

# The combustion chamber

The combustion chamber is the part where energy is inserted into the gas turbine. In this chapter, we're going to examine it in detail.

## 1 The combustion process

First, we will look at the combustion process. What reaction is taking place? And what parameters influence this reaction?

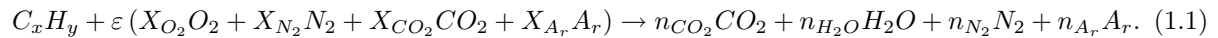
### 1.1 The combustion process

The combustor provides the energy input for the gas turbine cycle. It receives air, inserts fuel, mixes the two components and then it lets the mixture combust. This process is known as **internal combustion**. In a gas turbine, it is generally done at constant pressure. (Although small pressure losses are generally present.)

An important parameter during combustion is the  $T_{04}$  temperature. It effects the power output and the thermal efficiency.  $T_{04}$  is generally limited by material properties. The materials must be able to withstand large temperatures and temperature gradients. If not, the gas turbine might fail.

### 1.2 The reaction

Gas turbines mainly use kerosene-type fuels. These fuels consist of **hydrocarbons** with the chemical composition  $C_xH_y$ . They are mixed with air and then combusted. The **ideal reaction** is then given by



In this equation, the  $X$ 's indicate the composition of air. We thus have

$$X_{O_2} = 0.2095, \quad X_{N_2} = 0.7808, \quad X_{CO_2} = 0.0003 \quad \text{and} \quad X_{A_r} = 0.0094. \quad (1.2)$$

The term  $\varepsilon$  is the number of moles of air necessary for every mole of fuel. It is given by

$$\varepsilon = \frac{x + \frac{1}{4}y}{X_{O_2}}. \quad (1.3)$$

Finally, the  $n$ 's denote the amount of **reaction products**. We find that we have

$$n_{CO_2} = x + \varepsilon X_{CO_2}, \quad n_{H_2O} = \frac{1}{2}y, \quad n_{N_2} = \varepsilon X_{N_2} \quad \text{and} \quad n_{A_r} = \varepsilon X_{A_r}. \quad (1.4)$$

In reality, we don't have this ideal reaction. In the real world, not all fuel gets combusted. Not all carbon atoms form carbon dioxide  $CO_2$ . (We will also have carbon monoxide  $CO$ .) And there will be various other reaction products as well. We won't examine all those reaction products though.

### 1.3 Reaction parameters

When combusting the mixture, the **fuel-to-air ratio**  $FAR = \dot{m}_{fuel}/\dot{m}_{air}$  is an important parameter. We know that, to combust 1 mole of fuel, we need  $\varepsilon$  moles of air. In stoichiometric conditions, there is precisely enough air to combust all fuel. The stoichiometric fuel-to-air ratio is therefore given by

$$FAR_{st} = \left( \frac{\dot{m}_{fuel}}{\dot{m}_{air}} \right)_{st} = \frac{1}{\varepsilon} \frac{M_{C_xH_y}}{M_{air}} = \frac{X_{O_2}}{x + \frac{1}{4}y} \frac{M_{C_xH_y}}{M_{air}}. \quad (1.5)$$

The symbols  $M_{C_xH_y}$  and  $M_{air}$  denote the molar mass of the fuel and the air, respectively. Similar to the  $FAR$ , we also have the **air-to-fuel ratio**  $AFR$ . This is simply given by  $AFR = 1/FAR$ . Since the value of the  $FAR$  is usually quite small, the  $AFR$  might be easier to work with.

