Near-blowoff dynamics of bluff-body-stabilized premixed flames in a narrow channel

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ABSTRACT

The dynamics of lean premixed hydrogen/air flames stabilized behind a square box in a two-dimensional meso-scale channel is investigated with high-fidelity numerical simulations by varying the mean inflow velocity. As the inlet velocity is increased, the initially stable steady flames undergo a transition to an unsteady asymmetric fluctuation until the flame is eventually blown off. A range of the mean inlet velocity is identified in which the flames exhibit local extinction and re-ignition repeatedly.

1. Introduction

Towards the development of combustion-based micro-device for power generation [1, 2], there have been efforts to understand the combustion characteristics of premixed flame in meso-scale combustors, in particular for the flame stability.

Recent studies reported that the blowoff limit of hydrogen/air premixed flames in a micro-combustor can be significantly extended using a bluff-body flame stabilizer [3-6]. Vortex shedding to the flow due to the presence of a bluff-body [7, 8] may affect the stability of flames anchored to it [9]. In the present study, high-fidelity numerical simulations are carried out to investigate the onset of instability of hydrogen/air premixed flames in a meso-scale channel with a square bluff-body. Through two-dimensional numerical simulations for a range of inflow velocities, flame dynamics and associated combustion characteristics are illustrated and discussed.

2. Method

Compressible, multi-species reacting Navier-Stokes equations are solved with a high-fidelity finite difference method using 8th order central difference and 4th order explicit Runge-Kutta time integration. For a lean hydrogen/air mixture of equivalence ratio 0.5, a detailed reaction mechanism [10] with 9 species and 19 reactions is used.

A two-dimensional computational domain (Fig.1) is set for a channel of 1 mm height and 10 mm length, with a square bluff-body of size 0.5 mm by 0.5 mm acting as a flame holder, whose center is located at 2.25 mm downstream of the inflow boundary. To fully resolve reaction layers, a uniform grid spacing of 5 microns is chosen.

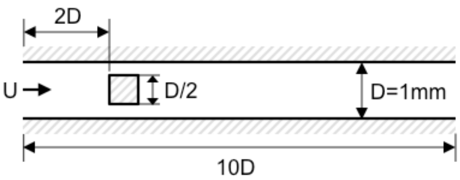

Fig. 1 Two-dimensional computational domain.

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No-slip, adiabatic conditions are applied to the channel walls and bluff-body surfaces. Non-reflecting characteristic boundary conditions are applied for both inflow and outflow boundaries [11, 12]. A fully developed channel flow velocity profile is imposed at the inflow boundary. Cases with a mean inflow velocity U ranging from 15 m/s to 25 m/s are investigated.

3. Results and Discussion

At the inflow velocities below U = 19 m/s, the flames anchored to the bluff-body remains stable and steady, suppressing the shedding of vortex, as shown in Fig. 2. At U = 19 m/s, however, a transition from steady to unsteady asymmetric flame starts to occur over time, as shown in Fig. 3. While the flame instability is gradually developed, the flame still remains anchored to the bluff-body. At U = 20 m/s, the flames how saw-tooth like dynamics (Fig. 4), coupled with the shedding of vortices, at this unstable regime.

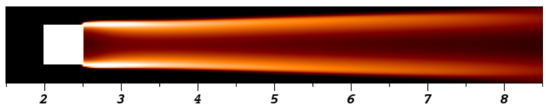

Fig. 2 Heat release rate at U = 15 m/s.

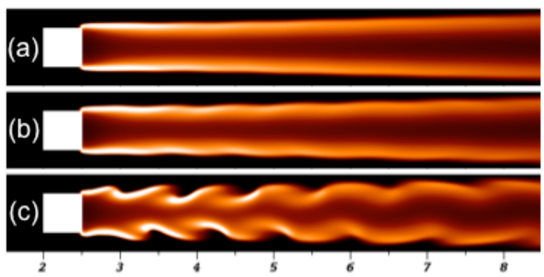

Fig. 3 Heat release rate at U = 19 m/s at times
(a) 4.0 ms, (b) 4.2 ms, (c) 5.0 ms.

