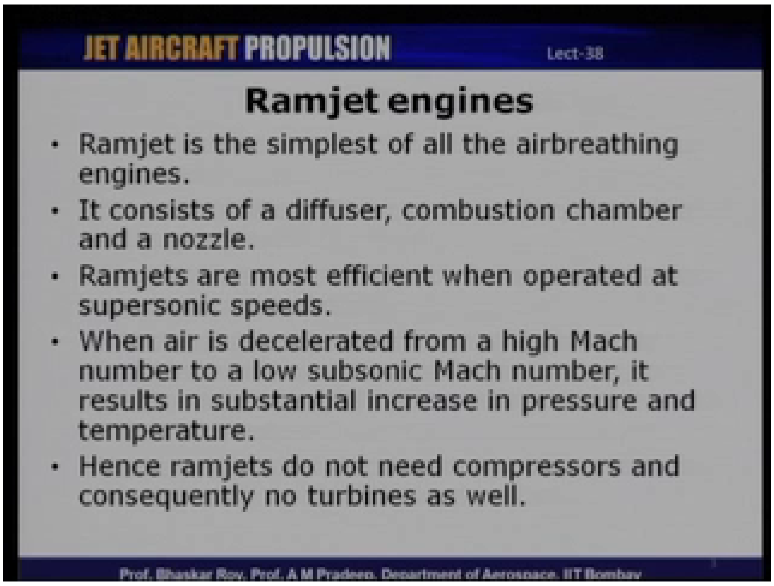

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Ramjet engines

- Ramjet is the simplest of all the airbreathing engines.
- It consists of a diffuser, combustion chamber and a nozzle.
- Ramjets are most efficient when operated at supersonic speeds.
- When air is decelerated from a high Mach number to a low subsonic Mach number, it results in substantial increase in pressure and temperature.
- Hence ramjets do not need compressors and consequently no turbines as well.

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So, ram jet is as I said the simplest form of an air breathing engine the reason why I say it is simple is because it consist of only three components consists of a diffuser a combustion chamber and the nozzle and ram jets are designed or by their very construction or the thermodynamic principles ram jets are most efficient of; obviously, when they operate at supersonic speeds and in such very high speeds, when the air is decelerated from a very high Mach number to a very low sub sonic Mach number. It results in a substantial increase in static pressure and temperature, which means that ram jets do not really need any compressors.

Since they do not need any compressors you also do not need any turbines in a ram jets because turbines in an air breathing engine are meant primarily to drive a compressor in a ram jets you do not have a compressors. So, you do not need turbines as well. So, this is probably the single most important advantage of ram jets, besides the fact that they are air breathing engines that you do not need rotating machines and that is a substantial advantage both mechanical advantage as well as an aerodynamic advantage. Well the mechanical advantage is the fact that you do not need to carry so much weight. You do not have mechanical complexities of a rotating machine and the other advantage the aerodynamic advantage I would put it is the fact that since you do not have rotating components you can actually operate the cycle at very high temperatures much higher than what one would use in a normal jet engine, because you do not have rotating components.

So, higher the temperature as you have seen results; obviously, in higher thrusts, thrust to weight ratio and also it can lead to slightly better efficiency thermodynamically, but in actual transits the efficiency is significantly affected by the presence of shocks through which the flow is decelerated in the intake. Ram jets have a variety of advantages, but the major disadvantage is the fact that it cannot operate from zero velocity or it cannot generate static thrust, which means an aircraft cannot take off on a ram jet engine. It requires another form of thrust generation, which can accelerate the aircraft to a certain speed, at which the ram jets can begin to operate and generate thrust. So, that is a single most glaring disadvantage of a ram jet the fact that it cannot generate static thrust.

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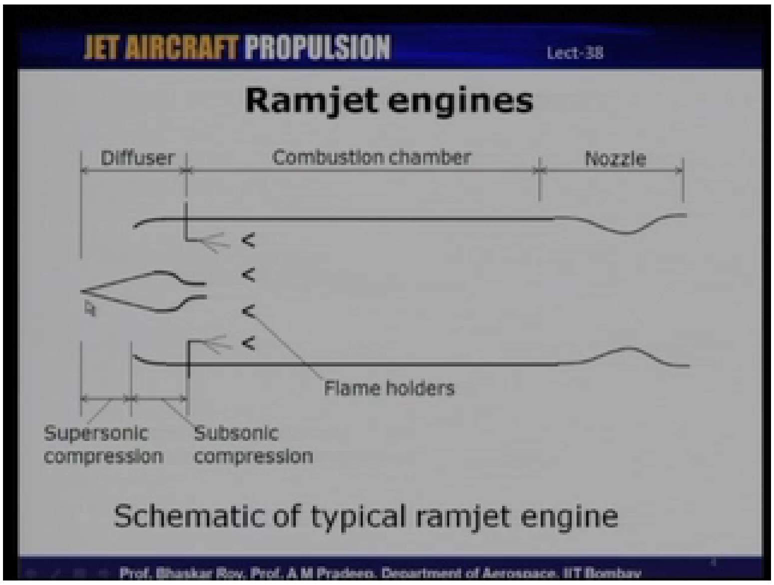
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Ramjet engines

Schematic of typical ramjet engine

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So, let us take a look at: a schematic of a ram jet, you have already seen the working of a ram jet in the last class. So, ram jet as I said is a very simple engine there are only three components basically: ram jets a typical ram jet would have a diffuser. This diffuser could usually it would basically have two components one is supersonic part of the diffuser and the subsonic part. We have already discussed about diffusers and intakes in a great detail in few lectures, where we had seen a typical supersonic intake will have two components: one is the supersonic compression part that is what we see here where there is a spike or a fore body, which generates the necessary oblique shocks to decelerate the flow.

So, here there is a single spike, which means that there could be one oblique shock and then there would be a normal shock after which the flow becomes subsonic. So, after the normal shock which under design condition or critical operation would originate from the lip of this intake and after the normal shock the flow becomes sub sonic and then therefore, you have a sub sonic compression taking place. Now, there is another counter part of the ram jets, which you will probably discuss a little later in some of the later lectures that is known as this scram jet, which is basically supersonic combustion ram jet. It is very similar to ram jet, but combustion in a scram jet occurs in at supersonic speeds, which means that you will not have a sub sonic compression there.

Flow is only decelerated through oblique shocks, but it is still supersonic and scram jets are designed to operate at very high Mach numbers; above Mach five that is in hyper sonic speeds. So, here the flow has to be decelerated sub sonic speeds, because in conventional combustors combustion stable combustion can occur only when the flow is sub sonic. Supersonic combustion has its own limitations and lot of challenges associate with that. So, after the diffuser, you can see the combustion chamber, it is a straight through flow combustion chamber as you can see and let us say schematically, we have a few injection fuel injection system as you can see here, fuel is injected and then how do you maintain the flame inside the combustion chamber.

So, in order to maintain combustion stable combustion we need what are known as flame holders. So, flame holders are basically bluff bodies as we can see these are bluff bodies placed in the flow, which means that in the downstream of the bluff body you would have a wake and a wake is a region where you have a recirculating low velocity flow. So, these flame holders will act as devices, which can allow combustion to be stable and there is a certain stable flame, which is associated or attached to these flame holders. So, flame holders are meant to keep the flame in place and that you have combustion, which is completed as much as possible within the length of this combustion chamber.

So, the length of this combustion chamber will be decided by the fuel itself and the fuel particles size the spray droplet size, because it there is a certain length residence time as it is called required before which the fuel particles can completely ignite and combust. The last component of ram jet is a nozzle and the flow, which the hot combustion products coming from the combustion chamber are expanded through the nozzle and this, generates the required thrust by the ram jet. So, you can see schematically that at least in principle ram jets are very simple devices you have just three components here you have a diffuser a combustion chamber and a nozzle.

So, these three components put together generate a thrust which we have discussed in the last several lectures in a typical turbo jet engine requires much more complexity like it requires a fan or well a compressor then the combustion chamber which is also there here and a turbine. So, a ram jets is able to produce thrust without using these other components. The basic thermodynamic cycle of a ram jet continues to be the simple Brayton cycle. We have already discussed Brayton cycle in a lot detail; we have also seen Brayton cycle as applied to jet engines like these turbo jets turbo fans. On let us now take a look at: what is a thermodynamic cycle which constitutes a ram jet. So, ram jets work on the basis of the Brayton cycle for an ideal ram jet we are going to look at the simple Brayton cycle.

