HYBRIDISATION OF THE THICKENED FLAME MODEL AND EDDY DISSIPATION CONCEPT FOR HIGH-FIDELITY MULTI-REGIME COMBUSTION MODELLING

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Abstract
High-fidelity simulations of gas turbine combustors face challenges due to multi-regime combustion and high-Reynolds-number flows, making turbulence–chemistry interaction (TCI) modelling essential. This study proposes a hybrid approach combining the Thickened Flame Model (TFM) for premixed combustion with the Eddy Dissipation Concept (EDC) for non-premixed regions. Two EDC variants are evaluated on pseudo-2D counterflow flames, followed by the first application of TFM–EDC to a rich-lean configuration. The impact of flame index formulation on regime detection is also assessed.

Introduction
Driven by the global push for decarbonisation, modern gas turbine combustor design increasingly targets low-emission technologies [1-2]. These systems often involve complex flame stabilisation, leading to multi-regime combustion [3]. To capture distinct premixed and non-premixed behaviours, multi-regime models typically rely on a flame index to trigger regime-specific TCI closures. The common species-transport-based approach applies TFM in premixed zones, disabling thickening in non-premixed regions, effectively defaulting to a Finite-Rate (FR) model [4-5]. However, FR neglects TCI and requires DNS-like resolution, limiting its use in high-Reynolds-number flows and introducing significant inaccuracies [6].
This work introduces a hybrid approach combining TFM for premixed regions with EDC for non-premixed zones. Two LES-adapted EDC formulations are compared against FR to assess accuracy and robustness. The influence of flame index choice on regime detection and heat release prediction is also evaluated. Finally, the first implementation and validation of the TFM–EDC model is presented.

Multi-regime Combustion Modelling: TFM-EDC
The proposed approach is built around the Dynamic TFM for LES (DTFLES), originally developed by Legier et al. [7], utilising Colin's [8] formulation for the

efficiency function (*E*). Here, the transport equation for the *i-th* species is written as:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \vec{v} Y_i) = \nabla \rho (EFD_l + (1-S)D_t)\nabla Y_i + \frac{E}{F}\dot{\omega}_i \qquad (1)$$

with *S* the flame sensor and *F* the thickening factor.
When a non-premixed regime is detected via a flame index, Equation (1) becomes:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \vec{v} Y_i) = \nabla \rho (D_l + D_t)\nabla Y_i + \kappa \dot{\omega}_i \qquad (2)$$

where κ is the fine structure volume fraction from the EDC model. Two LES-adapted EDC variants – EDC-S and EDC-PF – are compared in non-premixed conditions. For model details, the reader is referred to [9] and [10].

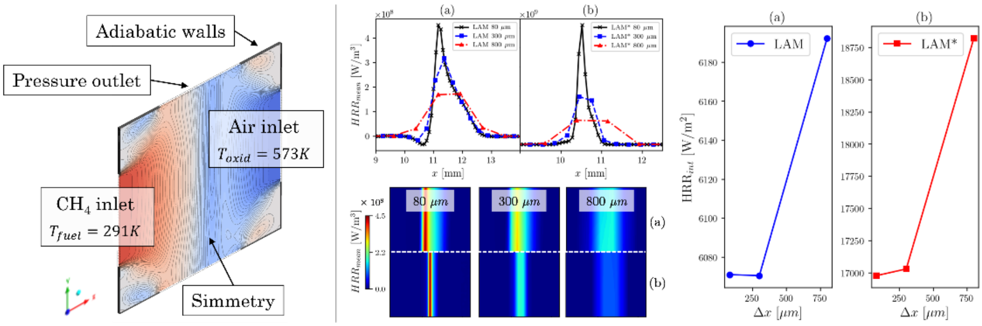

Figure 1. Computational domain (left) and laminar case results (right).

Computational Domain and Setup Validation

A pseudo-2D CH_4–air counterflow diffusion flame was used for setup validation, replicating results by Cuenot et al. [11] on the effects of mesh resolution on heat release rate (HRR). The domain is a 20 *mm* square, with a single cell in the z-direction. Walls are adiabatic. A 19-species, 62-reaction reduced UCSD mechanism was used. Three mesh sizes (80, 300, 800 μm) and two strain levels were tested. Results in Fig. 1 show that coarsening reduces the HRR peak while significantly overestimating its integral – especially at higher strain – matching reference trends and validating the setup.

