Gas turbine types

Gas turbines can be used for many purposes. They can be used to deliver power, heat or thrust. Therefore, different gas turbine types exist. In this chapter, we will examine a few. First, we examine shaft power gas turbines. Then, we examine jet engine gas turbines.

1 Shaft power gas turbines

A **shaft power gas turbine** is a gas turbine whose goal is mainly to deliver shaft power. They are often also referred to as **turboshaft engines**. These gas turbines are often used in industrial applications. Gas turbines used for electricity production are also of this type.

1.1 The shaft power

For shaft power gas turbines, the shaft power is very important. It mainly depends on the temperature drop in the **power turbine** (PT). This drop is given by

$$T_{0g} - T_{05} = T_{0g}\eta_{is,PT}\left(1 - \left(\frac{p_{05}}{p_{0g}}\right)^{\frac{k_{gas}-1}{k_{gas}}}\right) = T_{0g}\left(1 - \left(\frac{p_{05}}{p_{0g}}\right)^{\eta_{\infty,PT}\frac{k_{gas}-1}{k_{gas}}}\right). \quad (1.1)$$

The efficiencies $\eta_{is,PT}$ and $\eta_{\infty,PT}$ are the isentropic and polytropic efficiencies, respectively, of the power turbine. To apply the above equation, we do need to know the properties of point 5. These properties can be derived from the exhaust properties, according to

$$\Delta p_{exh} = p_{05} - p_{exh} \qquad \text{and} \qquad T_{05} = T_{0,exh} = T_{exh} + \frac{c_{exh}^2}{2c_{p,gas}}, \quad (1.2)$$

where c_{exh} is the velocity of the exhaust gas. (By the way, the exhaust point is often also denoted by point 9.) Once this data is known, the actual shaft power can be derived. For this, we use the equation

$$P_{shaft} = \dot{m}\, c_{p,gas}\,(T_{0g} - T_{05})\,\eta_{m,PT}, \quad (1.3)$$

with $\eta_{m,PT}$ being the mechanical efficiency of the gas turbine.

1.2 Other performance parameters

There are also some other parameters that are important for shaft power gas turbines. Of course, the **thermal efficiency** $\eta_{thermal}$ is important. (The thermal efficiency is not the thermodynamic efficiency η_{th}, introduced in chapter 1. In fact, it is lower. This is because the thermal efficiency also takes into account various types of losses.) This efficiency is given by

$$\eta_{thermal} = \frac{P_{shaft}}{\dot{m}_{fuel}\, H_{fuel}}, \quad (1.4)$$

where H_{fuel} is the **heating value** of the fuel. Other important parameters are the **specific fuel consumption** sfc and the **heat rate**. The sfc is given by

$$sfc = \frac{\dot{m}_{fuel}}{P_{shaft}} = \frac{1}{H_{fuel}\,\eta_{thermal}}. \quad (1.5)$$

The heat rate is given by

$$\text{heat rate} = \frac{\dot{m}_{fuel}\, H_{fuel}}{P_{shaft}} = \frac{1}{\eta_{thermal}}. \quad (1.6)$$

Finally, there is the **equivalence ratio** λ, also known as the **percentage excess air**. It is defined as

$$\lambda = \frac{\dot{m}_{air} - \dot{m}_{st}}{\dot{m}_{st}}, \tag{1.7}$$

where $\dot{m}_{st}$ is the air mass flow required for a complete combustion of the fuel. If there is just enough air to burn the fuel, then we have a **stoichiometric combustion**. In this case, $\lambda = 1$. However, usually λ is bigger than 1.

1.3 Exhaust gas of the shaft power turbine

Shaft power gas turbines usually produce quite some heat. This heat can be used. When applying **cogeneration**, we use the heat of the exhaust gas itself. (For example, to produce hot water or steam.) In a **combined cycle** the heat is used to create additional power. This can be done by expanding the heat in a steam turbine.

The process of creating steam deserves some attention. In this process, heat is exchanged from the exhaust gas to the water/vapor. This is caused by the temperature difference between the exhaust gas and the water/vapor. An important parameter is the temperature difference ΔT_{pinch} at the so-called **pinch point**. This is the point where the water just starts to boil. The entire process, including the pinch point, is also visualized in figure 1.

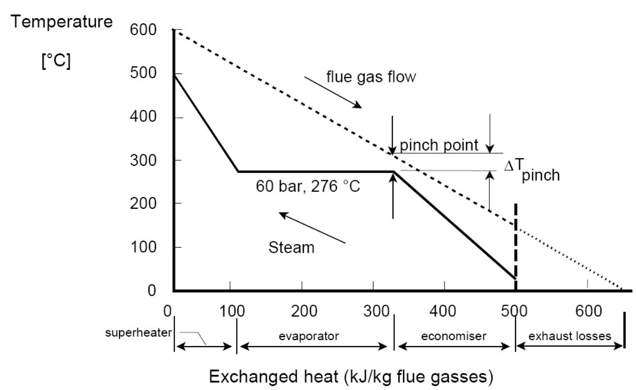

Figure 1: Exchanged heat versus temperature diagram for creating steam, using exhaust gas.

We want to minimize the exhaust losses. One way to do that, is to increase the initial exhaust gas temperature. This makes the heat exchange a lot easier. Another option is to split up the process into multiple steps, where each step has a different pressure. In this case, there will also be multiple pinch points.