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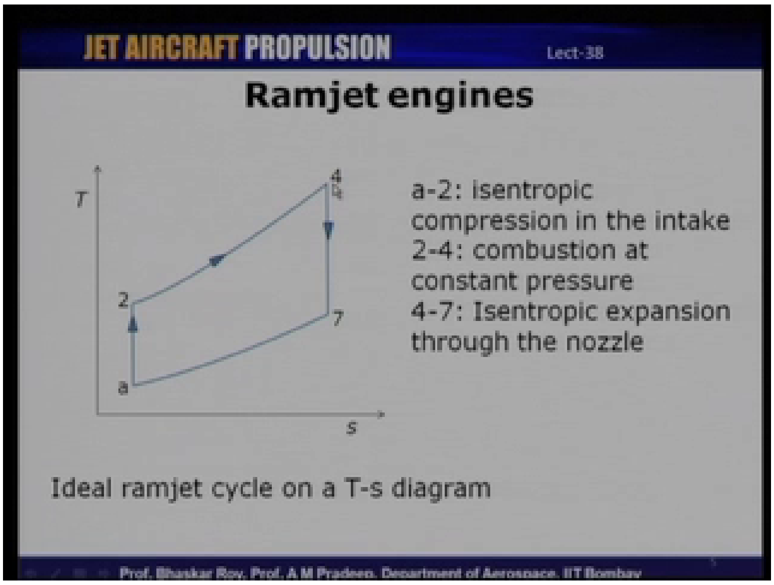

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Ramjet engines

a-2: isentropic compression in the intake
2-4: combustion at constant pressure
4-7: Isentropic expansion through the nozzle

Ideal ramjet cycle on a T-s diagram

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So, the simple Brayton cycle as is shown here in this temperature entropy diagram consists of two isentropic processes; an isentropic compression followed by a constant pressure heat addition or combustion. The third process is the isentropic expansion through the nozzle and since it is an open cycle the last process is the exhaust process. So, I have retained the numbering scheme, which we have been following throughout the course. So, as is for the ambient two is for compressor or in this case just the compression exit four in the case of a jet was turbine inlet here there is no turbine. So, that is the expansion beginning of the expansion and seven was nozzle exit.

So, I have that is why you might wonder why I have put this numbering scheme of two and then four because I have just been consistent with what we have used earlier. So, in this ram jet the ideal ram jet cycle, you can see there are two processes which are isentropic: the first process which is the compression process and also the last process, which is an expansion process through the nozzle; the combustion process is at the constant pressure .

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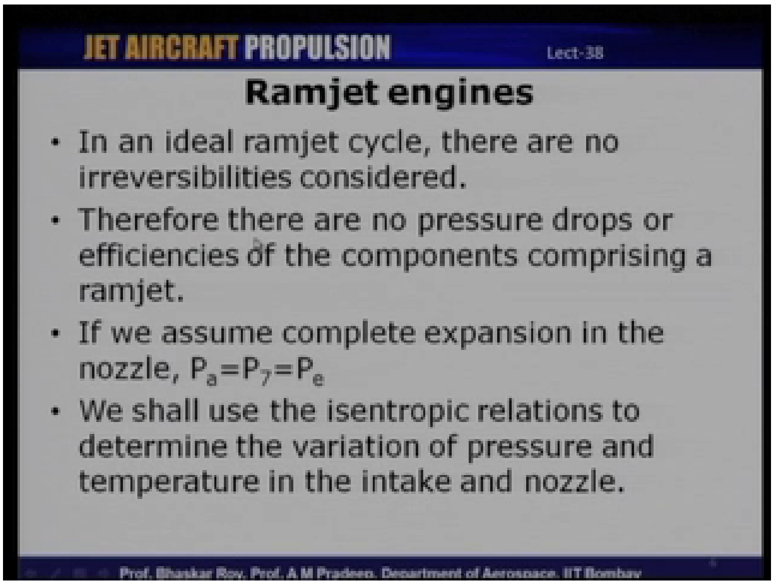

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## Ramjet engines

- In an ideal ramjet cycle, there are no irreversibilities considered.
- Therefore there are no pressure drops or efficiencies of the components comprising a ramjet.
- If we assume complete expansion in the nozzle, $P_a=P_7=P_e$
- We shall use the isentropic relations to determine the variation of pressure and temperature in the intake and nozzle.

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Now, we will first analyze the ideal ram jet cycle ideal ram jet cycle is one, where there are no irreversibilities which means there are no pressure drops taking place efficiencies of components etcetera. We are going to neglect and once we neglect some of these assume that some of these irreversibility’s are absent then that cycle is basically an ideal cycle. We have already discussed ideal cycle of turbo jets and turbo fans and so on… So, in this ram jet cycle for an ideal idealized version of this ram jet cycle. There are no irreversibilities in the intake, which means that the compression process is isentropic there is no frictional losses no shock losses etcetera the heat addition occurs at constant pressure, which means the there are no pressure losses occurring in the combustion chamber and also the expansion process through the nozzle is again assumed to be isentropic.

So, with these assumptions in mind let us now carry out a cycle analysis of a ram jet and we will be able to now derive expression for the thrust and fuel consumption that a typical ram jet would generate and then subsequently we are going to take up a real cycle we will also see what are the efficiencies and pressure losses etcetera. That needs to be incorporated to get a realistic estimate of the performance of a ram jet an actual ram jet. So, in this ideal cycle analysis; obviously, we are going to us the isentropic relations because the compression and the expansion processes are isentropic. So, we can very safely use the isentropic relations to determine properties in a performance in a ram jet.

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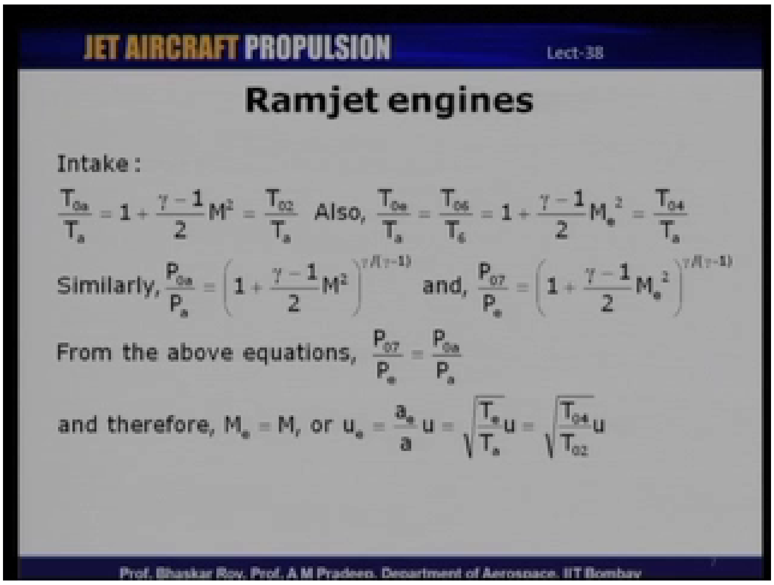

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Ramjet engines

Intake:

$\frac{T_{0a}}{T_a} = 1 + \frac{\gamma - 1}{2}M^2 = \frac{T_{02}}{T_a}$ Also, $\frac{T_{0e}}{T_a} = \frac{T_{06}}{T_6} = 1 + \frac{\gamma - 1}{2}M_e^{\ 2} = \frac{T_{04}}{T_a}$

Similarly, $\frac{P_{0a}}{P_a} = \left(1 + \frac{\gamma - 1}{2}M^2\right)^{\gamma/(\gamma-1)}$ and, $\frac{P_{07}}{P_e} = \left(1 + \frac{\gamma - 1}{2}M_e^{\ 2}\right)^{\gamma/(\gamma-1)}$

From the above equations, $\frac{P_{07}}{P_e} = \frac{P_{0a}}{P_a}$

and therefore, $M_e = M$, or $u_e = \frac{a_e}{a}u = \sqrt{\frac{T_e}{T_a}}u = \sqrt{\frac{T_{04}}{T_{02}}}u$

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So, let us begin with the intake. So, in an intake we have the stagnation temperature T 0 a, which corresponds to the stagnation temperature of the ambient condition. T 0 a by T a is the stagnation temperature to static temperature ratio this is related to the Mach number by the isentropic relation. So, T 0 a by T a is 1 plus gamma minus one by 2 M square. Now, since there are there are no heat losses or it is an isentropic compression which means it is also adiabatic therefore, T 0 a is equal to T 0 2. So, we get T 0 this right hand side is also equal to T 0 2 by T a.

Similarly, for the exit we have T 0 e by T a is equal to T 0 7 by T 7 that is 1 plus gamma minus 1 by 2 M e square and that is also equal to the nozzle entry temperature, because it is again an adiabatic expansion. So, we have T 04 by T a. Similarly, we can also write the pressures P 0a by P a is one plus gamma minus 1 by 2 M square raised to gamma by gamma minus 1 and P 0 7 by P e which is the exit static pressure is 1 plus gamma minus one by 2 M e square raise to gamma by gamma minus 1. So, what we see here is that we can from the above equations we can basically infer that P 0 7 by P e is equal to P 0a by P a.

