POWER PLANT SYSTEM ENGINEERING

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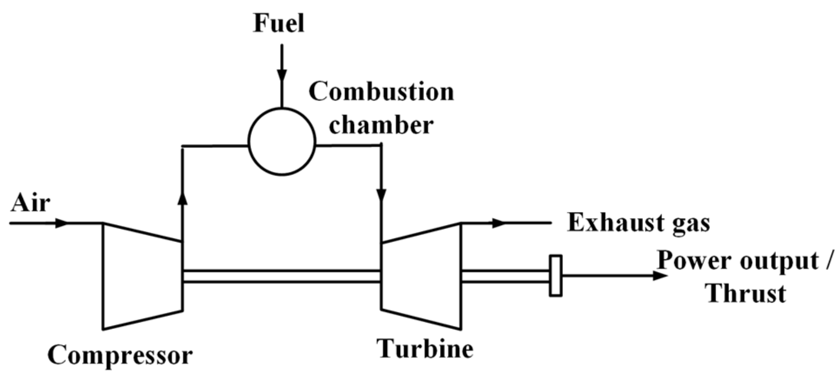
Module 3

Lec 4: Gas Turbines for Aircraft Propulsion

Dear learners, greetings from IIT, Guwahati. We are in the MOOCs course Power Plant System Engineering module 3 that is Gas Turbines and Combined Power System. So, in the last lecture of this module, we will try to emphasize the importance of gas turbine as a propulsion device. So, till the last lecture, we have been giving emphasis on the gas turbine engine as a power production device. In this lecture, we will try to see that how gas turbine can be used as a propulsion device. Although this is not the part of this course, but as a continuation of gas turbine systems, it is felt that we should give some emphasis on the gas turbine applications as a propulsion device.

So, in this lecture, I will briefly introduce this gas turbine cycle as aircraft propulsion cycle. In addition to that, I will try to demonstrate a simple turbojet engine in which gas turbine concepts are introduced and through this process, we will see how the thermodynamic concepts will help us for the gas turbine engines as a thrust generating device. Then we will also introduce some of the aircraft engines, in fact, that are also driven by this gas turbine engines.

So, if you look at the basic cycle of gas turbine system, we have like a compressor, turbine combustion chamber. Air is fed into the compressor and after compression high pressure air, whose temperature also increases to some extent, enters to the combustion chamber in which fuel is added. So, this is the heat addition process and then after combustion chamber, the gaseous products expands in the turbine. And we can use this exhaust gas to generate this thrust. But for the conventional turbine, as this turbine is meant for power production that is why it is coupled to generator and side by side it is coupled to compressor. So, these are power production devices, but that same kind of components cannot be used for thrust generation.



So, you require some kind of modifications and that modification is called as an aircraft propulsion cycle. So, this particular cycle which is shown in this figure, is called as a shaft power cycle and this is something like static power plants, gas turbine plants typically used in marine engines, combined cycle power plant all these things. And for aircraft propulsion cycle, we expect that it should give the thrust and it should give you the forward speed and altitude dependent. So, some modification is needed to be done for this conventional gas turbine cycle to be used for propulsion devices. However, we have seen many kind of modifications in the shaft power cycle like multistage compression, expansion, heat exchange, reheat, intercooling. So, these are kind of improvements in production of power and efficiency. But our main attention in this lecture would be how gas turbine cycles are used as a propulsion device. So, let us try to understand the very basic concepts that here same Brayton cycles is modified in two forms. So, we have two concepts here, one is called jet engine concept, other is called propeller engine concept.

