Basics of gas turbines

In this first chapter, we're going to look at the basics of gas turbines. What are they? When were they developed? How do they work? And how do we perform basic calculations?

1 Introduction to gas turbines

This is where our journey into the world of gas turbines takes off. And we start with a very important question: what is a gas turbine?

1.1 What is a gas turbine?

A **gas turbine** is a machine delivering mechanical power or thrust. It does this using a gaseous working fluid. The mechanical power generated can be used by, for example, an industrial device. The outgoing gaseous fluid can be used to generate thrust.

In the gas turbine, there is a continuous flow of the working fluid. This working fluid is initially compressed in the **compressor**. It is then heated in the **combustion chamber**. Finally, it goes through the **turbine**. The turbine converts the energy of the gas into mechanical work. Part of this work is used to drive the compressor. The remaining part is known as the **net work** of the gas turbine.

1.2 History of gas turbines

We can distinguish two important types of gas turbines. There are **industrial gas turbines** and there are **jet engine gas turbines**. Both types of gas turbines have a short but interesting history.

Industrial gas turbines were developed rather slowly. This was because, to use a gas turbine, a high initial compression is necessary. This rather troubled early engineers. Due to this, the first working gas turbine was only made in 1905 by the Frenchman **Rateau**. The first gas turbine for power generation became operational in 1939 in Switzerland. It was developed by the company **Brown Boveri**.

Back then, gas turbines had a rather low thermal efficiency. But they were still useful. This was because they could start up rather quickly. They were therefore used to provide power at peak loads in the electricity network. In the 1980's, natural gas made its breakthrough as fuel. Since then, gas turbines have increased in popularity.

The first time a gas turbine was considered as a jet engine, was in 1929 by the Englishman **Frank Whittle**. However, he had trouble finding funds. The first actual jet aircraft was build by the German **Von Ohain** in 1939. After world war 2, the gas turbine developed rapidly. New high-temperature materials, new cooling techniques and research in aerodynamics strongly improved the efficiency of the jet engine. It therefore soon became the primary choice for many applications.

Currently, there are several companies producing gas turbines. The biggest producer of both industrial gas turbines and jet engines is **General Electric** (GE) from the USA. **Rolls Royce** and **Pratt & Whitney** are also important manufacturers of jet engines.

1.3 Gas turbine topics

When designing a gas turbine, you need to be schooled in various topics. To define the compressor and the turbine, you need to use **aerodynamics**. To get an efficient combustion, knowledge on **thermodynamics** is required. And finally, to make sure the engine survives the big temperature differences and high forces, you must be familiar with **material sciences**.

Gas turbines come in various sizes and types. Which kind of gas turbine to use depends on a lot of criteria. These criteria include the required **power output**, the bounds on the **volume** and **weight** of the turbine, the **operating profile**, the **fuel type**, and many more. Industrial gas turbines can deliver a power from $200kW$ to $240MW$. Similarly, jet engines can deliver thrust from $40N$ to $400kN$.

2 The ideal gas turbine cycle

To start examing a gas turbine in detail, we make a few simplifications. By doing this, we wind up with the **ideal gas turbine**. How do we analyze such a turbine?

2.1 Examining the cycle

Let's examine the thermodynamic process in an ideal gas turbine. The cycle that is present is known as the **Joule-Brayton cycle**. This cycle consists of five important points.

We start at position 1. After the gas has passed through the **inlet**, we are at position 2. The inlet doesn't do much special, so $T_1 = T_2$ and $p_1 = p_2$. (Since the properties in points 1 and 2 are equal, point 1 is usually ignored.) The gas then passes through the **compressor**. We assume that the compression is performed isentropically. So, $s_2 = s_3$. The gas is then heated in the **combustor**. (Point 4.) This is done isobarically (at constant pressure). So, $p_3 = p_4$. Finally, the gas is expanded in the turbine. (Point 5.) This is again done isentropically. So, $s_4 = s_5$. The whole process is visualized in the enthalpy-entropy diagram shown in figure 1.