Now, if that has to be true then we should have the exit Mach number, which is M e equal to the flight Mach number M. So, M e is equal to M, which is also equal to U e which is the exit velocity which is since Mach number is U e by a e we have U e is equal to a e by a which is speed of sound of at the exit divided by speed of sound of the ambient condition multiplied by U, which is the flight speed this is equal to square root of T e by T a multiplied by U and that is T 0 4 by T 0 2 multiplied by U. The exit velocity we have now, expressed in terms of stagnation temperature ratios T 0 4 by T 0 1 and the flight speed. So, exit velocity is now expressed as a function of these we will further simplify a little a later.

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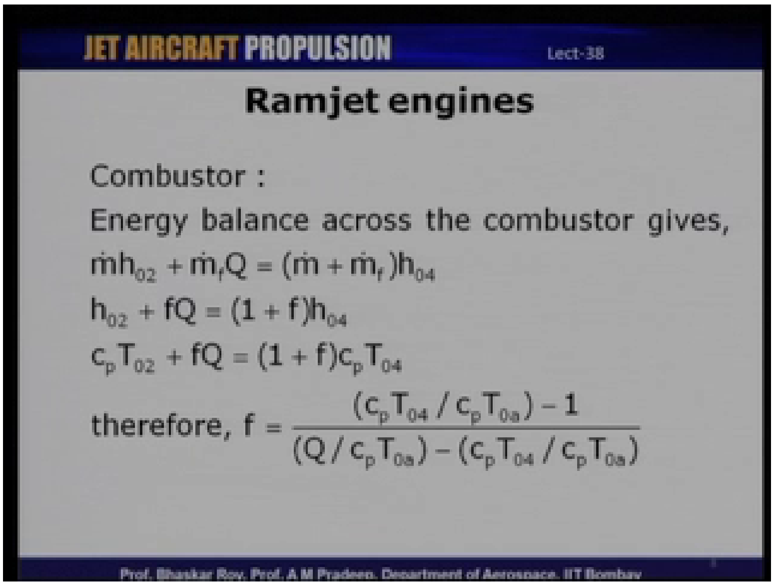

JET AIRCRAFT PROPULSION Lect-38

## Ramjet engines

Combustor :

Energy balance across the combustor gives,

$$\dot{m}h_{02} + \dot{m}_f Q = (\dot{m} + \dot{m}_f)h_{04}$$

$$h_{02} + fQ = (1 + f)h_{04}$$

$$c_pT_{02} + fQ = (1 + f)c_pT_{04}$$

therefore, $f = \dfrac{(c_pT_{04} / c_pT_{0a}) - 1}{(Q / c_pT_{0a}) - (c_pT_{04} / c_pT_{0a})}$

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We now, go to the combustion chamber or the combustor. So, in the combustor as we have done even in the other cycle analysis for the jet engines; the other forms of jet engines we basically carry out an energy balance across the combustion chamber. So, for the energy balance, we have the incoming air which is coming in at the from the after the compression process with a certain enthalpy then fuel is added with a certain enthalpy or heat of reaction. So, this sum of these two will be equal to what is going out of the combustion chamber that is the exit enthalpy. So, that from this we can actually find out what is the fuel to air ratio that is used or required for developing these temperatures or for developing these enthalpies.

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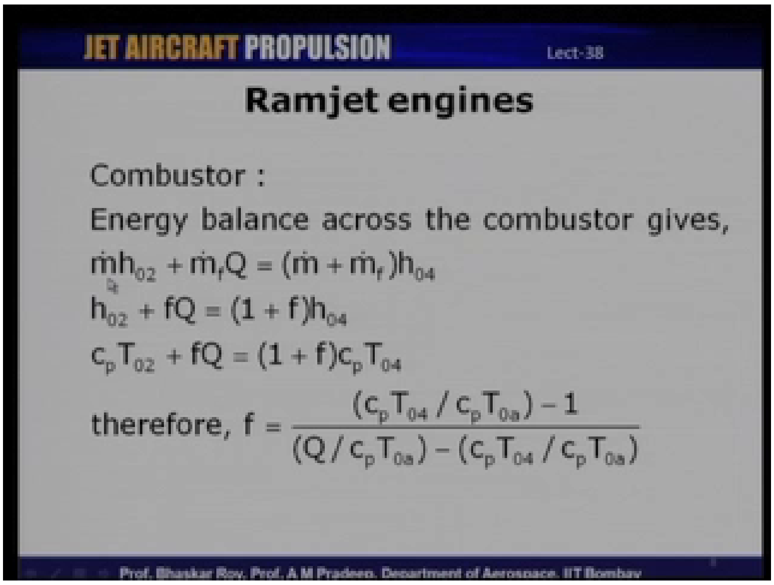

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## Ramjet engines

Combustor :

Energy balance across the combustor gives,

$\dot{m}h_{02} + \dot{m}_f Q = (\dot{m} + \dot{m}_f)h_{04}$

$h_{02} + fQ = (1 + f)h_{04}$

$c_pT_{02} + fQ = (1 + f)c_pT_{04}$

therefore, $f = \dfrac{(c_pT_{04} / c_pT_{0a}) - 1}{(Q / c_pT_{0a}) - (c_pT_{04} / c_pT_{0a})}$

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So, let us carry out the energy balance here for the combustor we have m dot which is mass flow rate of air multiplied by the enthalpy at the inlet that is h 0 2 plus m dot f which is the fuel flow rate multiplied by heat of reaction Q this is equal to m dot plus m dot f multiplied by h 0 4 which is the enthalpy at the exit of the combustion chamber. So, we simplify this we have h 02 plus f which is m dot f by m dot into Q, Q corresponds to the heat of reaction of the calorific value of the fuel that is used this is equal to 1 plus f into h 04. So, enthalpy we know is C p times the corresponding stagnation temperature therefore, C p into T 02 plus f into Q is one plus f C p T 04 this is again simplified in terms of f we have f is C p T 04 by C p T 0a is equal to or C p T 0a is also equal to T 02.

So, we have written it as T 0 a minus one divided by q by C p T 0a minus C p T 04 divided by C p T 0 a. So, here T 0a is also equal to T 02 because it is an isentropic compression there is no heat loss occurring in the intake. So, this is the energy balance for the combustor we get the fuel to air ratio from this energy balance.

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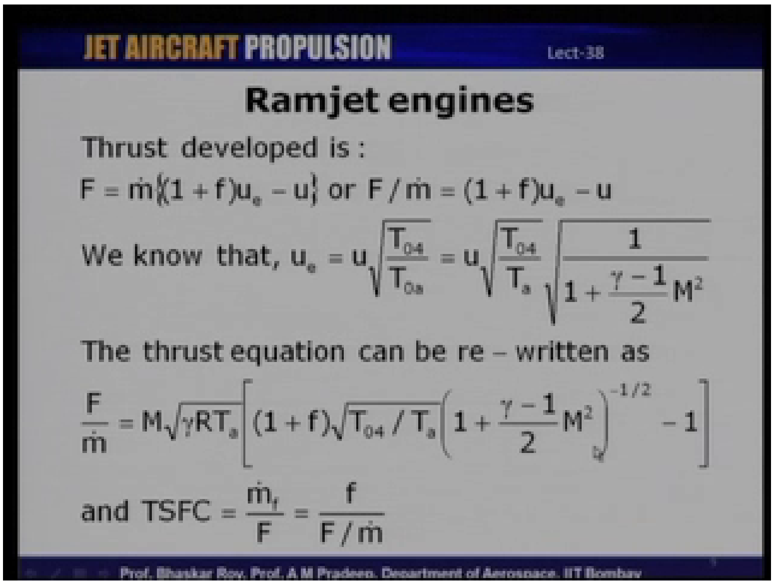

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## Ramjet engines

Thrust developed is :

$F = \dot{m}\{(1+f)u_e - u\}$ or $F/\dot{m} = (1+f)u_e - u$

We know that, $u_e = u\sqrt{\frac{T_{04}}{T_{0a}}} = u\sqrt{\frac{T_{04}}{T_a}}\sqrt{\frac{1}{1+\frac{\gamma-1}{2}M^2}}$

The thrust equation can be re – written as

$$\frac{F}{\dot{m}} = M\sqrt{\gamma R T_a}\left[(1+f)\sqrt{T_{04}/T_a}\left(1+\frac{\gamma-1}{2}M^2\right)^{-1/2} - 1\right]$$

and TSFC $= \frac{\dot{m}_f}{F} = \frac{f}{F/\dot{m}}$

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Now, we can calculate the thrust. So, the basic thrust equation as we have seen is m dot into 1 plus f into U e minus U plus of course, there is the pressure thrust term here we have already assumed that the static pressure exit is equal to ambient pressure, therefore P e is equal to P a and therefore, the pressure thrust term is 0. So, the thrust per mass flow or the specific thrust is F by m dot is 1 plus f into U e minus U. Let us express U e in terms of Mach number and temperature U e. we have already seen is u into square root of T 04 by T 0a, which is equal to U into square root of T 04 by T a square root of 1 by 1 plus gamma minus 1 by 2 M square.