2 Jet engine gas turbines

A **jet engine gas turbine** is a turbine whose goal is mainly to deliver **thrust**. This can be done in two ways. We can let the gas turbine accelerate air. We can also let the gas turbine shaft power a propeller. Often, both methods are used. Jet engine gas turbines are mainly used on aircraft.

2.1 Finding the thrust

The goal of a jet engine is to produce thrust. The **net thrust** F_N can generally be found using

$$F_N = \dot{m}\left(c_j - c_0\right). \tag{2.1}$$

c_0 indicates the air velocity before the air entered the gas turbine. c_j indicates the air velocity after it entered the turbine. $(c_j - c_0)$ indicates the acceleration of the flow.

We can use the above equation to find the thrust of an actual aircraft. But to do that, we have to define some control points. Point 0 is infinitely far upstream, point 1 is at the inlet entry, point 8 is at the exhaust exit and point ∞ is infinitely far downstream. To calculate the thrust, we have to use points 0 and ∞. The velocity c_0 at point zero is simply equal to the airspeed of the aircraft. However, c_∞ is very hard to determine. Luckily, we can use the momentum relation, which states that

$$\dot{m}\left(c_\infty - c_8\right) = A\left(p_8 - p_\infty\right) = A\left(p_8 - p_0\right), \tag{2.2}$$

where we have used that $p_0 = p_\infty = p_{atm}$. If we use this relation, then the net thrust becomes

$$F_n = \dot{m}\left(c_\infty - c_0\right) = \dot{m}\left(c_8 - c_0\right) + A\left(p_8 - p_0\right). \tag{2.3}$$

The parameter A is the area of the gas turbine at the exhaust. Once the thrust has been found, we can derive the **effective jet velocity** c_{eff}. It is the velocity that is (theoretically) obtained at point ∞, such that the thrust F_n is achieved. It satisfies

$$F_n = \dot{m}\left(c_{eff} - c_0\right). \tag{2.4}$$

2.2 Jet engine power

From the net thrust, we can find the **thrust power**. It is defined as

$$P_{thrust} = F_n c_0 = \dot{m} c_0 \left(c_{eff} - c_0\right). \tag{2.5}$$

This is the 'useful' power of the aircraft. We can also look at the change in kinetic energy of the air passing through our jet engine. If we do that, then we find the **propulsion power** P_{prop}. This can be seen as the 'input' power. It is defined as

$$P_{prop} = \frac{1}{2}\dot{m}\left(c_{eff}^2 - c_0^2\right). \tag{2.6}$$

The difference between the propulsion power and the thrust power is known as the **loss power**. It is defined as

$$P_{loss} = P_{prop} - P_{thrust} = \frac{1}{2}\dot{m}\left(c_{eff} - c_0\right)^2. \tag{2.7}$$

2.3 Efficiencies

From the propulsion power and the thrust power, we can derive the **propulsive efficiency** η_{prop}, also known as the **Froude efficiency**. It is given by

$$\eta_{prop} = \frac{P_{thrust}}{P_{prop}} = \frac{2}{1 + \frac{c_{eff}}{c_0}}. \tag{2.8}$$

To increase the propulsive efficiency, we should keep c_{eff} as low as possible. So it's better to accelerate a lot of air by a small velocity increment, than a bit of air by a big velocity increment. Now let's examine the **thermal efficiency** $\eta_{thermal}$ of the jet engine. It is given by

$$\eta_{thermal} = \frac{P_{prop}}{\dot{m}_{fuel} H_{fuel}}. \tag{2.9}$$

It is a measure of how well the available thermal energy has been used to accelerate air. We can also look at the **jet generation efficiency** η_{jet}. It is defined as

$$\eta_{jet} = \frac{P_{prop}}{P_{gg}}. \tag{2.10}$$

This is a measure of how well the energy from the power turbine has been used to accelerate air. And now, we can finally define the **total efficiency**. It is given by

$$\eta_{total} = \frac{P_{thrust}}{\dot{m}_{fuel} H_{fuel}} = \eta_{prop}\eta_{thermal}. \tag{2.11}$$

2.4 Other important parameters

Next to the efficiencies, there are also quite some other parameters that say something about jet engines. First, there is the **specific thrust** F_s. It is defined as the ratio between the net thrust and the air intake. So,

$$F_s = \frac{F_N}{\dot{m}}. \tag{2.12}$$

Second, we have the **thrust specific fuel consumption** $TSFC$, which is the ratio between the fuel flow and the thrust. We thus have

$$TSFC = \frac{\dot{m}_{fuel}}{F_N} = \frac{c_0}{\eta_{total} H_{fuel}}. \tag{2.13}$$

2.5 Improving the jet engine

We have previously noted that it's best to give a small velocity increment to a large amount of air. However, jet engines theirselves usually give quite a big acceleration to the air. For this reason, most commercial aircraft engines have big propellers, called **turbofans**. These fans are driven by the shaft of the jet engine. And they give, as iss required, a small velocity increment to a large amount of air. This air then **bypasses** (flows around) the jet engine itself.

The relation for the thrust of a turbofan engine is similar to that of a normal jet engine. The only difference, is that we need to add things up. So,

$$F_N = \dot{m}_{jet} (c_8 - c_0) + A_{jet} (p_8 - p_0) + \dot{m}_{fan} (c_8 - c_0) + A_{fan} (p_8 - p_0). \tag{2.14}$$

The rest of the equations also change in a similar way.