Of course, in the real world, the reaction isn't stoichiometric. In fact, we define the **fuel-to-air equivalence ratio**  $\varphi$  as

$$\varphi = \frac{FAR}{FAR_{st}} = \frac{AFR_{st}}{AFR} = \frac{\dot{m}_{fuel}}{\dot{m}_{air}} \frac{1}{FAR_{st}}. \quad (1.6)$$

If  $\varphi = 1$ , then our combustion is performed at stoichiometric conditions. If we have more fuel, then  $\varphi > 1$  and we have a **fuel-rich mixture**. If we have less fuel, then  $\varphi < 1$  and we have a **fuel-lean mixture**. From  $\varphi$ , we can also find the **percentage stoichiometric air**, defined as

$$\text{percentage stoichiometric air} = \frac{100\%}{\varphi}. \quad (1.7)$$

We can also use  $\varphi$  to find the percentage excess air  $\lambda$ . We do this according to

$$\lambda = \frac{1 - \varphi}{\varphi}. \quad (1.8)$$

If  $\lambda$  is positive, then there is plenty of air: we have a fuel-lean mixture.

## 1.4 The heat formed during combustion

We will now examine the heat produced during the combustion. To do this, we will use a concept called **absolute enthalpy**. The absolute enthalpy doesn't only take into account the temperature of a substance. Also the enthalpy of formation plays a role.

Now let's examine a combustion chamber operating at a constant temperature. So-called **reactants**, with absolute enthalpy  $h_{react}$ , enter the chamber. Reaction **products**, with enthalpy  $h_{prod}$ , leave the chamber. The heat  $\Delta h_c$  leaving the chamber (called the **enthalpy of combustion**) is now given by

$$\Delta h_c = h_{react} - h_{prod}. \quad (1.9)$$

The unit of  $\Delta h_c$  is Joule per mole of mixture. Usually, we want to know the lower heating value  $LHV$  of the fuel. This is the heat produced per kilogram of fuel. To find it, we can use

$$LHV = \frac{\Delta h_c}{M_{mix}} \frac{\dot{m}_{mix}}{\dot{m}_{fuel}}, \quad (1.10)$$

where  $M_{mix}$  is the molar mass of the mixture. We can apply these ideas to the combustion process. If we then also make a few simplifying assumptions, then we wind up with

$$\dot{m}_{fuel} \eta_c LHV = \dot{m}_{air} c_{p,gas} (T_{04} - T_{03}). \quad (1.11)$$

The left part of the equation indicates the effective heat input. The right part indicates the result of this heat input. The parameter  $\eta_c$  is known as the **combustion efficiency**. We can also rewrite the above equation, by making use of the fuel-to-air equivalence ratio. We then get

$$T_{04} = T_{03} + \frac{\varphi FAR_{st}}{c_{p,gas}} \eta_c LHV. \quad (1.12)$$

Due to all the approximations, this equation is not very accurate for higher temperatures and equivalence ratios.

Finally, there is the concept of the adiabatic flame temperature. To introduce it, we suppose that we burn the mixture in a closed adiabatic chamber. In this case, no heat leaves the chamber. The absolute enthalpy thus stays the same ( $\Delta h_c = 0$ ). However, the temperature  $T$  does rise. In fact, it rises from the initial reactant temperature to the **adiabatic flame temperature**  $T_{ad}$ . So, we find that  $T_{ad}$  is defined such that

$$h_{prod}(T_{ad}) = h_{react}(T_{react}). \quad (1.13)$$

## 2 The layout of the combustion chamber

Designing a combustion chamber is not an easy thing. There are several complicated parts in it. So let's examine how a combustion chamber is build up.

### 2.1 The general layout

There are several types of combustion chambers. But virtually all combustion chambers have a diffuser, a casing, a liner, a fuel injector and a cooling arrangement. The entire general layout is visualized in figure 1.

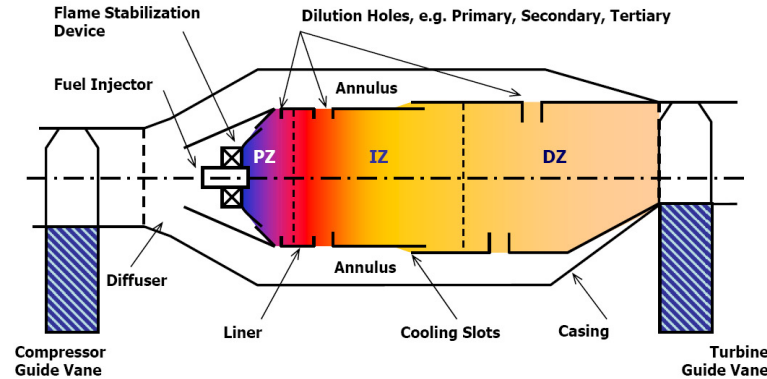


Figure 1: The layout of the combustion chamber.

