Popular science summary

Modern society heavily relies on combustion processes to satisfy the different energy demands of everyday life. Combustion still plays a vital role in fulfilling the needs of a vast range of sectors, e.g., transportation, heating, propulsion, and industrial processes. Although renewable energy sources, such as solar, hydro, and wind energy, exist, more than 80% of the total global energy is provided by combustion devices, e.g., internal combustion engines and gas turbines, using fossil fuels. However, the main drawback of the combustion of these types of fuels is the emission of unwanted species that represent health and environmental hazards. The primary emissions are carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons, particulate matter, nitrogen oxides (NO_x), and in some applications, sulfur oxides (SO_x) and heavy metals. Furthermore, the availability of fossil fuels is limited, representing a severe problem in modern times when the energy demand constantly increases over time. Therefore, it is of enormous interest to discover and develop alternative fuels that can (i) be easily accessed and (ii) be able to reduce the level of pollutants. To this end, a question arises: how is the performance of combustion devices affected by using a different fuel?

It is generally impossible to replace an existing fuel with another one, as different fuels have different burning speeds. Some fuels burn faster than others, while some burn slower. Ideally, the flame should be located in the combustion chamber of the device. However, if a fuel burns slower than the original fuel for which the device was designed, the flame may be pushed out of the combustion chamber. This phenomenon is known as a blow-out. On the other hand, if the fuel burns too quickly, the flame may move toward the fuel supply pipes. This is known as a flashback. Neither of these phenomena is desirable, as they can cause the flame to disappear or damage the device. Therefore, it is essential to carefully consider the fuel's properties and the device's design before attempting to replace the fuel. In some cases, modifications may need to be made to the device to ensure that the new fuel can be used safely and effectively.

This thesis addresses the above issues, focusing on gas turbine engines. Gas turbines are engines that can convert the chemical energy content of a fuel into mechanical power. In stationary applications, this power can be connected to a generator for electric power generation. Gas turbines typically consist of three main parts: a compressor, a combustor, and a turbine. The combustor is often operated using premixed natural gas flames. The need to address the challenge of reducing environmental impact has increased interest in carbon-free fuels such as green hydrogen. The absence of carbon atoms eliminates the production of some pollutant species such as CO and CO_2. However, hydrogen flames have much higher flame speeds than natural gas and are very unstable in existing gas turbine combustors. Therefore, it is common to blend hydrogen with other fuels, such as natural gas, rather than burning pure hydrogen.

In modern gas turbine engines for electricity production, the fuel and air are often premixed before being supplied to the combustion chamber. By reducing the amount of fuel mixed to the air to form a fuel-lean reactant mixture, it is possible to reduce the flame temperature, thus the emission of NO_x. However, the flame under this fuel-lean mixture conditions becomes harder to stabilize. The flame propagation depends on the chemical reaction, the turbulent flow in the combustor, the interaction of the fresh products with already burned gases, and the heat transfer of the flame with the surrounding environment. Investigating these various physical and chemical processes is crucial to understand flame propagation. This can be done using experimental methods and numerical simulations.

Accurate measurement techniques are required to visualize and observe what is happening during combustion. Within this context, laser-based diagnostic techniques represent a reliable method to investigate flames due to their capability of capturing very small phenomena that occur in a short time. Furthermore, these techniques give the possibility to provide information such as velocity field, species distribution, and temperature without disturbing the chemical processes and flame dynamics. Additionally, numerical simulations are commonly employed to investigate flame characteristics. In this approach, flames are described using mathematical equations solved using computer programs, providing an opportunity to achieve a deeper understanding of the flames.

In this thesis, I have utilized experimental and numerical approaches to investigate the flame dynamics of new fuels for gas turbine engines, including carbon-free hydrogen and biomass-derived syngas. The objective is to better understand flame propagation and its dynamics for different fuels under conditions relevant for gas turbines. The main contributions of this thesis are: (i) the understanding of the thermal expansion effect on the flame propagation speed; (ii) the characterization of flame structures and dynamic behavior of different fuels, including hydrogen, biomass-derived syngas, and mixtures of hydrogen and natural gas. Since applying laser-based measurement techniques in actual gas turbines is impossible, the experiments reported in this thesis were carried out in a smaller model gas turbine combustor that mimics the behaviour of the ones used to electric power generation. The results explain the processes leading to CO and NO_x emissions under various fuel/air mixture conditions. A fundamental understanding of local flame propagation characteristics is provided using high-fidelity numerical simulations. The results provide insights into the basic combustion processes in the combustor, aiding in the design of gas turbine engines operating on renewable carbon-free or carbon-neutral fuels to address the UN Paris agreement on the decarbonization of our society and industry.