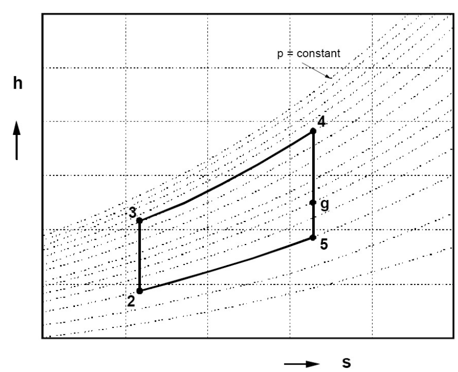

Figure 1: The enthalpy-entropy diagram for an ideal cycle.

We can make a distinction between open and closed cycles. In an **open cycle**, atmospheric air is used. The exhaust gas is released back into the atmosphere. This implies that $p_5 = p_1 = p_{atm}$. In a **closed cycle**, the same working fluid is circulated through the engine. After point 5, it passes through a **cooler**, before it again arrives at point 1. Since the cooling is performed isobarically, we again have $p_5 = p_1$.

When examining the gas turbine cycle, we do make a few assumptions. We assume that the working fluid is a **perfect gas** with constant specific heats c_p and c_v. Also, the specific heat ratio k (sometimes also denoted by γ) is constant. We also assume that the kinetic/potential energy of the working fluid does not vary along the gas turbine. Finally, pressure losses, mechanical losses and other kinds of losses are ignored.

2.2 The steps of the cycle

Let's examine the various steps in the gas turbine cycle. During step $2-3$, the compressor requires a certain **compressor power** $\dot{W}_{2-3}$. During step $3-4$, a certain amount of **heat input** $\dot{Q}_{3-4}$ is added. And, during step $5-2$, a certain amount of **waste heat** $\dot{Q}_{5-2}$ is discarded. These quantities can be found using

$$\dot{W}_{2-3} = \dot{m}c_p\left(T_3 - T_2\right), \qquad \dot{Q}_{3-4} = \dot{m}c_p\left(T_4 - T_3\right) \qquad \text{and} \qquad \dot{Q}_{5-2} = \dot{m}c_p\left(T_5 - T_2\right). \tag{2.1}$$

Here, $\dot{m}$ denotes the mass flow through the turbine. Now let's examine step $4-5$. We can split this step up into two parts. We do this, by creating an imaginary point g between points 4 and 5. This point is such that $\dot{W}_{4-g} = \dot{W}_{2-3}$. In other words, the power produced in step $4-g$ generates the power needed by the compressor. ($\dot{W}_{4-g}$ is called the **turbine power**). The remaining power is called the **gas power**, and is denoted by $\dot{W}_{g-5} = \dot{W}_{gg}$. Both $\dot{W}_{4-g}$ and $\dot{W}_{g-5}$ are given by

$$\dot{Q}_{4-g} = \dot{m}c_p\left(T_4 - T_g\right) \qquad \text{and} \qquad \dot{Q}_{g-5} = \dot{m}c_p\left(T_g - T_5\right). \tag{2.2}$$

2.3 Performing calculations

Now let's try to make some calculations. We know that steps $2-3$ and steps $4-5$ are performed isentropically. Also, $p_2 = p_5$ and $p_3 = p_4$. This implies that

$$\varepsilon = \frac{p_3}{p_2} = \frac{p_4}{p_5} = \left(\frac{T_3}{T_2}\right)^{\frac{k}{k-1}} = \left(\frac{T_4}{T_5}\right)^{\frac{k}{k-1}}, \tag{2.3}$$

where ε is the **pressure ratio**. Now let's find a relation for T_g. Since $\dot{W}_{4-g} = \dot{W}_{2-3}$, we must have

$$T_g = T_4 - T_3 + T_2 = T_4 - T_2\left(\varepsilon^{\frac{k-1}{k}} - 1\right). \tag{2.4}$$

The important **specific gas power** $W_{s,gg}$ is now given by

$$W_{s,gg} = \frac{W_{gg}}{\dot{m}} = c_p\left(T_g - T_5\right) = c_pT_4\left(1 - \frac{1}{\varepsilon^{\frac{k-1}{k}}}\right) - c_pT_2\left(\varepsilon^{\frac{k-1}{k}} - 1\right). \tag{2.5}$$

Having a high specific gas power is positive. This is because, to get the same amount of power, we need less mass flow. Our gas turbine can thus be smaller.