### 2.2 The diffuser

The gas entering the combustion chamber usually has quite a high velocity. This velocity will be responsible for a pressure drop. (This pressure drop is called the **cold loss**.) Also, the flame in the combustion chamber can not survive if the air has a high velocity. Therefore, the airflow needs to be slowed down. And this is exactly the task of the **diffuser**.

Diffusers can be distinguished by how quickly they decrease the velocity. In the **aerodynamic diffuser**, the flow is slowed down gradually, while in the **dump diffuser**, it is slowed down quickly. The dump diffuser has more losses, but is also smaller. It is therefore mainly used in aircraft jet engines.

### 2.3 The casing and the liner

After the airflow has passed the diffuser, it is split up by the **liner**. One part of the airflow goes through the region between the liner and the casing. This region is called the **annulus**. Another part of the airflow enters the mixing chamber, where fuel is injected.

There are several reasons for splitting up the flow. First, the air-to-fuel should have the right value. If it is too high, the mixture will not ignite. Also, the velocity of the flow leaving the diffuser is still too high. The part of the flow that will be ignited has to be slowed down even further.

The liner is divided into three sections. There is a **primary zone (PZ)**, a **secondary/intermediate zone (SZ/IZ)** and a **tertiary/dilution zone (TZ/DZ)**. The main function of the PZ is to provide enough time for the fuel to mix and combust. The goal of the SZ is to provide enough time to achieve full combustion. This significantly reduces bad reaction products like **carbon monoxide CO** and **unburned**

**hydrocarbons** (UHC). Finally, the goal of the DZ is to reduce the temperature of the outlet stream, such that it is acceptable for the turbine.

## 2.4 The fuel injector

The **fuel injector** injects the fuel into the flow. It is important that the fuel is vaporized before it enters the flame zone. Otherwise, it might not combust properly.

To promote vaporization, the fuel should be **atomized**. This means that the fuel is converted into small drops. This increases vaporization rates. To accomplish this, an **atomizer** is used. To atomize fuel, it has to be given a high relative velocity, with respect to the airflow. So-called **pressure-assist atomizers** give the fuel a high velocity. On the other hand, **air blast atomizers** inject slow-moving fuel into a high-velocity air stream.

## 2.5 Flame stabilization

After the fuel has been injected into the flow, the flow will enter the flame region. It does this with quite a high velocity. To make sure the flame isn't blown away, **flow reversal** can be applied in the PZ. This causes the flow to reverse direction. The best way to reverse the flow, is to **swirl** it. This is done using **swirlers**. The two most important types of swirlers are **axial swirlers** and **radial swirlers**.

The most important advantage of flow reversal, is that the flow speed varies a lot. So there will be a point at which the airflow velocity matches the **flame speed**. (The flame speed is the speed, relative to the airflow, at which the flame can move.) This is the point where the flame **anchors**.

## 2.6 Cooling

The liner is exposed to high temperatures, during combustion. It therefore needs to be cooled, using the airflow in the annulus. There are several ways to do this.

In **film cooling**, stacks of holes are put in the liner. These holes inject air along the inner surface of the liner, providing a protective cooling film. A downside is that the liner is not cooled evenly. The best way to cool the liner evenly, is by using **transpiration cooling**. Now, the liner wall is constructed from a porous material that allows air to pass through it.

Next to these cooling methods, we can also put **metallic tiles** onto the inner surface of the liner. This provides some protection. Finally, the airflow passing through the annulus will also automatically provide some **convection cooling**.

## 2.7 Combustor types

We can distinguish combustors by their shape. **Can-type combustors** (also known as **tubular combustors**) consist of several cylindrical tubes, placed around the turbine shaft. Each tube has both a liner and a casing. Although these types of turbines are easy to develop, their weight is relatively high.