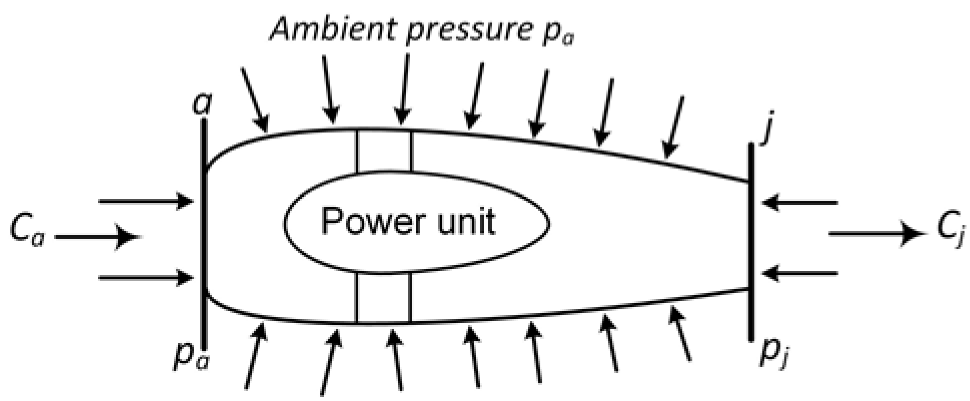
So, in a jet engine what happens? Air comes to the compressor, it is compressed and in the combustion chamber you add fuel. So, we get the combustion product at state 3 and it expands and after expansion you just do two things. One is in the turbine whatever power is being developed that is to be used by the compressors and we can feed the expanded gas to the nozzle and this nozzle after expansion it will give you the thrust. So here the Newton's third law of motion comes into picture that is for every action there is an equal and opposite reaction. So, when the exhaust comes back at the state 5 and if this entire gas turbine system is taken as a single system, so aircraft velocity we can get in the opposite direction. So, we get the thrust in the reverse direction.

So, here the changes that we can see is that compressor process remains as it is, but expansion is done in two stage, one is from turbine expansion, other is through the nozzle. And this is shown as 3- 4 is the expansion the turbine and 4- 5 is the expansion in the nozzle. But only difference is that now turbine expansion gives you power, expansion in the nozzle gives you thrust. This is one concept.

And the propeller engine concept is also similar. Here we do not have a nozzle rather exhaust goes out and through that exhaust we get some thrust. Side by side we have a propeller which is driven by this turbine. So, essentially turbine plays the dual role. Some bare minimum thrust is achieved due to the exhaust velocity, other than that the primary thrust is being achieved through the propeller and the power is supplied from turbine as well as from the propeller to compressor. So, we do not have a two stage expansion, we do not have a nozzle here rather single stage expansion in the turbine solve the purpose. But they have their own limitations and application. At lower speed < 200 m/s, combination of propeller and exhaust gas provide propulsive efficiency & we call this as a turboprop engine or propeller engine. At very high subsonic speed maybe > 280 m/s, we have another device called as turbofan or bypass engine. We will talk about that later. But actually the jet engine which is called as a turbojet engines, somewhere falls between a turboprop engine and turbofan engine. So, in a turbojet engine, we have a turbine that produces enough power to drive the compressors and gas leaving from the turbine at high pressure and temperature and is expanded to atmospheric pressure in a propelling nozzle.

Another engine that we have is turbo shaft engine. These are normally used in helicopters. But very basic difference is that we do not have provisions for heat exchanger in aircraft propulsion systems. Because these units make the system very bulky and add more weight which is normally not expected for aircraft engines. Rather propelling nozzles and propellers are integral part of gas turbine engine. So, our main focus would be on these two kinds; nozzles, diffusers. These devices are more appropriate for gas turbine applications.

So, let us try to consider very simple classical example, just to demonstrate Newton's law of motion. First thing is that rate of change of momentum is the force. So, that means, entire thrust is being generated from the rate of change of momentum for the gas. Then another law says that for every action there is equal and opposite reaction. The power unit in this figure is your gas turbine cycle which supplies necessary power to the aircraft. So, we call this schematic diagram, a propulsive duct in which air enters at certain velocity, which is equal and opposite to the forward speed of the aircraft.



