Narrative Report

PRF# 58173-DNI9

Project Title: A Computational study of the lean blow-off mechanisms for a bluff-body stabilized premixed flame

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Lean but stable combustors have received significant technological interest in gas turbine combustors, afterburners and industrial furnaces, due to the increasingly stringent emission requirements. Bluff-bodies are frequently employed to stabilize flames in premixed fuel-air streams, where lean blowoff is a safety and operational concern. The dynamic physicochemical events leading to lean blowoff are still not well understood, due to the highly-transient turbulent flow fields, the important role of finite-rate chemistry and their complex competition. The objective of the proposed research is to understand the intimate interactions between turbulence and chemistry, through computational studies that account for multi-step finite-rate chemistry with a mildly thickened flame (TF) model.

Over the second year of the project, we focused on 1) development, implementation, and *a posteriori* test of new flame sensors that are more robust and more suitable for extinction conditions; and 2) understanding the thermochemical states of bluff-body stabilized flames near blowoff. For Focus 1, a few flame sensors, including HCO concentration, overlapping zones of OH and CH_2O, and heat release rates, are implemented and compared, using one-dimensional laminar flames. The HCO radical and OH/CH_2O markers successfully recover the laminar flame speed for lean flames with different inlet temperatures at atmospheric pressure. Both of the radical-based sensors out-perform the heat release rates, because a low-intensity heat release rate zone unnecessarily broadened the post flame zone. Due to its simple implementation, HCO is chosen and implemented into the thickened flame model (TF) that was implemented in OpenFOAM in year 1. The HCO based flame sensor is further examined using a counter-flow twin premixed flames configuration, by marching through the upper branch of the S-curve. As shown in Fig. 1, thickening of a flame alters the corresponding extinction strain rates, due to modification of the diffusion process. With the HCO based flame sensor, the extinction strain rate is predicted to be within 30% of the laminar case, with $F = 1.5$. To achieve the same accuracy with a constant thickening factor, a value of $F = 1.33$ is required, indicating that the HCO based sensor can work with a coarser mesh near the extinction condition. A dynamic thickening procedure is also implemented into the modeling framework, to account for the local variation of grid resolution and flame thickness.

To assess the performance of the new sensor and dynamic thickening procedure, a Bunsen flame and a dual-swirl gas turbine combustor are simulated through large-eddy simulations (LES) using the TF model. For both flames, a methane/air mixture is employed, and a 16-species reduced mechanism is used to describe the finite-rate chemistry. The configuration of the Bunsen flame is adopted from an existing DNS study, and the LES results are compared to the filtered DNS. The LES grid is taken to be twice and four times the DNS grid, and good agreement with DNS has been observed for both cases. The dual-swirl gas turbine combustor from DLR has been studied extensively both experimentally and numerically. For comparison, a transported probability density function method (PDF) is also applied to simulate the gas turbine combustor. Relatively coarse mesh is used, compared to most existing studies in the literature. The mean velocity fields, temperature and species are captured by the TF model and the PDF model. Slightly better agreement with experimental data is observed for CO prediction using the PDF model than using the TF model, although the cost of the PDF model is five times that of the TF model.

The ultimate goal is to incorporate information obtained from Chemical Explosive Mode Analysis (CEMA) into the TF model, to dynamically select the thickening factor suitable for capturing extinction. CEMA is performed on the lean propane/air flame modeled in year 1. It is observed in Fig. 3 that the recirculation zone becomes explosive near blowoff. For regions where diffusion contributes more significantly to the re-ignition propensity (i.e., blue and green), thickening should be limited. This information will be built into the TF model in year 3.

During the second year of this grant, the PI and her lab continued their exploration of the critical problem of flame extinction. The PI was invited to Technische Universität Darmstadt, Germany in May 2019 to give a seminar on her efforts in high-fidelity turbulent combustion modelling, where she presented results obtained from the bluff-body stabilized flame simulations. With the international relationship she established through support from the PRF funds, her lab started collaboration with researchers from DLR, Germany since Fall 2018. The project provides two graduate students significant training opportunities, in terms of understanding of turbulence-chemistry interactions, numerical methods, and professional development in presenting their findings through international conferences and journal publications. One student presented his findings on robust flame sensor and its performance in capturing extinction during the 71st annual American Physical Society Division of Fluid Dynamics meeting. Another student presented her effort in analyzing the bluff-body stabilized premixed flame near blowoff using CEMA during the 2019 AIAA Scitech.

