Abstract

The global urgency to reduce greenhouse gases emissions has accelerated the search for sustainable solutions in the transportation sector, traditionally dominated by fossil fuel-powered engines. Among the various alternatives, the use of hydrogen in internal combustion engines (H_2-ICEs) represents a promising path due to its zero carbon content and its compatibility with the existing fleet. In this context, High Pressure Direct Injection (H_2-HPDI) technology—already successfully tested on heavy-duty engines—offers high efficiency and the ability to avoid major abnormal combustion phenomena commonly associated with hydrogen combustion systems, such as knock, preignition and backfire.

However, the current technical literature lacks studies dedicated to the application of H_2-HPDI technology in light-duty engines, although this segment accounts for around 60% of CO_2 emissions in road transport. This thesis addresses that gap through a comprehensive numerical investigation of the potential of H_2-HPDI combustion for light-duty engines, employing a synergetic approach that combines high-fidelity 3D-CFD simulations with system-level 0D/1D-CFD modeling.

The work initially focused on the development and validation of a 3D-CFD model for H_2-HPDI combustion, starting from experimental data obtained on a 2.1 L/cylinder heavy-duty engine. The model demonstrated excellent predictive capabilities in terms of in-cylinder pressure, heat release rate, and NO_x emissions. The model was then employed to analyze the combustion process in a 0.5 L/cylinder light-duty engine, highlighting the differences with respect to the larger scale in terms of efficiency, thermal losses, and combustion phenomenology.

Subsequently, a predictive combustion model was calibrated for the 1D-CFD environment, using the dataset generated through 3D-CFD simulations. This model enabled the construction of a complete operating map for the H_2-HPDI engine,

considering real mechanical constraints and engine components, defining an optimal calibration strategy in terms of efficiency and NO_x emissions.

The results show that the H_2-HPDI configuration can achieve a peak indicated thermal efficiency close to 49% and a peak IMEP exceeding 21 bar, with a drastic reduction in specific CO_2 emissions compared to the Diesel configuration. However, NO_x emissions remain high in the absence of EGR, indicating the need for mitigation strategies such as exhaust gas recirculation.

Finally, the H_2-HPDI engine results were compared with alternative solutions implemented on the same engine, including conventional Diesel and H_2-PFI with spark ignition systems. The H_2-HPDI technology stood out for its combination of high efficiency, high power density, and strong CO_2 reduction, albeit requiring careful balancing between efficiency and NO_x control. This thesis contributes to bridging a significant knowledge gap by assessing the potential of H_2-HPDI technology for light-duty engines and providing a solid numerical analysis foundation for its development.