So, in this case if you take this entire unit as a single entity we see that air enters to the duct at a velocity C_a. We call this as intake air velocity. And combustion products leaves at velocity C_j which is called as exit jet velocity. So, we have two velocities, one is air velocity other is jet velocity. So, mC_a stands as intake momentum or drag and drag means it is the force that being experienced by this duct.

Net thrust, $F = m(C_j - C_a) + A_j(p_j - p_a)$;

A_j:Jet exit area; C_a:Intake air velocity C_j:Exit jet velocity;

mC_a:Intake momentum drag; mC_j:Gross momentum thrust

Then mC_j is the gross momentum thrust that means the exit jet that gives the thrust. So, resultant thrust becomes Momentum thrust=$m(C_j - C_a)$.

There is another thrust that comes due to the pressure difference. So, essentially the aircrafts are flying at very high altitude, where pressure is less and side by side there is also a pressure difference on the surface. So, there is significant difference between the ambient pressure and the pressure on the surface of the aircraft. So there is another thrust add to the fact, we call it as pressure thrust. Pressure thrust=$A_j(p_j - p_a)$

So, these two thrust necessarily gives the total thrust to the vehicle. However at lower speed the pressure thrust is not significant. So normally it is the momentum thrust acting, hence Net thrust, $F = m(C_j - C_a)$.

Now putting this net thrust, we define the propulsive efficiency which is defined as the ratio of useful propulsive energy to the sum of the propulsive energy and unused kinetic energy. Essentially speaking when air enters, it has a kinetic energy and when air leaves, it is also has some kinetic energy. So, the entry energy and leaving energy they are equated by this energy balance with the fact that one energy gives you the necessary power for this thrust, other energy called as unused kinetic energy, gives you necessary enthalpy difference between entry and exit state. So, that part if you actually calculate we call this as unused kinetic energy. So, we can define a term which is called a propulsive efficiency which is defined by the following ratio. Now this equation gets simplified below.

Net thrust, $F = m(C_j - C_a)$

$$\eta_p = \frac{mC_a(C_j - C_a)}{m\left[C_a(C_j - C_a) + \frac{1}{2}(C_j - C_a)^2\right]} = \frac{2}{1 + \left(\frac{C_j}{C_a}\right)}$$

One significant inference we can see here that

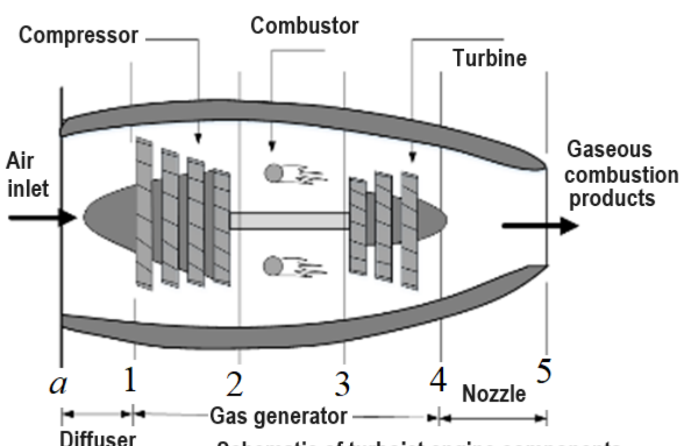
$C_a = 0 \Rightarrow F \rightarrow$ maximum; $\eta_p \rightarrow 0$

$C_a = C_j \Rightarrow F \rightarrow 0; \eta_p \rightarrow$ maximum

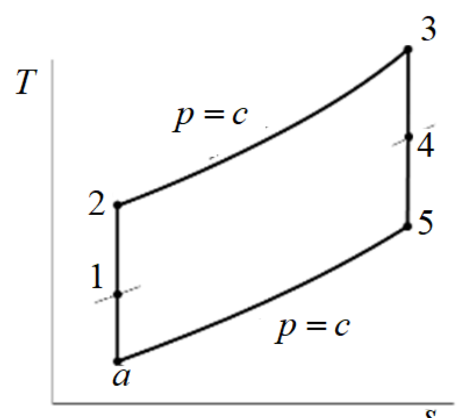
$\Rightarrow C_j > C_a$(But difference should not be high)