Because T 0a by T a is 1 plus gamma minus 1 by 2 M square. So, we substitute this in the thrust equation and get a simplified expression for that and so if we simplify we can rewrite the thrust equation as F by M dot, which is the specific thrust is equal to Mach number M into square root of T gamma RT a this multiplied by 1 plus f into U e. we have just now rewritten and that is square root of T 04 by T a into 1 plus gamma minus one by 2 M square raised to minus 1 by 2 minus 1. The other expression that is U is what is written here as M into square root of gamma R T a. Similarly, once you find out thrust you can also find out the thrust to fuel or the thrust specific fuel consumption, which is the fuel flow rate fuel into air ratio divided by the specific thrust this gives you the T s thrust specific fuel consumption.

So, this is the basic cycle analysis, which we have done few times even in the earlier lectures we talked about cycle analysis for jet engines like turbo jets, turbo fans and all that. So, the same procedure was employed there, but there is a slight difference here in the cycle analysis procedure as compared to what we have done earlier on basically because at least for the ideal cycle we have here the exit Mach number is equal to the ambient Mach number. Therefore the corresponding simplifications in terms of the exit velocity in terms of the flight speed and that is how the thrust equation gets slightly modified and it is slightly different from what we have seen in our earlier analysis.

One of the reasons for that is the fact that most of the ram jets will have a conversion, diversion nozzle unlike in let us say a turbo fan engine where it could be simply a diverging nozzle. So, the flow could be chocking just at the nozzle exit. In a C-D nozzle also the flow could be chocking, but then the exit conditions are basically if it is a fully expanded nozzle then the exit static pressure and the ambient static pressure are equalized, the analysis will the cycle analysis procedure might be slightly different depending upon, what kind of an engine we are dealing with and also the flight conditions under which the particular engine is operating.

So, this the basic cycle analysis procedure for an ideal cycle, we are going to now slightly modify this analysis for a real cycle, where we are going to account for some of the losses that are likely to occur like the total pressure loss in the intake; in the combustion chamber and the nozzle some of these losses and the efficiency of the intake the efficiency of the combustion and nozzle. All these performance parameters will now be taken into account to derive the cycle analysis for a real ram jet. Subsequently, we will I will just show you one typical variation of thrust as well as specific fuel consumption with Mach number for a ram jet. So, we will discover a few interesting aspects, when we will take a look at those performance characteristics.

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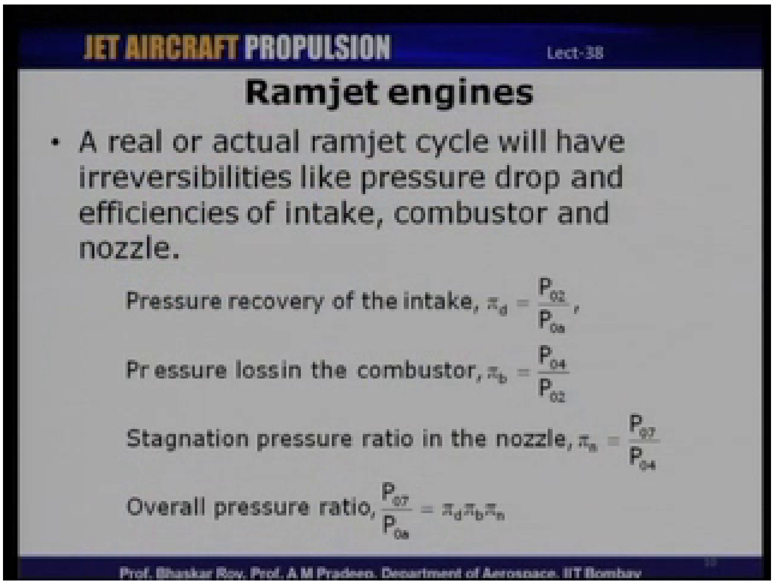

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Ramjet engines

- A real or actual ramjet cycle will have irreversibilities like pressure drop and efficiencies of intake, combustor and nozzle.

Pressure recovery of the intake, $\pi_d = \frac{P_{02}}{P_{0a}}$,

Pr essure lossin the combustor, $\pi_b = \frac{P_{04}}{P_{02}}$

Stagnation pressure ratio in the nozzle, $\pi_n = \frac{P_{07}}{P_{04}}$

Overall pressure ratio, $\frac{P_{07}}{P_{0a}} = \pi_d \pi_b \pi_n$

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So, let us proceed towards an actual ram jet; real ram jet. Real ram jet as I said will have all these irreversibility’s pressure drop efficiencies. One of the irreversibility will be the pressure recovery of the intake which is denoted by pi d that is P 02 by P 0a for an ideal cycle this was equal to 1. There could be pressure loss in the combustor which is pi b P 04 by P 02 you may also have stagnation pressure ratio in the nozzle which is the nozzle pressure ratio P 07 by P 04. So, the overall pressure ratio is basically the product of the three; P 07 by P 0a is pi d times pi b times pi n. Ideal cycle would have this ratio as equal to 1 in a real cycle it will not be 1 it will be less than 1.

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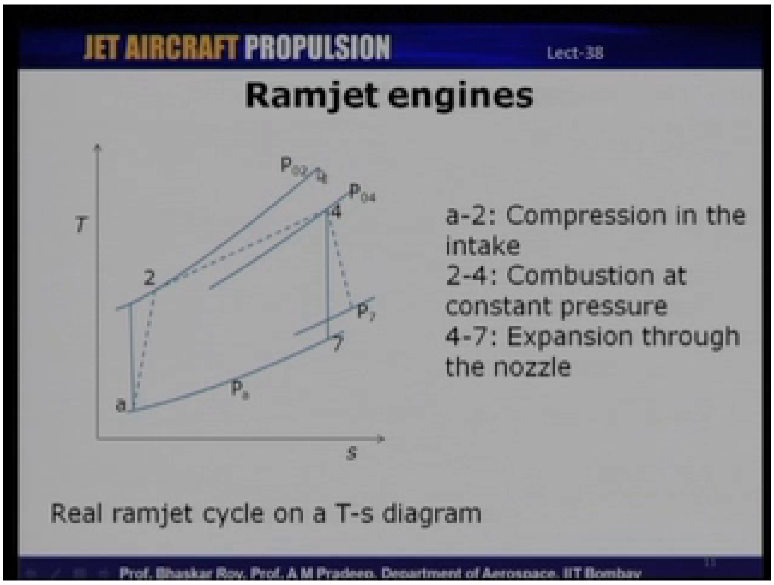

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Ramjet engines

a-2: Compression in the intake
2-4: Combustion at constant pressure
4-7: Expansion through the nozzle

Real ramjet cycle on a T-s diagram

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So, this is how a real cycle of a ram jet would look like a real ram jet would have irreversibility's in all the processes, if you take a look at the first process; which is the compression process you can see that there is a loss in or it is non-isentropic process eight to two is non-isentropic compression. The second process was a heat addition in the combustion chamber here of course, there is a pressure loss occurring you can see P 02 and P 04 are not the same where as for an ideal cycle they were the same pressures it was constant pressure combustion, here it is no longer constant pressure.

The third process is the nozzle expansion process, which is again non-isentropic. So, you can that this process is also non-isentropic that is process between four and seven is non-isentropic one may also have a difference in the pressures the nozzle may not be fully expanded, which is why one may have a difference between these two pressure P 7 and P a may not be the same, which was not true for the ideal cycle where both these pressures where the same.

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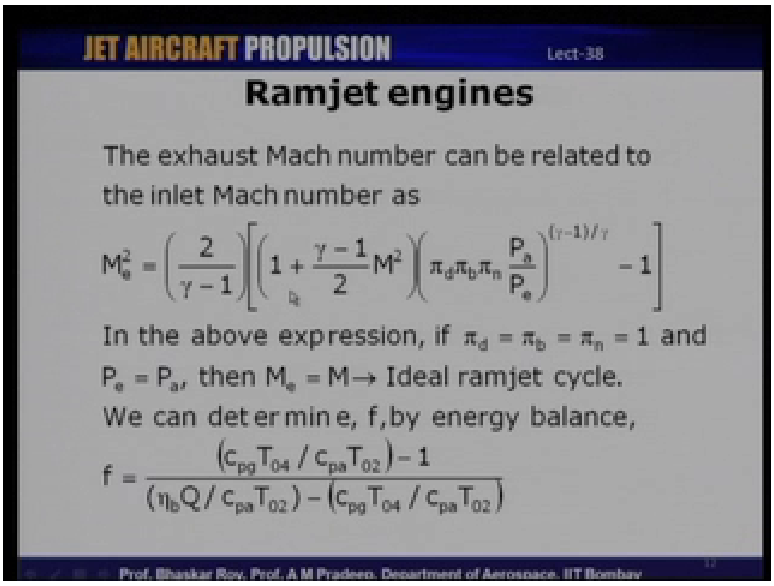

JET AIRCRAFT PROPULSION Lect-38

## Ramjet engines

The exhaust Mach number can be related to the inlet Mach number as

$$M_e^2 = \left(\frac{2}{\gamma-1}\right)\left[\left(1+\frac{\gamma-1}{2}M^2\right)\left(\pi_d\pi_b\pi_n\frac{P_a}{P_e}\right)^{(\gamma-1)/\gamma}-1\right]$$

In the above expression, if $\pi_d = \pi_b = \pi_n = 1$ and $P_e = P_a$, then $M_e = M \rightarrow$ Ideal ramjet cycle.