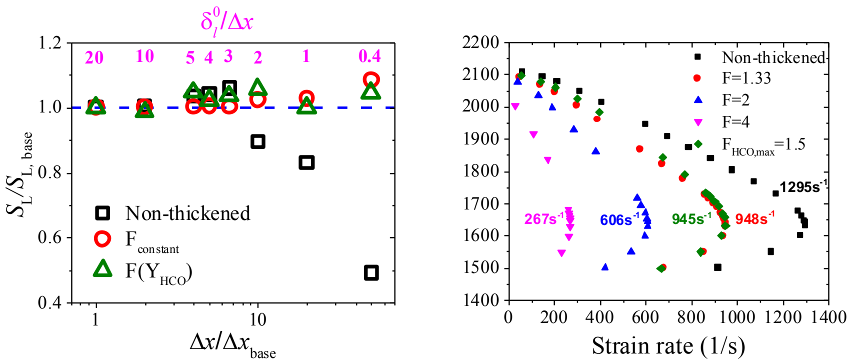

Figure 1 Performance of the new flame sensor (HCO radical). Left: HCO based sensor recovers the laminar flame speed for grid spacing as long as $50\Delta_{DNS}$. Right: HCO based sensor can allow the usage of coarser grid while recovering the extinction strain rate, which is a critical quantity for capturing flame extinction.

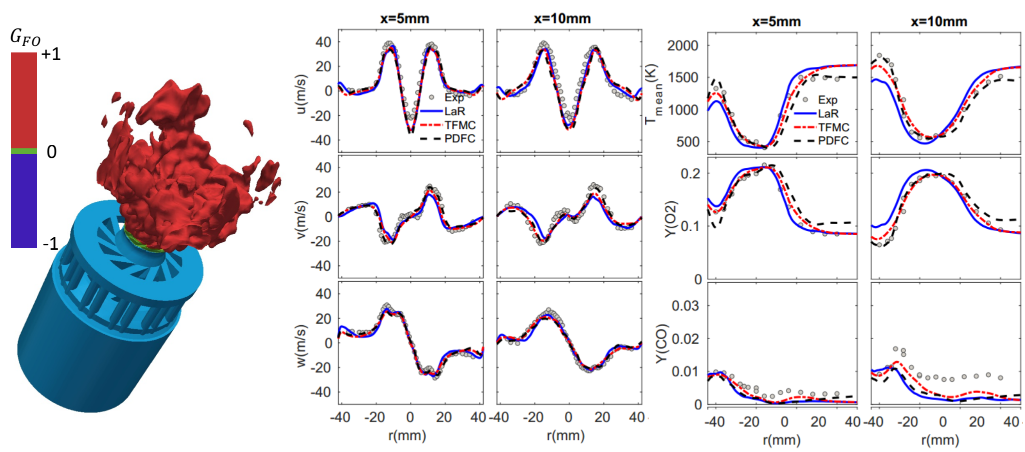

Figure 2 Simulation of a DLR dual-swirl combustor. Left: flame index indicating dominant premixed mode. Right: comparison with experimental measurements and with a PDF model.

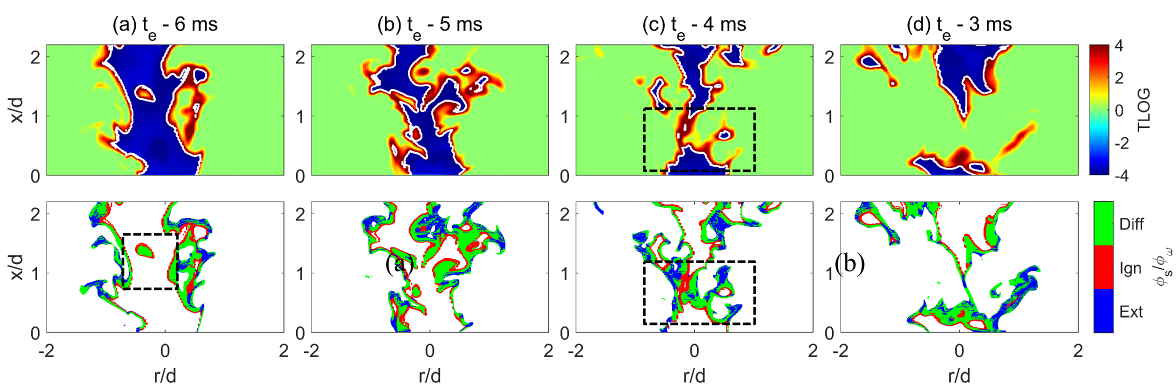

Figure 3 CEMA of four snapshots of a bluff-body stabilized turbulent premixed propane flame. Top: chemical explosive mode indicating explosive mixtures. Bottom: analysis of contribution from diffusion and the chemical reactions, demarcating diffusion-controlled region (green and blue).