So, this gives the concept of propeller jet and or jet engine. Now what happens is that we require a balancing approach between $C_a \& C_j$ such that, at a given speed we get best propulsive efficiency. So, thereby you we use the concept of propeller or jet engines. For example, if we use a propeller driven engine, it has efficiency much higher than the jet engine, but beyond certain aircraft velocity let us say maybe 500 km/hr, this propulsive efficiency drops. That means, propeller concept does not work beyond this aircraft velocity. But still if you want to travel faster, then you have to use the other concept that is called jet engine. So, higher speed means jet engine is the best approach, lower speed means propeller driven is the better approach because they give best possible propeller efficiency. So, this is how the jet engine concept comes into pictures.

So, one such simplified jet engine is a turbo jet engine. And this turbo jet engine idea comes as aircraft propulsion cycle and its main intention starts with gas turbine engine because they favor high power to weight ratio and when you say turbo jet engine, we can expect a higher power at relatively lower weight. We also try to emphasize that we are not using any kind of heat exchanger or bulky devices to make it unnecessarily bulky or increase the weight. So, essentially this turbo jet engine has a few main sections; one is called as a diffuser section, second is gas generator section and third is the nozzle section.



Schematic of turbojet engine components



Temperature - entropy diagram

So, if you look at this particular figure, there are three sections shown that are diffuser, gas generator and nozzle. And some important events happen at various locations and locations are noted as a 1, 2, 3, 4 and 5. So, these numbers essentially says that when air enters into this engine, it passes through different components. So, the first component that it enters is the diffuser. What does it do? It increases its pressure at the cost of velocity. So, velocity drops, initial velocity is high and it drops to 0 velocity ideally. So, when it enters to the compressor, air velocity is relatively close to 0 and the pressure suits up. So, 1-2 process is called as compression process.

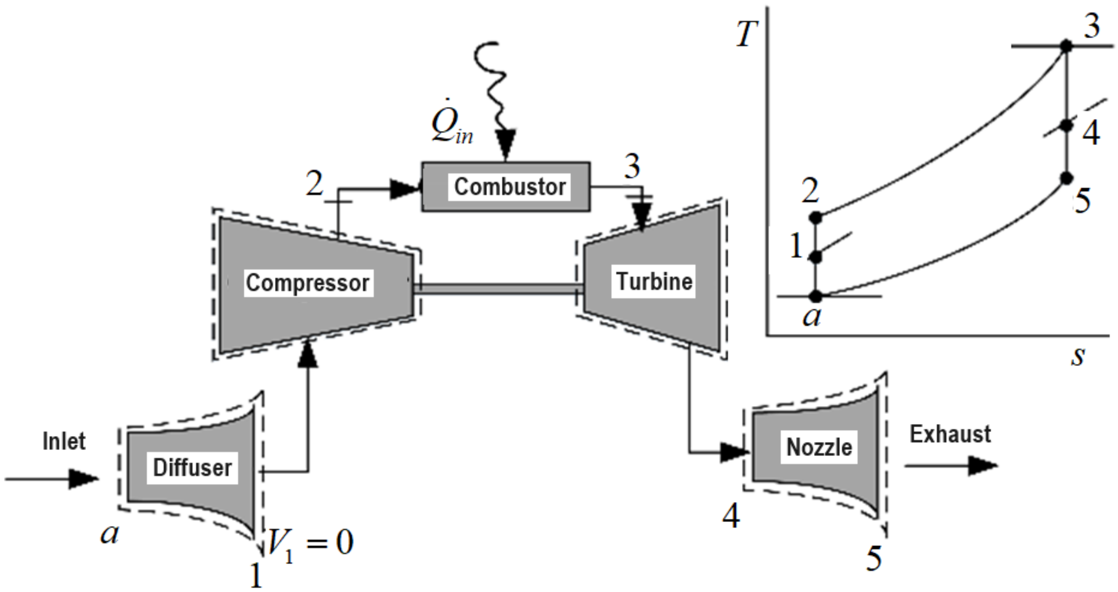
So, first process is a-1 in the diffuser, in which we can see rise in the temperature and also rise in pressure from p_a to p_1, but drop in the velocity. And from 1- 2 is the compression process. So, it goes in the manner shown in T-s diagram. And ideally we can see this entire process to be isentropic both in the diffuser as well as in the compressor.