We can determine, f, by energy balance,

$$f = \frac{\left(c_{pg}T_{04}/c_{pa}T_{02}\right)-1}{\left(\eta_b Q/c_{pa}T_{02}\right)-\left(c_{pg}T_{04}/c_{pa}T_{02}\right)}$$

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So, this is how real ram jet cycle would look like now let us go to the cycle analysis of this. So, the exhaust Mach number we are going to relate it to the inlet Mach number with this expression that is n e square the exit Mach number is two by gamma minus one multiplied by one plus gamma minus 1 by 2 M square this multiplied by the pressure ratio that is pi d pi b pi n and P a by P e this raised to gamma minus 1 by gamma minus 1. So, if in this expression we equate this that is expression that is if the pressures ratios were equal to one pi d pi b pi n are equal to one and P a and P e are the same then what would we get we basically would get the fact that these Mach numbers M e is equal to M.

So, if M e is equal to M then this means that it is an ideal ram jet cycle like we have discussed earlier for a actual ram jet the exit Mach number is not going to be equal to the flight Mach number there would be a slight difference between the flight Mach number and the exit Mach number, which is not the case in this case which would happen only if these parameters that is pi d pi b pi n were same and equal to 1 and P e is equal P a. So, the second aspect is the fuel to air ratio fuel to air ratio, we basically calculate by energy balance like we did for the ideal cycle the same energy balance is valid here except the fact that in this case we also have an efficiency of the combustion associated with the fuel addition.

So, the air that is coming in has a certain enthalpy. So, mass flow rate multiplied by h 02 plus the fuel that is added that is M dot f into Q which is the heat of reaction of the fuel, but this has a certain efficiency that the combustion efficiency. So, that multiplied by eta b which is the combustion efficiency the sum of these two will be equal to what is going out of the combustion chamber. The total mass flow mass flow rate of air plus mass flow rate of fuel multiplied by the enthalpy at station 4, if you do the energy balance we should be able to find out the fuel to air ratio the only difference between what is happening in an ideal cycle and real cycle is that here there is an efficiency of combustion coming in.

So, if you look at: the expression for the fuel to air ratio it is exactly the same except for a slight difference in an actual of course, cycle we will also be taking into account the variation of specific heat with temperature. So, you can notice that there is specific heat difference here for combustion products. We will associate a specific heat, which is let us say C p g this multiplied by T 04 divided by C p air multiplied by T 02 minus 1 divided by eta b which is the combustion efficiency into Q divided by C p eight T 02 minus the other product that is C p g into T 04 divided by C p a T 02.

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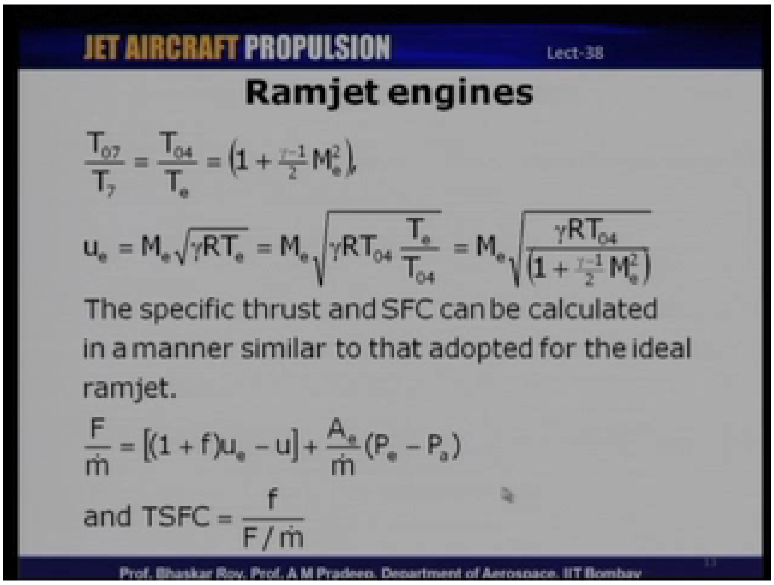

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Ramjet engines

$$\frac{T_{07}}{T_7} = \frac{T_{04}}{T_e} = \left(1 + \frac{\gamma-1}{2} M_e^2\right),$$

$$u_e = M_e\sqrt{\gamma R T_e} = M_e\sqrt{\gamma R T_{04}\frac{T_e}{T_{04}}} = M_e\sqrt{\frac{\gamma R T_{04}}{\left(1 + \frac{\gamma-1}{2} M_e^2\right)}}$$

The specific thrust and SFC can be calculated in a manner similar to that adopted for the ideal ramjet.

$$\frac{F}{\dot{m}} = \left[(1+f)u_e - u\right] + \frac{A_e}{\dot{m}}(P_e - P_a)$$

$$\text{and TSFC} = \frac{f}{F/\dot{m}}$$

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So, this is the fuel to air ratio as applied for a real cycle now we also know that the temperature ratios T 07 by T 07 is equal to T 0e by or T 04 by T e because there is no again we can assume that there is no loss of stagnation temperature in the nozzle that is true even for a real cycle this is equal to one plus gamma minus 1 by 2 M e square. Now, the exit velocity u e is also related to the Mach number M e times square root of gamma R T e this we can simplify and how do we simplify that we can simplify that by adding or expressing T e in terms of the temperature ratios. So, we have M e into square root of gamma R T 04 multiplied by T e by T 04 which is basically expressed in terms of the Mach number. So, M e square root of gamma R T 04 divided by 1 plus gamma minus 1 by 2 M e squared.

So, based on this expression for the exit velocity where we have expressed exit velocity in terms of the stagnation temperatures and the Mach number we can now proceed to calculate the specific thrust which we have formula for specific thrust does not change it remains the same. So, specific thrust is basically a hum one plus f into U e minus u plus area divided by m dot into the pressure ratio that is pressure difference P minus P a. So, U e you can calculate based on what we have just now derived and once you substitute that expression for u e there you get an expression for e specific thrust and therefore, one can find the specific thrust and there enhance the fuel consumption that is TSFC thrust specific fuel consumption.

I am not written down the expression for specific thrust because that is that will be become a pretty lengthy expression, if you were to substitute for the equation for u e it becomes rather complicated. So, the procedure is still the same as what we have followed even in the past. The thrust can be expressed will basically thrust specific thrust is one plus f into u e minus u plus a e minus u plus a e by m dot into P e minus P a. So, if you substitute for U e here and also express U in terms of the Mach number and temperature one can express the specific thrust in terms of non parameters.

Thrust T S F C is basically; the fuel to air ratio divided by the specific thrust. So, this is the basic procedure for calculating or carrying out a cycle analysis a real cycle analysis which is as you have seen very identical to the ideal cycle analysis as well, but we have the performance parameters which have been included in this particular cycle analysis. So, what we will see next is that if let us say we have these performance parameter known and we were to calculate or determine the performance of a ram jet in terms of the thrust and the fuel consumption with Mach number then we will see how the performance is going to vary what happens as Mach number changes and how the performance of a typical ram jet is likely to vary.

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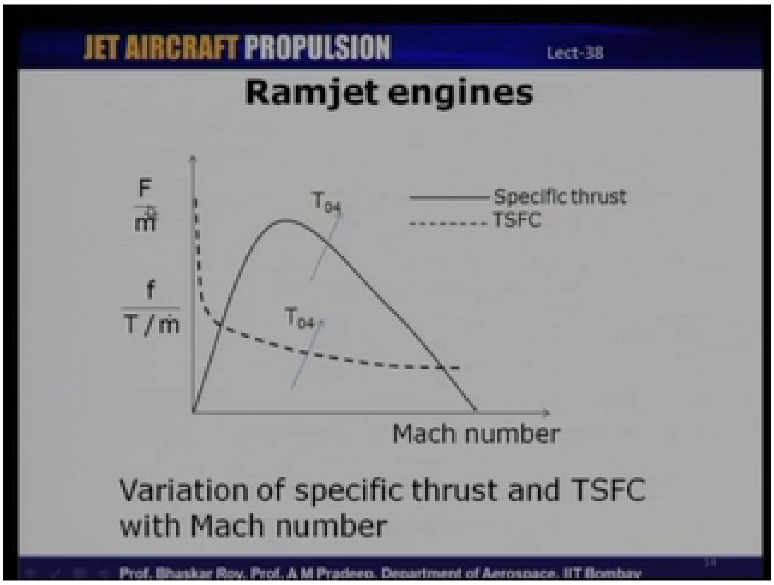

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Lect-38

Ramjet engines

Variation of specific thrust and TSFC with Mach number

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We will take a look at that and how basically the performance changes as we change the combustion temperature, that is T 04 with increasing combustion temperature what happens to the performance of a ram jet. So, what I have plotted here is rather simplistic expression or view of what really happens as the performance changes with Mach number. So, on one axis we have, that is the y axis we have the specific thrust as well as the fuel consumption that is in terms of TSFC, and the x axis is let us say Mach number. So, the solid line that is shown here is the specific thrust and the dotted line is the TSFC. So, for a typical Mach number the performance is going to vary like this, where it is initially 0 and why should it be 0, for a ram jet as we have seen is an engine which cannot really generate a static thrust. So, for 0 Mach number very low Mach numbers the thrust developed the ram jet is 0.

