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Combined LES and Experimental Approaches for Analyzing Combustion Variability in a Spark-Ignition Hydrogen Engine under Ultra-Lean, Low-Load Regimes

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Under ultra-lean conditions, hydrogen-air mixtures are highly sensitive to thermodynamic variations, and the differential diffusion effects strongly influence flame structure and propagation, especially under strain and curvature. These phenomena contribute to cyclic variability in spark-ignition engines, a critical yet still poorly understood issue for hydrogen combustion. To address this, a combined numerical and experimental study is conducted on a spark-ignition engine operating under perfectly premixed ultra-lean and low-load conditions. A dedicated validation framework is established, leveraging experimental data [1] and Large-Eddy Simulations (LES) using the Extended Coherent Flame Model (ECFM-LES) [2,3].

To strengthen this approach, simultaneous analyses of numerical in-cylinder pressure, heat release rate, and velocity fields, along with their experimental counterparts, including in-cylinder pressure measurements, chemiluminescence imaging, and PIV in multiple planes, were conducted. This comprehensive dataset served three main objectives: (1) reduce uncertainties in the numerical boundary conditions, (2) calibrate the parameters of the ECFM-LES model, and (3) characterize and compare flame behavior, focusing on flame development and cyclic variability. For the latter, instantaneous resolved velocity fields and High-speed PIV measurements in different planes are used to investigate the influence of in-cylinder flow structures on turbulent flame dynamics. Comparisons between flame radii obtained via chemiluminescence and LES highlight three-dimensional effects. The impact of flow on combustion cyclic variability is further analyzed across three equivalence ratios: 0.35, 0.40, and 0.45.

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