

Project Goals

The project aims to analyze the physics of turbulent hydrogen combustion in an atmosphere of oxygen and water vapor mixture, as well as hydrogen and ammonia mixture in air, and to control these processes. In the first case, eliminating nitrogen results in water vapor being the only combustion product, making the process exceptionally clean. Combustion of the hydrogen and ammonia mixture, although it leads to the formation of harmful NO_x compounds at high temperatures, does not produce carbon dioxide, eliminating the main cause of the greenhouse effect. The project involves studying flames in the vicinity of typical injection system components, such as the fuel nozzle and non-streamlined body. The project's tasks focus on thoroughly understanding the mixing process and its intensification or suppression by enhancing interactions between large and small flow scales. These phenomena, still not fully understood, currently limit the development of low-emission and safe industrial devices, especially in the case of hydrogen and ammonia combustion and hydrogen combustion in oxygen, whose kinetics are not yet well known compared to hydrocarbon fuels. Particular attention will be given to the following issues: (i) controlling the shapes of internal and external recirculation zones formed in the wake of the bluff body and near the fuel nozzle; (ii) flame dynamics and stability; (iii) pollution reduction; (iv) strongly unsteady phenomena such as ignition and flame propagation or extinction, which are key factors for safety, reliability, environmental cleanliness, and efficiency. The key result of the project will be a better understanding of the mechanisms of turbulent mixing and combustion of hydrogen in oxygen and water vapor, as well as hydrogen and ammonia, and information on how these processes can be optimized. The specific objectives of this project are as follows:

- Development and verification of passive/active optimization methods that will enable effective utilization of interactions between flow/flame scales across the entire energy spectrum.
- Deepening knowledge on strongly unsteady phenomena (ignition, flame propagation) that are crucial for the development of innovative, efficient, and environmentally friendly fuels.

Research Methodology

The project will utilize passive and active flow control techniques. The former will involve adjusting the shapes of nozzles and bluff bodies and changing the topology of their walls. Previous studies have shown that the liquid/gas stream flowing from nozzles and channels with irregular shapes, sharp edges, or along wavy surfaces is characterized by an elevated level of turbulence and intensified mixing. The project will verify to what extent this affects the combustion of hydrogen and ammonia. Beyond deepening the knowledge of turbulent flames behind fuel nozzles and bluff bodies, we will seek their preferred shapes for various fuel and oxidizer parameters (velocity, composition, temperatures) depending on the adopted optimization criterion (e.g., maximum/minimum flame lift-off height, maximum/minimum flame surface area, most uniform temperature distribution, etc.). Regarding flame control under different flow conditions, active control methods seem more effective. They assume the delivery of external energy (excitation), the type and level of which can be predetermined or changed depending on the flow behavior (interactive approach). In the project, active control will be achieved through modulated excitation introduced into the flow as axial and axial combined with helical (azimuthal) forcing. The research will be conducted using advanced CFD tools (DNS, LES, Eulerian PDF methods, computational program base on high-order discretization) and will be supplemented by experimental analyses. Optimization will be supported by the application of machine learning methods (Bayesian optimization, deep learning).

Expected Impact of the Research Project on the Development of Science

The widespread use of hydrogen and ammonia is currently limited by insufficient knowledge of the interactions between flow and flame and the lack of effective methods for controlling strongly unsteady combustion processes (e.g., flame stabilization, propagation, autoignition, and spark ignition). Autoignition, flame spread, and stabilization are conditioned by the mixing of fuel and oxidizer in high-temperature areas, while spark ignition depends on whether it is initiated in a well-mixed flammable mixture region. It can be assumed that through accurate and precise prediction of mixing phenomena, both spark and autoignition processes, as well as flame propagation/stabilization, can be effectively controlled, which is crucial for the efficiency and safety of many industrial devices. The ability to change the shape and dynamics of the flame is very enticing, and work in this direction will open new perspectives for both scientists and engineers.