So, there is no thrust developed at low very low Mach numbers or zero Mach numbers, it cannot generate any static thrust, which is why an aircraft cannot really take off with a ram jet on its own. So, with increasing Mach number you can see the performance the thrust developed by the ram jet increases, but it reaches a certain peak and this peak is usually around Mach number of 3 to 4 it somewhere between 3 and 4 after which again the performance droops and at a certain Mach number which is a very high Mach number it will eventually becomes zero. Now, the reason for this drop in performance after certain after the peaking performance is because of the fact that in a ram jet we are decelerating the flow from supersonic Mach numbers to sub sonic Mach numbers combustion in a ram jet occurs at sub sonic speeds.

Therefore, if you have if you have noticed as you decelerate the flow across from very high Mach numbers to very low Mach numbers. The stagnation pressure loss becomes substantial, which is why after a certain peak the thrust developed by the engine starts dropping, because the stagnation pressure loss across the intake across all the shocks wills start dropping and it becomes significant that very high Mach numbers start the thrust development eventually becomes very, very low. This is the reason, why beyond a certain Mach number ram jets are not really efficient anymore and one would need to go for an engine, which can actually afford to have supersonic speeds in the combustion chamber. That is why; we have scram jet engines where combustion occurs at supersonic speeds and in a scram jet engine one would not decelerate the flow to sub sonic speeds the flow continues to remain supersonic and therefore, scram jets are supposed to operate efficiently even at very high Mach numbers.

So, this is how the specific thrust is likely to vary for a typical ram jet with increasing combustion temperature, which T 04 the graph that is shown here the trend is going to go up that is it will generate higher specific thrust. The other performance curve that is shown here is for TSFC. You can see that TSFC initially could be very high that is basically because the thrust is very, very low. It is close to zero. So, the TSFC will drop as the performance as the thrust increases as the thrust peaks and reaches its maximum that is when one would likely to have a very low value of TSFC and then it continues to remain very low after that. Again with increasing combustion temperature the T S graph also would shift upward, because you would not need higher fuel to generate higher and higher temperatures and that is why this curve is likely to move up.

Now, if you were to carry out a cycle analysis for a real cycle as well as for an ideal cycle, what you will observe is that both the cycle analysis will give you very similar results in the sense that the trend would be exactly the same Just that the graph would be displaced slightly for an ideal for a real cycle. The thrust would be slightly lower than what it is for an ideal cycle and fuel consumption is likely to be slightly higher than what it is for an ideal cycle that is because of the fact; that real cycle one would have all the performance parameters put in like the pressure losses and efficiency.

For a real cycle one would actually get slightly lower thrust than what is predicted by an analysis. The other hand: you would also end up spending little more fuel because of all the losses that are taking place than what it is predicted by an ideal cycle analysis, but the trends remain identical. What you have seen. So, far is the ram jet cycle it is performance for an idealized version of the cycle; ideal cycle as well as the performance of a ram jet when you put in all these parameters like pressure losses efficiency and we have also seen how the performance would change, as one changes the Mach number that is there is a certain Mach number, at which the performance of the ram jet becomes or the thrust developed by the ram jet reaches the peak.

Beyond which the thrust, eventually drops and becomes zero and which is why we have seen that ram jets cannot really operate at very, very high Mach numbers because of the fact that the flow has to be decelerated to sub sonic speeds in the combustion chamber of a ram jet. So, if you can maintain supersonic combustion supersonic speeds then you are likely to be able to operate at very high Mach numbers and that is how a scram jet engine was devised and scram jets have supersonic combustion in the combustion chamber. So, for very high Mach number applications like beyond Mach five. So, scram jets have to be used ram jets cannot really generate thrust for operation at these speeds.

So, we will now move on to our discussion on pulse jets. You have already had some discussion on pulse jets in the last class, where you have looked at the performance of a pulse jet while the operation of a pulse jet and how pulse jets basically generate thrust. So, today we will take a look at the thermodynamic aspect of a pulse jet we will look at a cycle of a pulse jet and also see how we can carry out a cycle analysis for an ideal pulse jet and a real pulse jet and then see how performance of a pulse jet can be measured or calculated based on the cycle analysis.

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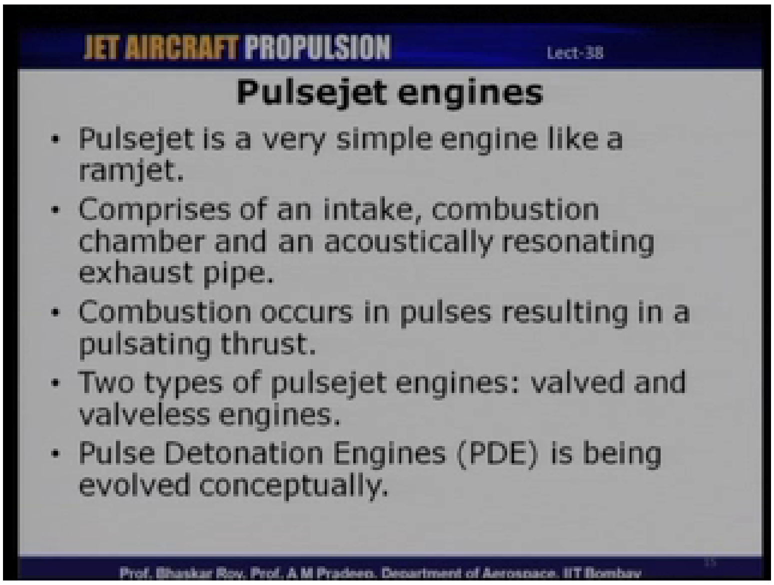

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## Pulsejet engines

- Pulsejet is a very simple engine like a ramjet.
- Comprises of an intake, combustion chamber and an acoustically resonating exhaust pipe.
- Combustion occurs in pulses resulting in a pulsating thrust.
- Two types of pulsejet engines: valved and valveless engines.
- Pulse Detonation Engines (PDE) is being evolved conceptually.

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Now, pulse jet as you have seen earlier and something that I discussed in the initial part of today’s class is a very simple engine like a ram jet. Pulse jet, basically consist of again very few components there are no rotating components; pulse jets comprise of an intake a combustion chamber and an acoustically resonating exhaust pipe. You have seen how a pulse jets works in the last class and here the combustion occurs in pulses and the thrust that is developed also is pulsating because the combustion itself is occurring in pulses and that is why it is called a pulse jet.

There are two basic types of pulse jet engines: the valve type and valve less type, which I think we will discuss in little more detail in the next class. There are also another class of engines, which are being developed at least conceptually that is known as pulse detonation engine and these engines are for certain specialized applications some of which we will discuss in the next class.

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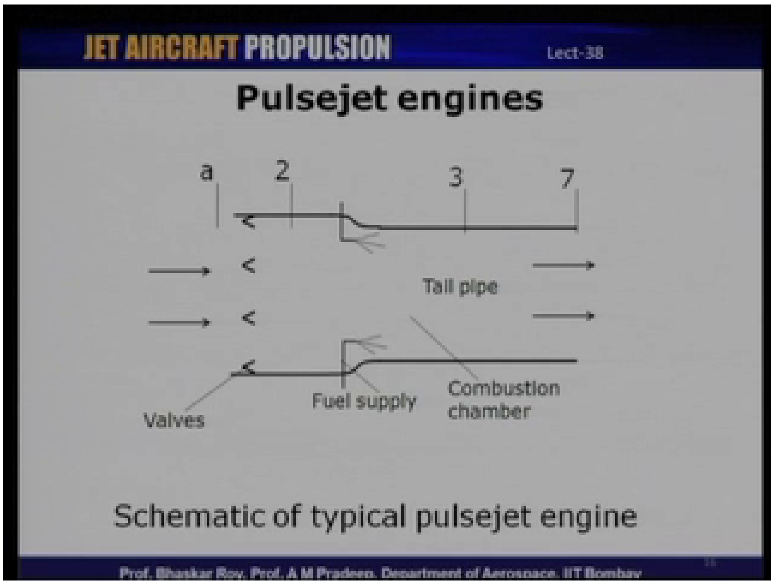
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Pulsejet engines

Schematic of typical pulsejet engine

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So, let us now take a look at: the thermodynamic cycle of a pulse jet. Now, this is a typical pulse jet a schematic of a pulse jet and what the different components which constitute a pulse jet. So, a pulse jet has an intake section and then there is a valve series of valves, which are operated based on the cycle on the cycle itself and downstream of the valve. We will denote by the station number two and then fuel is added in the tail pipe just before well just before the tail pipe in the combustion chamber and then the combustion products are exhausted through the tail pipe.