2.4 The efficiency of the cycle

Based on the equation we just derived, we can find the **thermodynamic efficiency** η_{th} of the gas turbine cycle. This rather important parameter is given by

$$\eta_{th} = \frac{E_{useful}}{E_{in}} = \frac{W_{s,gg}}{Q_{s,3-4}} = \frac{T_g - T_5}{T_4 - T_3} = 1 - \frac{T_2}{T_3} = 1 - \frac{1}{\varepsilon^{\frac{k-1}{k}}}. \tag{2.6}$$

So the efficiency of the cycle greatly depends on the pressure ratio ε. To get an efficient cycle, the pressure ratio should be as high as possible.

2.5 The optimum pressure ratio

Let's suppose we don't want a maximum efficiency. Instead, we want to maximize the power $W_{s,gg}$. The corresponding pressure ratio ε is called the **optimum pressure ratio** ε_{opt}. To find it, we can set $dW_{s,gg}/d\varepsilon = 0$. From this, we can derive that, at these optimum conditions, we have

$$T_3 = T_5 = \sqrt{T_2T_4}. \tag{2.7}$$

It also follows that the optimum pressure ratio itself is given by

$$\varepsilon_{opt} = \left(\frac{T_3}{T_2}\right)^{\frac{k}{k-1}} = \left(\frac{T_4}{T_2}\right)^{\frac{k}{2(k-1)}}. \tag{2.8}$$

The corresponding values of $W_{s,gg}$ and η are given by

$$\frac{W_{s,gg_{max}}}{c_p T_2} = \left(\sqrt{\frac{T_4}{T_2}} - 1\right)^2 \qquad \text{and} \qquad \eta = 1 - \sqrt{\frac{T_2}{T_4}}. \tag{2.9}$$

Note that we have used a non-dimensional version of the specific gas power $W_{s,gg}$.

3 Enhancing the cycle

There are various tricks, which we can use to enhance the gas turbine cycle. We will examine the three most important ones.

3.1 Heat exchange

The first enhancement we look at the **heat exchanger** (also known as a **recuperator**). Let's suppose we're applying a heat exchanger. After the gas exits the turbine (point 5), it is brought to this heat exchanger. The heat of the exhaust gas is then used, to warm up the gas entering the combustor (point 3). Let's call the point between the heat exchanger and the combustion chamber point 3.5.

It is important to note that a heat exchanger can only be used if $T_5 > T_3$. (Heat only flows from warmer to colder gasses.) And we only have $T_5 > T_3$ if $\varepsilon < \varepsilon_{opt}$. So a heat exchanger is nice for turbines with low pressure ratios.

Now let's examine the effects of a heat exchanger. The gas entering the combustor (at point 3.5) is already heated up a bit. So the combustor needs to add less heat. The heat input $Q_{s,3-4}$ is thus reduced, increasing the efficiency. In an ideal case, we have $T_{3.5} = T_5$. In this case, the heat input is given by

$$Q_{s,3-4} = c_p\left(T_4 - T_{3.5}\right) = c_p\left(T_4 - T_5\right) = c_p T_4\left(1 - \frac{1}{\varepsilon^{\frac{k-1}{k}}}\right). \tag{3.1}$$

The thermodynamic efficiency of the cycle is now given by

$$\eta_{th} = \frac{W_{s,gg}}{Q_{s,3-4}} = \frac{c_p T_4\left(1 - \frac{1}{\varepsilon^{\frac{k-1}{k}}}\right) - c_p T_2\left(\varepsilon^{\frac{k-1}{k}} - 1\right)}{c_p T_4\left(1 - \frac{1}{\varepsilon^{\frac{k-1}{k}}}\right)} = 1 - \frac{T_2}{T_4}\varepsilon^{\frac{k-1}{k}}. \tag{3.2}$$

In this case, the efficiency increases for decreasing temperature ratios. This is contrary to the case without heat exchange. There is a simple reason for this: The lower the pressure ratio, the more heat can be exchanged, and the more the efficiency can be improved by this heat exchange.

