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A Thermodiffusive Instability Aware Artifically Thickend Flame Model: From Laminar Instabilities to Internal Combustion Engines

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Hydrogen and other renewable fuels exhibit distinct combustion behaviors that expose key limitations in existing models, particularly under realistic combustor conditions. Lean hydrogen flames are especially susceptible to thermodiffusive (TD) instabilities, which are not adequately captured by conventional approaches such as the artificially thickened flame (ATF) model, even in laminar configurations [1].

To address this shortcoming, we previously introduced a thermodiffusive efficiency function tailored to laminar flames. In the present work, we extend this model to turbulent, engine-relevant conditions, explicitly accounting for effects such as fuel blending and exhaust gas recirculation. A generalized formulation is proposed to capture intrinsic instabilities across a broad range of operating conditions, including variations in equivalence ratio, elevated pressures, high temperatures, and hydrogen blends with ammonia and methane.

Following successful initial validation under well-defined laminar conditions, the extended model is applied to a turbulent jet flame and evaluated against benchmark DNS data to demonstrate its capability to accurately capture intricate flame dynamics. Satisfactory agreement is achieved when the new model extension is incorporated.

For an application-oriented test case, we perform three-dimensional engine simulations coupling detailed chemistry with the standard ATF model without model extensions. By systematically refining the local mesh resolution, we reduce the degree of flame thickening, consistently improving agreement with experimental observations. However, this comes at a considerable computational cost, underscoring that TD instability effects - better resolved at finer mesh levels - are insufficiently represented in the standard ATF framework.

To overcome this limitation, we implement our novel model extension that explicitly accounts for TD instability effects. This extension enables accurate predictions of consumption speeds and significantly enhances overall model fidelity, achieving accuracy comparable to high-resolution simulations but at substantially reduced computational cost.

The proposed model represents a significant advancement by enabling the widely used ATF approach to accurately predict flame speeds in configurations prone to thermo-diffusive instabilities, even in complex geometries and under technically relevant combustor conditions such as elevated pressures and temperatures.

References

[1] Schuh, V., Hasse, C., & Nicolai, H. (2024). An extension of the artificially thickened flame approach for premixed hydrogen flames with intrinsic instabilities. *Proceedings of the Combustion Institute*, 40(1-4), 105673.