So, the thrust developed by a pulse jet is basically occurring when the valves are closed and fuel is added in the combustion chamber. There is a certain instant of time, when it fuel addition or heat addition occurs in a volume mode and then that is when the combustion products are exhausted through the tail pipe leading to a certain thrust and then the cycle is of course, repeated to achieve thrust in a certain pulsating manner.

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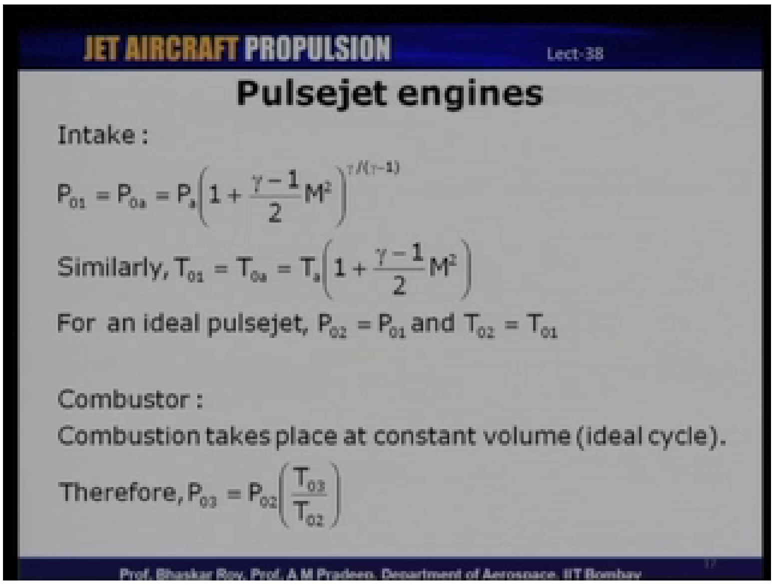

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Lect-38

## Pulsejet engines

Intake :

$P_{01} = P_{0a} = P_a\left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/(\gamma-1)}$

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

For an ideal pulsejet, $P_{02} = P_{01}$ and $T_{02} = T_{01}$

Combustor :

Combustion takes place at constant volume (ideal cycle).

Therefore, $P_{03} = P_{02}\left(\frac{T_{03}}{T_{02}}\right)$

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So, thermodynamically we will take a look at: how the cycle analysis well cycle of a pulse jet would look like well pulse jet as I said will consist of an intake and an intake is where part of the intake you can see was constituting a of these valves that we have seen just now and inside the valves operate in sequences that is in certain part of the combustion process; that is occurring the valves are closed; that is when the fuel is added in the pulse jet and when fuel is added it fuel is added at constant volume here and as fuel is added. There the combustion products are eventually exhausted through the tail pipe and in the next cycle, again the valves are open air is drawn in through the intake and the cycle is repeated.

So, in the intake we basically for the ideal cycle of a pulse jet we are going to assume that the stagnation there is no stagnation pressure loss in the intake part of the pulse jet P 0 1 will be equal P 0a. So, that is what you see here P 01 is equal to P 0a and that is the static pressure ambient static pressure multiplied by one plus gamma minus1 by 2 M square raised to gamma by gamma minus 1. This is basically from the isentropic relation. For an ideal pulse jet, we are going to assume that this is an isentropic process. Now, for the similarly, the temperatures can be expressed the temperature stagnation temperature is going to be the same T 01 is equal to T 0a, which is T a multiplied by 1 plus gamma minus 1 by 2 M square.

Then for an ideal pulse jet: We are going to again assume that P 01 there are no losses across the valves P 02 is equal to P 01 and T 02 is equal to T 01 and combustion as I said occurs at constant volume because it is an ideal cycle. So, an ideal cycle where in the constant volume process. So, at the exit of the combustion chamber we have P 03 equal to P 02 multiplied by T 03 by T 02, because it is constant volume. So, from the state equation we have P 03 related to P 02 and the temperature ratios.

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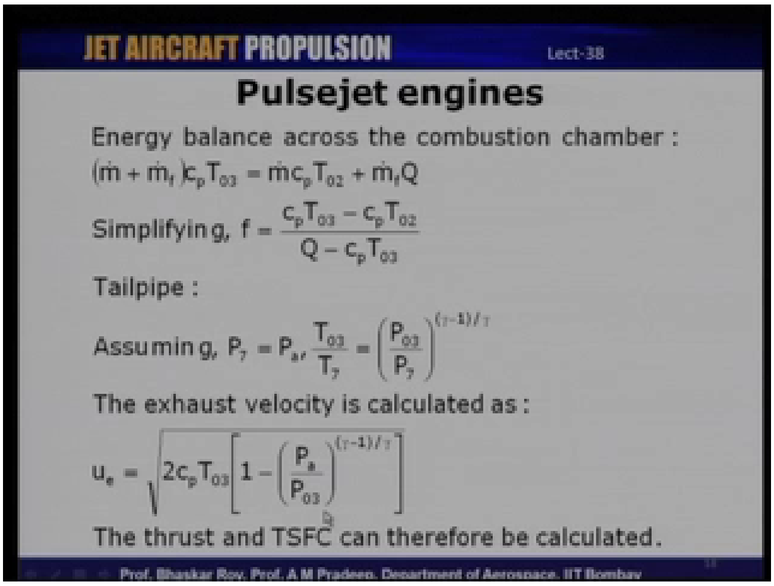

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## Pulsejet engines

Energy balance across the combustion chamber :

$$(\dot{m} + \dot{m}_f)c_pT_{03} = \dot{m}c_pT_{02} + \dot{m}_fQ$$

Simplifying, $f = \frac{c_pT_{03} - c_pT_{02}}{Q - c_pT_{03}}$

Tailpipe :

Assuming, $P_7 = P_a$, $\frac{T_{03}}{T_7} = \left(\frac{P_{03}}{P_7}\right)^{(\gamma-1)/\gamma}$

The exhaust velocity is calculated as :

$$u_e = \sqrt{2c_pT_{03}\left[1 - \left(\frac{P_a}{P_{03}}\right)^{(\gamma-1)/\gamma}\right]}$$

The thrust and TSFC can therefore be calculated.

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Now, in the combustion chamber we can also have the energy balance. We have done this a few time earlier already so this is the enthalpy of the stream exiting the combustion chamber, which is m dot plus m dot f into C p into T 03 this is equal to m dot into C p into T 02 the incoming enthalpy plus the fuel flow rate, if you simplify this we get f, which is the fuel to air ratio that is C p T 03 minus C p T 02 divided by Q minus C p T 03. Now, in the tail pipe we will assume P 7, which is the exit static pressure is equal to the ambient static pressure and T 03 by T 7 is T 03, P 03 by P 7 raised to gamma minus 1 by gamma.

The exit velocity can be calculated from again the enthalpy balance across the tail pipe we get U e which is the exit velocity is equal to square root of two C p T 03 multiplied by1 minus P a by P 03 raised to gamma minus 1 by gamma. So, once we calculate the exit velocity, you can also calculate the thrust and specific fuel consumption. Thrust will be and TSFC, basically are related to 1 plus f into U e minus U plus the pressure thrust term in an ideal cycle we will; obviously, assume pressure thrust to be 0. So, once you calculate U e you can calculate thrust and also the specific fuel consumption.