Now, similar to this air enters to the combustor, where heat is added. Essentially here we add fuel. So, in the cycle we can see that Q_{in} amount of heat added by means of fuel. So, 2-3 is your heat addition process at constant pressure. Then it enters to the turbine section. So, expansion is done in 2 stage, one is turbine & other is nozzle. So, we have 2 sections here one is from 3 - 4 that is turbine and 4- 5 that is nozzle. So, there are 2 expansions, the first expansion is just to produce power, second expansion in the nozzle is to produce thrust.

And finally, the combustion product goes out at certain velocity. So, when the combustion products leave the turbine at a pressure significantly greater than atmospheric pressure and expand through a nozzle to a very high velocity before being discharged to the surroundings. So, the overall change in the velocity relative to the engine gives rise to the propulsive force or thrust. So, this rate of change of velocity multiplied by the mass of the system, it gives the necessary thrust and we call this as propulsive force or thrust.

There are some advanced turbojet engines, where we have similar components like diffuser, gas generator, nozzle, but additionally we have a unit like afterburner. It should be emphasized that, the jet engines are mainly intended for thrust. So, we require the efficient usage of fuel. That is the reason, the entire fuel is not added at the combustor itself, rather some of the fuel is added in the combustor as a primary fuel and other amount of fuel gets added in the section, called as the afterburner and we call this fuel as secondary fuel. So, in order to have efficient use of fuel, we have different sections like a combustor and afterburner section for addition of the fuel. So, through this process, we can get an enhanced or increased thrust.

More details we can explore in various other aircraft propulsion systems. But in this particular domain or in the framework of our syllabus, we will just try to explain the thermodynamic aspects behind a gas turbine cycle which is used as a propulsion device.



One such simple cycle is the turbojet cycle and we call this as a turbojet engine. So, an ideal turbojet engine has five basic components diffuser, compressor, combustor, turbine and nozzle.

So, the process starts with a-1 in a diffuser. So what does this diffuser do? In the diffuser, the pressure increases at the cost of velocity. So, at the end of the diffuser process, ideally the high speed air velocity comes to a zero velocity that means, entire energy of air gets converted to the pressure energy. So, at state 1 we get pressure p_1 which is supposed to be higher than p_a.

So, after diffuser, air enters in to the compressors. Thereby the compressor load is also decreased. So, 1 -2 process now becomes the compression process. And 2 - 3 is your combustion process, which is a constant pressure heat addition process. So, we add Q_{in} and after this, we have two stage expansion. The first stage expansion is 3 - 4 that is turbine and second stage expansion is from 4 - 5 that is nozzle and finally, the exhaust goes out. So, because since it is, both side is open to atmosphere. So, it is not a closed cycle. So finally, the process stops at 5. So, there is no arrow from 5- a. So, in the diffuser there is a rise in the pressure due to deceleration of air and in the nozzle there is a drop in pressure due to acceleration of air.

So, this is just a thermodynamic estimate and we also encounter steady flow analysis based on the first law of thermodynamics. However, real cycles will have different numbers, when the component efficiency comes into pictures. So, owing to irreversibility of actual engines, there would be increase in the specific entropy. So, process will not be an isentropic process in the diffuser, compressor, turbine or nozzle. And of course, that with a possibility of combustion irreversibility, pressure drop in the combustors.

