CFD OF NONLINEAR THERMOACOUSTICS OF BLUFF-BODY STABILIZED PREMIXED FLAMES

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Introduction

Confined turbulent premixed flames are susceptible to thermoacoustic instability, and self-excited oscillations can occur if perturbations in the heat release rate are in phase with pressure fluctuations arising from the natural acoustic modes of the system [1]. For bluff-body stabilized flames of an afterburner type configuration, hydrodynamic instabilities induced by the Kelvin–Helmholtz [2] and Bernard/Von–Karman mechanisms [3] can lead to strong changes in the flame surface area. Intense rollup of the flame leads to strong perturbations of heat release and hence promotes thermoacoustic instability.

Nonlinear interactions come into play and dominate the system dynamics once the oscillations attain certain amplitude. Nonlinear aspects of thermoacoustics are prevalent in turbulent flames, as their dynamics can change dramatically at certain critical values of inlet velocity or equivalence ratio. Often, there is a sudden transition from a low amplitude oscillation under nominally stable conditions to an oscillation with much larger amplitude. Such behaviour has been observed in dump combustors [4], bluff-body stabilized flames [5] and swirl-stabilized combustion chambers [6], and may indicate that the system is bistable, which arises when the bifurcation from linear stability is subcritical.

A systematic approach to investigate flame dynamics during thermoacoustic instabilities is to evaluate the effect of individual parameters on stability, focusing on the transition of the system from a steady state to instability via a Hopf bifurcation. Using CFD, this methodology is applied to study the stability of the Volvo afterburner experiment [7] at six different equivalence ratios. Combustion instabilities have been reported to occur at specific operating conditions, and the transition to instability is well-documented [7]. Further LES simulations verify the presence of these instabilities and the corresponding mechanisms [8]. In this work, we validate our results against experiments, and examine the self-excited response using nonlinear dynamical systems theory, revealing rich nonlinear behaviour and the corresponding bifurcations. The flame structure is shown to change dramatically across the bifurcations and a stability map is constructed.

Numerical Approach

The governing equations for turbulent combustion are solved using the URANS approach, with Favre ensemble averaging and a Reynolds stress turbulence model [9]. The BML combustion model is used [10] with a reaction progress variable $c$ defined in terms of a normalised fuel mass fraction.

$$\frac{\partial c}{\partial t} + \sum_{i} \frac{\partial u_i c}{\partial x_i} = \frac{\partial \left( \rho u_i c \right) }{\partial x_i} + \frac{\partial \left( \rho \overline{u_i c'} \right) }{\partial x_i}$$

The turbulent scalar flux $\overline{\rho u_i c'}$ is modelled using a gradient transport hypothesis [11]. The term $\overline{\rho}$ is the mean turbulent reaction rate and is modelled as $\overline{\rho} = \rho_s S_l I_l$ where $\rho_s$ is the reactant density, $S_l$ is the unstrained laminar flame speed, $I_l$ is a correction factor accounting for strain and curvature effects, and $\Sigma$ is the flame surface density (FSD). Parameterisation of $S_l$ and details of the modelling for $\Sigma$ and $I_l$ are discussed elsewhere [12, 13] and the formulation has been applied successfully in previous work on the thermoacoustics of flames [13].

A two-dimensional domain is considered and the PISO solution algorithm [14] is adopted. The inflow axial velocity of the fully premixed propane–air mixture was fixed at 17.3 m/s with 4% turbulence intensity. The inlet temperature is 288 K, and a constant pressure boundary condition at 101325 Pa is applied at the outlet. A zero gradient is specified for all other variables at the boundary. The walls are treated as rigid, stationary, adiabatic and impermeable, and standard turbulence wall functions are used.

Results

Figure 1: Flame structure at different values of $\Phi$

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Conclusions

Nonlinear dynamics of turbulent premixed bluff-body stabilized flames have been studied using turbulent combustion CFD with dynamical systems theory. Transitions in the global flame dynamics have been observed as the equivalence ratio is varied. A steady flame is observed between $\Phi = 0.70$ and $\Phi = 0.75$. Such dynamical behaviour is confirmed by the fixed point attractor in phase space and the lack of a dominant frequency in the PSD. The system bifurcates to an oscillating state between $\Phi = 0.65$ and $\Phi = 0.70$ and between $\Phi = 0.75$ and $\Phi = 0.80$. The system at $\Phi = 0.60$ and $\Phi = 0.65$ exhibits quasiperiodic behaviour (torus attractor) and a limit cycle (closed-loop attractor) respectively whereas the system at $\Phi = 0.80$ and $\Phi = 0.85$ corresponds to a limit cycle (closed-loop attractor) and period–two state (double closed-loop).

References