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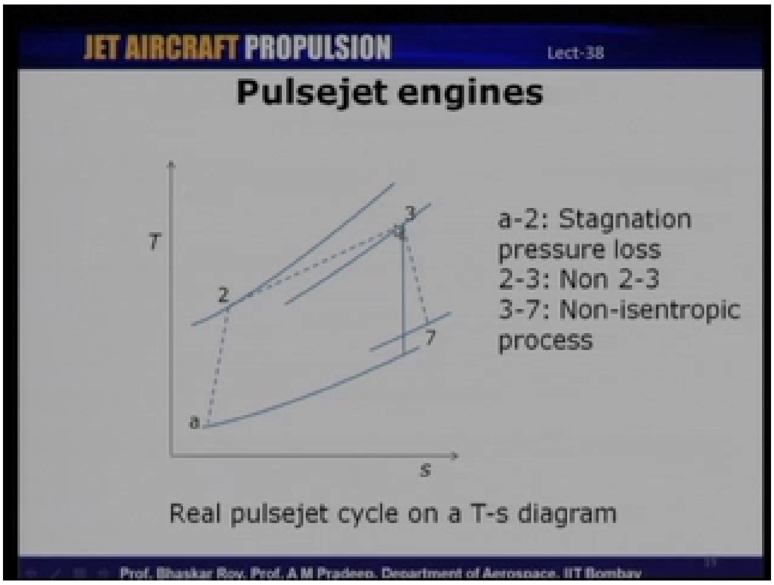

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Pulsejet engines

a-2: Stagnation pressure loss
2-3: Non 2-3
3-7: Non-isentropic process

Real pulsejet cycle on a T-s diagram

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So, this is the basic cycle analysis for an ideal pulse jet ,we will now take a look at: how a real pulse jet would be operating in very brief, we will not going to do the analysis in detail, because we have already done this for ram jets and several other cycles the process is very much the same. So, in a real pulse jet engine where we are going to corporate all the irreversibility this how a real pulse jet cycle would look like. The first process is again it was always non-isentropic even in the ideal cycle. In this cycle, we are going to assume the stagnation pressure loss is occurring between process a and 2 the second process is in the ideal cycle. It was a constant volume process, here in a real cycle there going to be certain amount of pressure losses taking place, it may not be any more a constant volume process; it could be a non-isochoric process.

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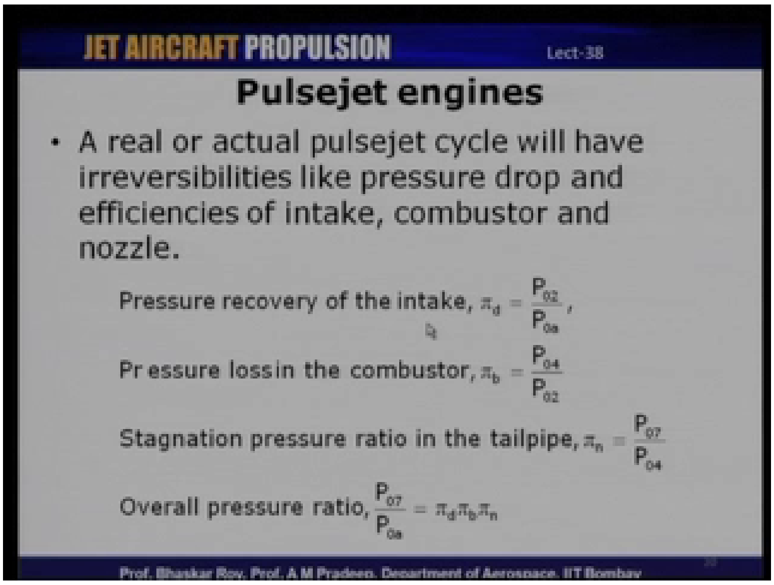

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## Pulsejet engines

- A real or actual pulsejet cycle will have irreversibilities like pressure drop and efficiencies of intake, combustor and nozzle.

Pressure recovery of the intake, $\pi_d = \frac{P_{02}}{P_{0a}}$,

Pressure lossin the combustor, $\pi_b = \frac{P_{04}}{P_{02}}$

Stagnation pressure ratio in the tailpipe, $\pi_n = \frac{P_{07}}{P_{04}}$

Overall pressure ratio, $\frac{P_{07}}{P_{0a}} = \pi_d \pi_b \pi_n$

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The expansion in the tail pipe is again non-isentropic as compared to the ideal cycle, where it was indeed isentropic. So, this is a real pulse jet cycle expressed on a T S diagram and how does it differ from the ideal cycle. Well, there are pressure losses in the diffuser given by P 02 by P 0a in the combustion chamber and the tail pipe and therefore, there is an overall pressure ratio, which in an ideal cycle was equal to 1.

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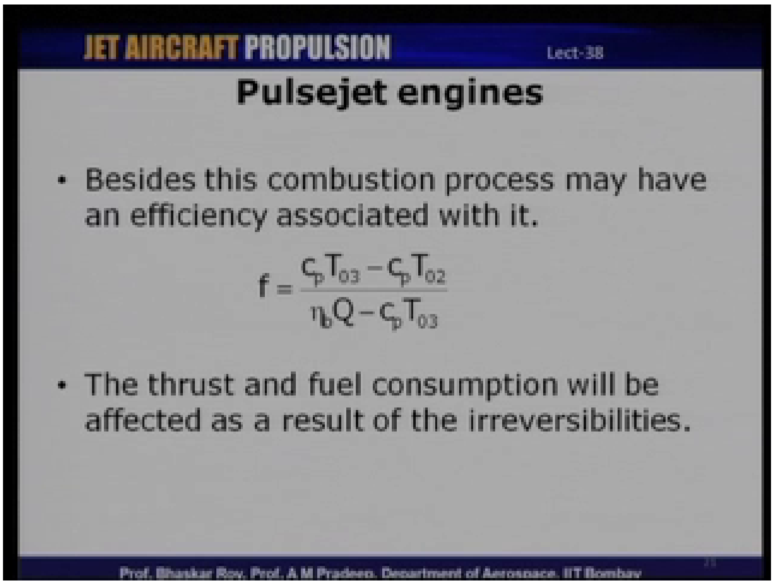

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## Pulsejet engines

- Besides this combustion process may have an efficiency associated with it.

$$f = \frac{c_p T_{03} - c_p T_{02}}{\eta_b Q - c_p T_{03}}$$

- The thrust and fuel consumption will be affected as a result of the irreversibilities.

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The other difference is that in the combustion chamber, we are going to assume efficiency for the combustion products. So, C p into T 03 minus C p T 02 divided by combustion efficiency into Q minus C p T 0 3. So, these are the irreversibilities, which will need to be considered in an actual pulse jet cycle, which was very similar to what it was in the case of an ideal well; an actual ram jet cycle as well in a pulse jet engine. The other difference or efficiency that might come into picture is the operation of the valves. And so there is certain efficiency associated with that process, because it is a mechanical entity there would be a certain efficiency that needs to be considered for these. As well, so considering all these efficiencies and performance parameters one can have an actual pulse jet cycle, which is slightly different from the idealized version of the ideal pulse jet cycle.

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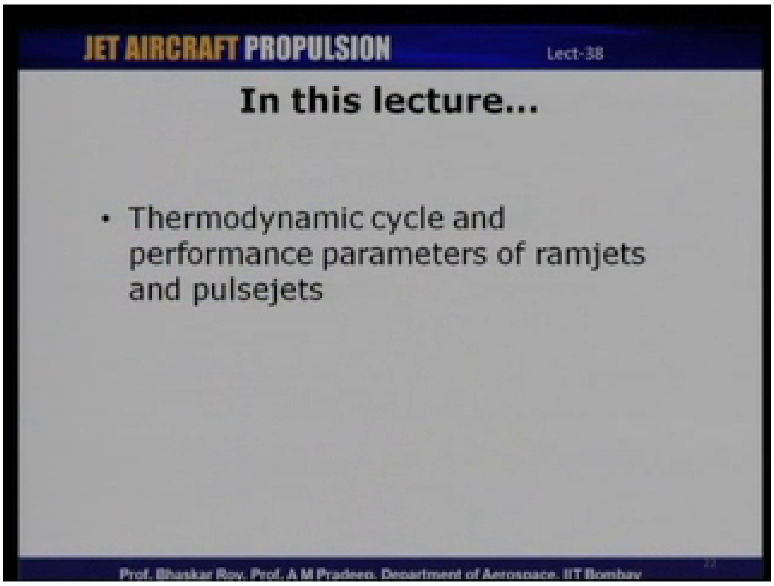

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In this lecture…

- Thermodynamic cycle and performance parameters of ramjets and pulsejets

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So, with this let me quickly recap what we had discussed in today's class in today's class. We had basically looked at thermodynamic cycle and performance parameters of ram jets and pulse jets. We started today's discussion with ram jets, we had a look at: the ideal ram jet cycle the thermodynamic cycle of a ram jet and then we also looked at real ram jet cycle and how we can incorporate performance of different components of ram jet like intake combustion chamber and nozzle incorporate that in the cycle analysis and get the actual performance of a ram jet. We have also looked at: how performance would vary with Mach number for a ram jet and why performance of a ram jet peaks at a certain Mach number and does not perform well at very low Mach numbers and very high Mach numbers.

Then we then discussed in brief about the pulse jet engines. we have looked at their ideal cycle, and also the real cycle which constitute a pulse jet. And also in brief, we have looked at how performance can be analyzed for ideal as well as real pulse jet engines. We will continue this discussion in the next class, we will take a look at some of the components, which constitute the ram jets and pulse jet. We look at the intakes combustion chambers, and also the tail pipe and nozzles which constitute ram jets and pulse jets. So, we will take up some of these topics for discussion during the next lecture.