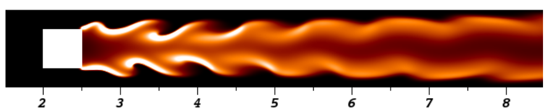

Fig. 4 Heat release rate at U = 20 m/s (t = 4 ms).

Critical flame dynamics near the blowoff limit is shown in Fig. 5 for the case U = 20.5 m/s, where periodic local extinction and recovery of flame occurs in the downstream. At U = 20.6 m/s (Fig. 6), the flame exhibits local extinction and recovery in a more intermittent and unstable manner than that in Fig. 5, and then eventually fails to recover, leading to the blowoff. Note that the blowoff of these flames is not caused by the flame detachment from the bluff-body, but by the local extinction which occurs at a certain distance downstream of the bluff-body. When the inflow velocity is further increased (U = 20.6 m/s), all the flames are eventually blown off.

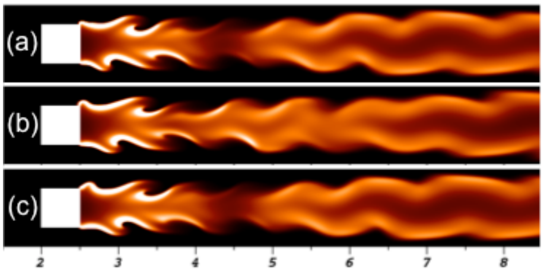

Fig. 5 Heat release rate at U = 20.5 m/s at times (a) 9.43 ms, (b) 9.47 ms, (c) 9.50 ms.

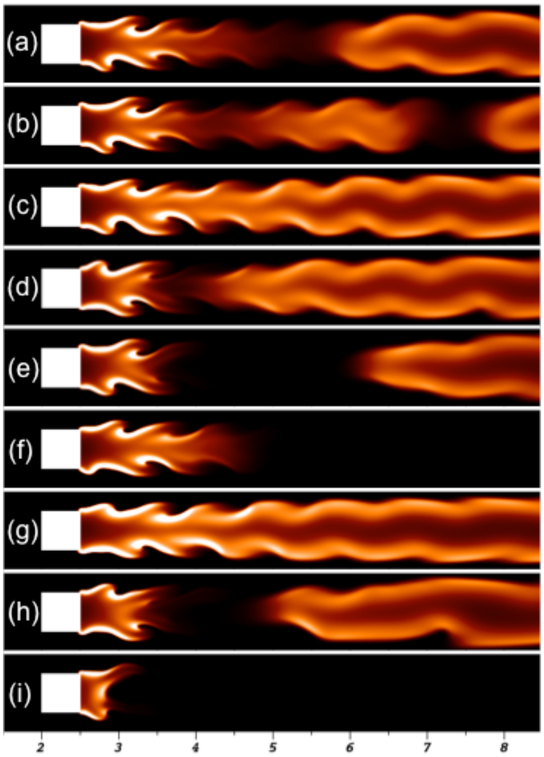

Fig. 6 Heat release rate at U = 20.6 m/s, at times (a) 2.60 ms, (b) 2.65 ms, (c) 2.75 ms, (d) 2.87 ms, (e) 2.96 ms, (f) 3.20 ms, (g) 3.30 ms, (h) 3.50 ms, (i) 3.70 ms.

The onset of local extinction generating holes in the flame, which leads to the blowoff of flame, has been observed experimentally at the near-blowoff limit of lean mixtures for larger scale flames [13-15]. It is found from the present simulations that the local extinction occurs near the downstream end of the recirculation area behind the bluff-body, where the heat supply from the recirculation is not maintained. A detailed analysis of the local extinction point is currently underway in order to provide further insights into the fundamental understanding of the blowoff mechanism.

4. Concluding Remarks

The present study presented highly unsteady dynamics of hydrogen/air lean premixed flame behind a bluff-body in a meso-scale channel by direct numerical simulations. When the local extinction of flame at near-blowoff conditions fails to be recovered, the detached bulk flame is blown-off, leading to the extinction of the anchored flame by losing the heat balance between the heat generation and loss. The detailed aerodynamic and chemical coupling that determines the limit conditions needs to be further analyzed.

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