So, all these things will be taken care, when you actually take an aircraft propulsion course separately, but our viewpoint is different. So, here in this lecture, based on our thermodynamic analysis, I will just try to find the thermodynamic estimates which is not an accurate number. Actually estimates means typically what type of velocity range we are looking at, for a gas turbine engine. So, assumptions goes like, components of an ideal turbojet operate at steady state. Except at the inlet and exit of the engine, changes of kinetic energy and potential energy effects are negligible at all other locations. The classical steady flow energy equation is stated below. And other important expressions that you can see are velocity at the exit of the nozzle for diffuser expressions & so on.

Steady flow energy balance: $\dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}\left[(h_4 - h_5) + \left(\frac{V_4^2 - V_5^2}{2}\right) + g(z_4 - z_5)\right] = 0$

Velocity at exit of nozzle, $V_5 = \sqrt{2(h_4 - h_5)}$

Diffuser: $h_1 = h_a + \frac{V_a^2}{2}$

Turbine & compressor: $\frac{\dot{W}_t}{\dot{m}} = \frac{\dot{W}_c}{\dot{m}}$

$$\Rightarrow h_3 - h_4 = h_2 - h_1$$

Ideally when you say jet engines, normally this particular relations holds good. Turbine drives the compressors. So, the work generated by the turbine is equal to work consumed by the compressor. So, with these working equations we can solve this turbojet cycle.

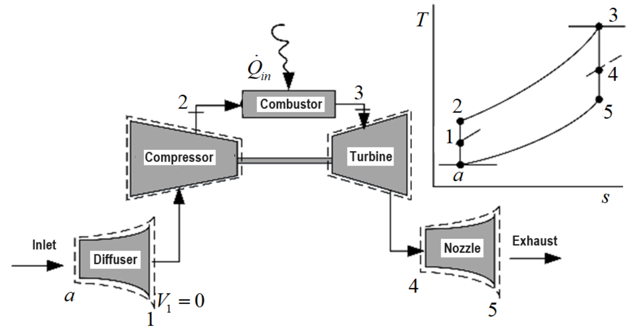
So, apart from this, there are other types of engines that are available. First thing we have two main category. One is when you operate at lower speed we have a turboprop engine. So, for turboprop engine, you see, we have a propeller here. So, most of the aircrafts wherever you see these rotating device, we call this as a propeller. And the other extreme case is where no turbo machine device is there. It is a simple duct and the pressure difference is created through the geometry of this duct. So, we call this as a ramjet engine. So, the shape of this duct essentially changes the pressure and temperature conditions within the medium. With this increase in the pressure conditions fuel is supplied. This is nothing, but your flame holder, where fuel is supplied. And finally, the jet expands. So, to run a ramjet engines we have to pass through these stages like, we initially run the engine to some speed then allow this ramjet engine to fire. So, we have seen the classical turbojet engine which is very basic and initial version of that is turboprop. But in order to improve the efficiencies of propeller and jet engine, we also have another engine called as turbofan engine. So, what does this do? We do the same concept with additional change in the structure or location of devices. We introduce a kind of a bypass flow that means, we will have one flow that goes in the engine core, other flow that goes out and they finally meet in the end and there, the air and that fuel gets added in the afterburner to generate extra thrust. So, we call this as a turbofan engine.

So, these are the kind of jet engines which are available as of now on a commercial viewpoint. So, turboprop engine consists of gas turbine in which gases are allowed to expand through the turbine at atmospheric pressure and here net power is directed to the propeller which provides thrust and typically the turboprop engines are capable up to the speed of 850 km/hr. Now, for turbofan engines, we add extra attachment where first thing we are using is nozzle. We also have two things, one is a core air movement & other is bypass air movement. So, through this process additional thrust enhancement is done and for which we can achieve speed up to1000 km/hr.

