Physics-informed machine learning for predicting flame attachment in hydrogen-air flames stabilized on a coaxial injector

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Hydrogen is increasingly seen as a promising low-carbon alternative to conventional hydrocarbon fuels, particularly in sectors like aeronautics. Its use in combustion, however, raises specific challenges, including flame flashback and NOx emissions, calling for advanced injector designs and predictive modeling strategies.

Recent experimental work by Leroy *et al.* [1–3] has shown that a dual-swirl coaxial injector can stabilize a range of hydrogen-air flame structures, including both attached and lifted configurations, depending on flow conditions. Those studies have also revealed a strong dependence of NOx emissions on the flame structure and tried to establish and validate scaling laws for NOx emissions. However, the proposed correlations struggled to generalize across the wide range of flame configurations observed, motivating the use of flame-shape classification as a preliminary step before applying adaptive, regime-specific scaling laws for improved prediction of pollutant emissions.

This study aims to predict flame attachment and detachment using machine learning techniques enriched by physically interpretable features. A comprehensive experimental database comprising 226 flame configurations is used, with 15 operating parameters varied during the test campaign. A reduced input set of five key parameters is selected to train a neural network classifier based on a multi-layer perceptron (MLP) architecture. The model achieves a classification accuracy of 98.7% in distinguishing attached from lifted flames, demonstrating its effectiveness. In parallel, non-reactive numerical simulations are used to extract strain-rate fields and other flow-derived features to enhance the capabilities of the neural network classifier and identify a minimal set of interpretable physical criteria governing flame stabilization.

This work blends physics-based modeling and data-driven tools to deliver a predictive and interpretable reduced-order model, while providing insight into the underlying mechanisms controlling flame attachment in hydrogen combustion systems.

References

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