

Early flame development characterization of ultra-lean hydrogen-air flames in an optical spark-ignition engine

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Hydrogen-fueled internal combustion engines (H2ICEs) represent a promising technology for decarbonizing the transport sector. In pursuit of this goal, research is needed on lean hydrogen-air combustion under engine conditions aiming to mitigate NO_x emissions. However, there is a limited amount of experimental data focusing on flame development at high pressure and temperature, especially in ultra-lean mixtures, which are recently considered to play an important role for future H2ICEs. This study investigates the behavior of very-lean to ultra-lean hydrogen-air flames ($0.20 < \phi < 0.55$) in an optical spark-ignition engine, focusing on the early flame development phase. Fuel-air equivalence ratio and engine speed ($900 < N < 1500$ rpm) effects on hydrogen combustion are addressed with pressure-based heat release analysis and chemiluminescence flame imaging techniques. The findings revealed an intrinsic association between these two approaches. Hydrogen flames development measured before 2% of Mass Fraction Burned (MFB) strongly correlates with pressure-based quantities up to 50% MFB, underscoring the critical role of understanding the early flame phase for predicting total combustion duration and in-cylinder pressure traces. A model for hydrogen turbulent flames in the initial combustion stages is formulated based on the Zimont equation and the experimental data. An equation for 0D/1D combustion duration prediction up to 10% MFB is proposed, demonstrating its validity from the wrinkled flame to the well-stirred reactor premixed combustion regimes. Additionally, flame chemiluminescence images for each zone within the Peters-Borghgi diagram are presented, offering valuable insights into the diverse characteristics of these flames.

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