A special type of engine which is of course, a simple engine, but flow physics is very complicated and this simple engine is without any turbo machine components and we call this as a ramjet engine. So, what is this ramjet engine? When we have a sufficient pressure rise in the air inlet or duct system, the decelerating effect of high speed air in the diffuser is known as ram effects. So, that is the reason we call this as a ramjet engine. So, for a ramjet engine to operate the aircraft must be in flight at high speed and initially it has to be powered through a conventional jet engine and subsequently ramjet engine has to be fired. And due to this ram effects, the combustion products are expanded in the nozzle to produce very high thrust. Another important aspect of all these engines, known as air breathing engines, as they breathe air to run the gas turbines. And all this jet engine or aircraft propulsion devices are air breathing engines. But at very high altitude or space travels, this is not possible, because at very high altitude or in the space there is no air. So, we require separate fuel and oxidizers, typically liquid oxygen. Thrust is produced when high pressure gases are obtained on combustion and expanded through the nozzle and discharged from the rocket. And they are known as non-air breathing engine or rocket engine. So, rocket engines are not air breathing engines, they are non-air breathing engines.

However, these concepts are of different nodes. So, it is better that we are not going deep into this concepts, but our main attention or focus of this lecture is to demonstrate this gas turbine cycle as a thrust production device. So, with this I come to the end of this lecture, but before we disperse, let me introduce the problem based on the analysis of our turbojet engine.

Q1. Air enters a turbojet engine at 0.8 bar & 240K with inlet velocity of 1000 km/hr. The pressure ratio across the compressor is 6. The turbine inlet temperature is 1200K and the pressure at the nozzle exit is 0.8 bar. The work developed by the turbine is equal to the compressor work. The flow processes are isentropic in the components (diffuser, compressor, turbine & nozzle) and no pressure drop for flow in the combustor. At steady state operation, determine the velocity at nozzle exit and pressure at each principal state. Neglect, kinetic and potential energy changes at all components except nozzle.



So, the problem statement goes like this. So, here I have given the sketch of a turbojet engine. This air enters the turbojet engine at 0.8 bar and 240 Kelvin.

So, inlet conditions is fixed at

$p_a = 0.8$ bar; $T_a = 240$ K

Side by side we know this particular location. Pressure ratio in the compressor is 6. After exit from this diffuser it reaches to state 1 and enters to the compressor. So, that number we do not know.

But $\frac{p_2}{p_1} = 6$

Turbine inlet temperature is 1200 Kelvin. So we say, $T_3 = 1200$ K Work developed by the turbine is equal to compressor work.

So we say, $\frac{\dot{W}_C}{\dot{m}} = \frac{\dot{W}_T}{\dot{m}}$

Turbine drives the compressor. The flow processes are isentropic for all the components like diffuser, compressor, turbine and nozzles. There is no pressure drop in the combustor. At steady state operations, we need to determine the velocity at the nozzle exit. So, essentially we are looking for what is velocity at state 5 that is at this nozzle exit. And also we expect what is the pressure at each principal stage like what is $p_1, p_2 p_3, p_4$ & p_5. So, to start the problem let us solve component wise. First thing you recall the equation for diffuser. So, the flow equation has two parts. So what this diffuser does? After the air reaches at the end of the diffuser, the velocity become 0, the entire kinetic energy is converted to pressure energy.

$$p_a + \frac{1}{2}\rho v_a^2 = p_1 + \frac{1}{2}\rho v_1^2;\ \text{Here } \frac{1}{2}\rho v_1^2 = 0; p_a = 0.8\text{ bar}; v_a = 1000\frac{\text{km}}{\text{hr}} = 278\frac{\text{m}}{\text{s}}$$

$$\Rightarrow p_1 = 80000 + \frac{1}{2}(1.2)(278)^2 = 126.3\frac{\text{kN}}{\text{m}^2}\text{ or kPa}$$

Then we also expect what is temperature and enthalpy as well. Of course, your velocity at state 1 is 0. So, total enthalpy now becomes

$$\text{Enthalpy equation}, h_1 = h_a + \frac{v_a^2}{2} = C_p T_a + \frac{v_a^2}{2};\ T_a = 240\text{K}; C_p = 1.005\frac{\text{kJ}}{\text{kg. K}}; v_a = 278\text{m/s}$$

$$\Rightarrow h_1 = 279.8\frac{\text{kJ}}{\text{kg}}$$

Then we have compressor.