3.2 Intercooling

We can also try to increase the specific gas power $W_{s,gg}$. One way to do this, is by making sure the compressor requires less power. This is where the **intercooler** comes in.

Let's suppose we're using an intercooler in the compressor. First, the compressor compresses the gas a bit (point 2.3). The applied pressure ratio is $\varepsilon_1 = p_{2.3}/p_2$. Then, the gas is cooled by the intercooler (point

2.5). (This is usually done such that $T_{2.5} = T_2$. Intercooling is also performed isobarically, so $p_{2.3} = p_{2.5}$.) Finally, the gas is compressed again, until we're at point 3. The applied pressure ratio during this step is $\varepsilon_2 = p_3/p_{2.5}$. The total applied pressure ratio is $\varepsilon_{tot} = \varepsilon_1\varepsilon_2 = p_3/p_2$. The entire process of intercooling has been visualized in figure 2 (left).

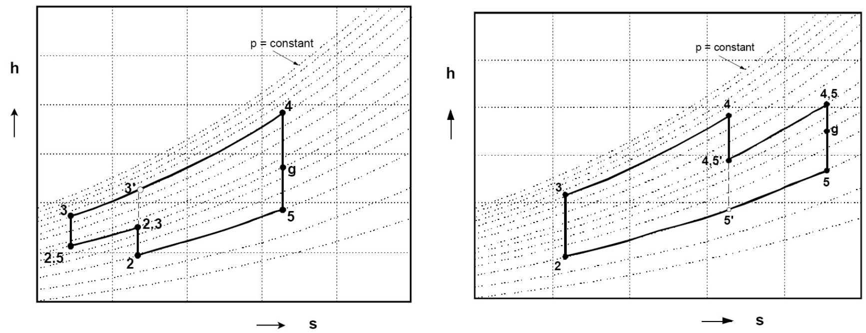

Figure 2: The enthalpy-entropy diagram for intercooling (left) and reheating (right).

Thanks to the intercooler, the specific work needed by the compressor has been reduced to

$$W_{s,2-3} = W_{s,2-2.3} + W_{s,2.5-3} = c_p\left(T_{2.3} - T_2\right) + c_p\left(T_3 - T_{2.5}\right). \tag{3.3}$$

The specific gas power $W_{s,gg}$ has increased by the same amount. The increase in specific gas power strongly depends on the pressure ratios ε_1 and ε_2. It can be shown that, to maximize $W_{s,gg}$, we should have

$$\varepsilon_1 = \varepsilon_2 = \sqrt{\varepsilon_{tot}}. \tag{3.4}$$

Intercooling may look promising, but it does have one big disadvantage. The combustor needs to do more work. It also needs to provide the heat that was taken by the intercooler. (This is because T_3 has decreased.) So, while $W_{s,gg}$ increases by a bit, $Q_{s,3-4}$ increases by quite a bit more. Intercooling therefore increases the work output, at the cost of efficiency.

3.3 Reheating

An idea similar to intercooling is **reheating**. However, reheating is applied in the turbine. Reheating increases the work done by the turbine. A well-known example of applying reheating is the afterburner in an aircraft.

From point 4, we start by expanding the gas in the turbine. We soon reach point 4.3. (Again, we define $\varepsilon_1 = p_4/p_{4.3}$.) The gas is then reheated, until point 4.5 is reached. (This is done isobarically, so $p_{4.3} = p_{4.5}$.) From this point, the gas is again expanded in a turbine, until points g and 5 are reached. We now have $\varepsilon_2 = p_{4.5}/p_5$ and $\varepsilon_{tot} = \varepsilon_1\varepsilon_2 = p_4/p_5$. The entire process of reheating has been visualized in figure 2 (right).

As was said before, reheating increases the work done by the turbine. Let's suppose that $T_4 = T_{4.5}$. In this case, the increase in turbine work is at a maximum if $\varepsilon_1 = \varepsilon_2 = \sqrt{\varepsilon_{tot}}$, just like in the case of the intercooler. Reheating also has the same downside as intercooling. Although the work increases, more heat needs to be added. So the efficiency decreases.