Another type of combustor is the **annular combustor**. The annular combustor has a single ring-shaped liner mounted inside a single ring-shaped casing. Due to the low weight, this type is mostly used in aircraft jet engines. A downside is that it's sensitive to buckling loads.

Finally, we can combine the can-type and the annular combustor. We then get a **can-annular combustor**. We now have several cylindrical liners (like in the tubular combustor) placed in a single ring-shaped casing (like in an annular combustor).

### 3 Unwanted phenomena

Gas turbines don't just deliver power, without any side-effects. We will now look at the bad sides of the combustion chamber.

#### 3.1 Combustion stability

An important property of a combustion chamber is **combustion stability**. To have combustion stability, the flame must remain stable at varying fuel mixtures, inlet temperatures, turbulence levels, flow speeds and so on. If it doesn't, things can go wrong.

To simplify the idea of combustion stability, we usually only consider the mixture. The combustion stability now depends on the range of the *FAR* at which the flame remains stable. If the flame dies due to too much fuel, we have **rich extinction**. Similarly, if there is too little fuel, we have **weak extinction**.

The two limits mainly depend on the mass flow of air  $\dot{m}_{air}$  passing through the combustion chamber. Flames have trouble surviving at high flow velocities. And a high flow velocity is, of course, linked to a high mass flow. So too high flow velocities/mass flows aren't good. On the other hand, if the flow velocity is too low, the flame will move upstream. This is called **flashback**. It's not very good either. So, we don't want a low flow velocity either.

#### 3.2 Losses

Several losses occur in the combustion chamber. First, there is a heat loss. This has several causes. Heat is being spent on heating up/vaporizing the fuel, and on heating the combustor itself. Another cause is **incomplete combustion**. If part of the fuel does not combust, then heat is wasted. To take this into account, we define the **factor of complete combustion**  $\eta_{complete}$  as

$$\eta_{complete} = \frac{\dot{m}_f^{reacted}}{\dot{m}_f^{injected}} = \frac{\dot{m}_f^{evaporated}}{\dot{m}_f^{injected}} \frac{\dot{m}_f^{mixed}}{\dot{m}_f^{evaporated}} \frac{\dot{m}_f^{reacted}}{\dot{m}_f^{mixed}}. \quad (3.1)$$

Luckily, we have  $\eta_{complete} \approx 100\%$  at normal operating conditions.

Next to heat losses, there are also pressure losses. The so-called **cold losses** are caused by skin friction and turbulence effects. These are, in turn, caused by the diffuser, the swirler and the liner. So, we have

$$(\Delta p_{03-04})_{cold} = (\Delta p)_{diffuser} + (\Delta p)_{swirler} + (\Delta p)_{liner}. \quad (3.2)$$

The **hot losses** are caused by changes in momentum of the flow. They are caused by temperature changes. An estimation of the hot pressure losses is given by

$$(\Delta p_{03-04})_{hot} = \frac{1}{2} \rho_3 V_3 \left( \frac{T_4}{T_3} - 1 \right), \quad \text{where} \quad V_3 = \frac{\dot{m}_3}{\rho_3} A_{casing}. \quad (3.3)$$

#### 3.3 Pollutants

Hydrocarbon-fueled gas turbines usually have several unwanted combustion products. The most important combustion products are  $H_2O$ ,  $CO_2$ ,  $O_2$  and  $N_2$ . These are the so-called **products of complete combustion**, and make up 99% of the combustion products.

The remainder of the combustion products can be split up into two groups. The group of **gaseous pollutants** consists of **nitrogen oxides**  $NO_x$ , **carbon monoxide**  $CO$  and a variety of **unburned**

**hydrocarbons UHCs**. The amount of gaseous pollutants is usually given by the **emission index** (EI). This is defined as

$$EI = \frac{\text{mass of the produced pollutant in } g}{\text{mass of fuel used in } kg}. \quad (3.4)$$

The second group of remaining combustion products is called **smoke**. It mainly consists of **soot particles**, which are particles with a high amount of carbon in them.