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}; \text{Data given } \frac{p_2}{p_1} = 6, \gamma = 1.4$$

$$\Rightarrow \frac{T_2}{T_1} = (6)^{\frac{1.4-1}{1.4}} = 1.66$$

Now we do not know T_1, but we know h_1.

$$h_1 = C_p T_1 \quad \Rightarrow T_1 = \frac{279.8}{1.005} = 278.4\text{ K}$$

$$\text{Now,}\quad \frac{T_2}{T_1} = 1.66 \ \Rightarrow T_2 = 1.66 \times 278.4 = 463.9\text{ K}$$

Then we move to turbine. So, for turbine we write the working equation as follows.

$$\frac{\dot{W}_T}{\dot{m}} = \frac{\dot{W}_C}{\dot{m}} \Rightarrow h_3 - h_4 = h_2 - h_1$$

So, we have calculated

$$h_1 = 279.8 \frac{\text{kJ}}{\text{kg}};\ h_2 = C_p T_2;\ h_3 = C_p T_3\ \ \&\ T_3 = 1200K$$

So, knowing this we can arrive at the expression $h_4 = 1019.6\ {}^{\text{kJ}}/_{\text{kg}}$

Then we move on to nozzle. So, for nozzle we can say the working equation

$$V_5 = \sqrt{2(h_4 - h_5)};\text{Here } h_4 = 1019.6\ {}^{\text{kJ}}/_{\text{kg}};h_5 = C_p T_5$$

So T_a is entry temperature & T_5 is the temperature of exhaust. As the exhaust also goes to atmosphere. So, we can say it is T_a& T_5 can be assumed to be ambient.

Data Given, $T_a = 240$ K, so $T_5 = 240$ K

Now, $h_5 = C_p T_5 = 241.2\,{}^{\text{kJ}}/_{\text{kg}}$ & $V_5 = \sqrt{2(1019.6 - 241.2)} = 1247.7$ m/s

So, we say velocity at the exit is 1247.7 m/s. But the extra terms that we require are pressure values at each principal state. So, we have already noted down various pressures at all other components. What we have not noted down is p_4.

So, p_4 can be calculated from this turbine working equations.

$$\frac{T_3}{T_4} = \left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}};T_3 = 1200\text{ K}$$

For T_4 we have, $h_4 = C_p T_4 = 1019.6 \frac{\text{kJ}}{\text{kg}} \Rightarrow T_4 = 1014.5$ K

Now, $\frac{T_3}{T_4} = \left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow \frac{p_3}{p_4} = 1.78$; and we know, $p_3 = p_2$

$\Rightarrow p_4 = 4.25 \text{ bar}$

So, ultimately at end of our analysis if I express my answers in a single chart for pressures at each principal states, then we can say

$p_a = \text{Ambient pressure} = 0.8 \text{ bar}$

$p_1 = \text{Exit pressure from diffuser} = 1.263 \text{ bar}$

After compression of pressure rise 6 , $p_2 = 7.58 \text{ bar}$

$p_3 = p_2 = 7.58 \text{ bar}$

We have calculated, $p_4 = 4.25 \text{ bar}$

$p_5 = \text{atmosphere or ambient condition} = p_a = 0.8 \text{ bar}$

So, this is all about the pressure conditions at all principal states in the cycle and finally, the velocity $V_5 = 1247.7 \text{ m/s}$. So, this demonstrates that jet velocity is too high to give necessary thrust through this concept of gas turbine cycle implemented in this turbojet engine. With this I conclude this module. Thank you for your attention.