Turbulent Counter-diffusion flames

The goal of this study is to recover the global HRR on coarse meshes by incorporating TCI, which is absent in the FR approach. A turbulent campaign on the same domain was conducted to evaluate the two EDC formulations and their sensitivity to mesh resolution. As shown in Fig. 2, both EDC variants show reduced dependence on mesh coarsening compared to FR, with PF performing best – despite a slight HRR underestimation due to its more conservative κ expression.

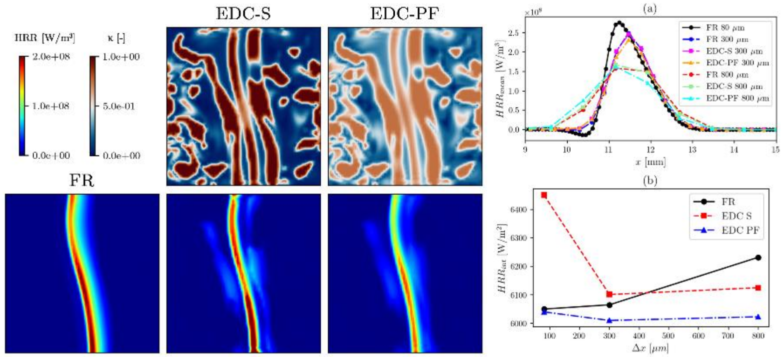

Figure 2. Effects of κ on the instantaneous HRR (left) and turbulent results (right).

Rich-lean Configuration: Flame Index impact and TFM-EDC

A rich-lean configuration was used to assess the impact of flame index formulation on regime detection and global HRR prediction using the DTFLES-FR approach. In Fig. 3 (left), the Takeno index (FI_T) [12] and premixedness index (FI_{PF}) [13] are compared and overlaid with the thickening factor (F). Despite the globally diffusive nature of the flame, FI_T incorrectly identifies a nearly fully premixed regime, activating F and overestimating HRR by ~50%. In contrast, FI_{PF} correctly identifies a non-premixed regime, leading to an FR closure and accurate flame reconstruction. Finally, the TFM-EDC model was applied to the same case using EDC-S and FI_{PF}. As shown in Fig. 3 (right), the results align with the FR reference, with $\kappa \approx 1$ near the flame front. The TFM-EDC is successfully implemented and shows strong potential for future application to more complex 3D flames.

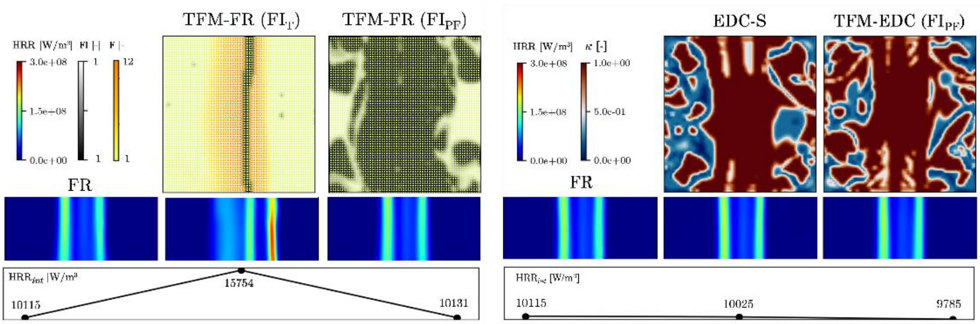

Figure 3. Comparison of FI impact on F and HRR prediction (left), and results from the TFM-EDC model with EDC-S and FI_{PF} (right).

Conclusion

This study demonstrates the feasibility and advantages of the TFM-EDC hybrid approach for multi-regime combustion modelling in LES. By enabling accurate HRR prediction on coarse meshes, the method offers a promising foundation for future applications in realistic 3D combustor configurations.

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