Control of a Diffusion Flame By Polygonal Orifices and External Modulation

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Abstract: Efficiency of combustion processes is related to fuel-oxidizer mixing and interactions between a flame and a flow field. Their control can be achieved by passive and/or active techniques and may lead to considerable improvement in performance of various technological devices. Passive control involves manipulation of the flow by changing shape of the flow domains. Active control relies on manipulation of a flow field by an external forcing. The present study aims to give a deeper insight into the applicability of passive devices combined with active control strategy for mixing enhancement in jet type flames. We apply the passive control approach for a geometrically simple problem in which a fuel (hydrogen/nitrogen mixture) issues from a shaped nozzle into a hot co-flowing stream. Additionally at the end of the nozzle we add a periodic forcing, which amplifies natural instability mechanisms. At short distance from the outlet the fuel auto-ignites, the flame propagates through the domain and eventually stabilizes as a lifted flame. We analyze how the shape of the nozzle or parameters of the forcing affect these phenomena. The research is performed using Large Eddy Simulation for turbulent flow modelling combined with a Conditional Moment Closure as the combustion model.

1 Introduction

Control of the mixing processes in turbulent flows lead to improvement of efficiency, safety and performance of various technological devices. It can be obtained applying passive and active methods. The former often involves trial-and-error attempts, which are based on geometry modifications and adding fixed elements to the flow domains. In the combustion science, prominent examples of passive control methods are combustion chambers where the efficiency of combustion process is directly related to fuel-oxidizer mixing and interactions between the flame and the flow field. From the point of view of better flame control under variety of different flow regimes, the active control approaches seem to be much more flexible. Active methods involve energy input, which type and level may be fixed (predetermined approaches) or can be varying in time depending on instantaneous flow regimes (interactive approach). In combustion science the active methods have been the focus of research since the early 1990s. The active methods are often combined with passive techniques, e.g., in combustion chambers where bluff-bodies and swirlers represent passive control elements and active control is ensured by an acoustic excitation which, with carefully chosen frequency, acts on large flow structures that drive combustion instabilities. The present work concerns application of the passive and active control techniques to a simple diffusion flame. We focus on changes of the flame dynamics, its position and shape. The research is performed using large eddy simulation (LES) method [1] for turbulent flow simulation and Conditional Moment Closure (CMC) approach [2,3] for combustion modelling.

2 Mathematical Modelling

We consider reacting low Mach number flow described by the continuity equation, the Navier-Stokes equations and the equations for scalar quantities (e.g., mass fractions, total enthalpy). The

CMC model belongs to the family of the mixture fraction based models. It is defined in four-dimensional space, i.e., in physical coordinates and in mixture fraction space. The flow inside complex shape of the nozzles is modeled applying immersed boundary (IB) method [4] in which additional terms (source terms) are added to the Navier-Stokes equations. Its role is to act on the flow domain as if they were solid objects embedded on the computational mesh.

3 Solver Description

We use an academic LES solver called SAILOR which was previously validated in various studies including wall bounded flows, jet flows and flames [5,6]. The Navier-Stokes and continuity equations are discretized using the 6th order compact difference method for half-staggered meshes [7]. In the equation for the mixture fraction the 5th order WENO (Weighted Essentially Non-Oscillatory) and 6th order compact schemes are used for the convection and the diffusion terms, respectively. The time integration is performed using the Adams-Bashforth/Adams-Moulton predictor-corrector approach combined with the projection method for pressure velocity coupling.

4 Computational Configuration

Computational configuration corresponds to the so-called Cabra flame [8]. The cold fuel (300 K) is a mixture of hydrogen and nitrogen ($25.4\%H_2/74.6\%N_2$) and issues to a hot co-flow (1045 K), which is a product of hydrogen combustion. The fuel velocity is $U_j = 107$ m/s and co-flow is at 3.5 m/s. The cold fuel jet is heated up and ignites a few pipe diameters (D = 0.00457 m) downstream. We modified this configuration in the following way: (i) for passive control we added various shape orifices inside the nozzle, as shown in Fig. 1; (ii) for active control we applied sinusoidal modulation combined of axial and flapping terms with amplitude $A=0.15U_j$ and frequency (f) defined by the Strouhal number equal to St = $Df/U_j = 0.3$ and 0.45. The axial and flapping modes are schematically presented in Fig. 1 on the right hand side. In case of the passive control the computational procedure is divided as in Fig. 1. First the flows in the pipe are computed using the IB method and are stored as the input signals for LES-CMC computations. They are provided as the boundary conditions for the second part of the computations.
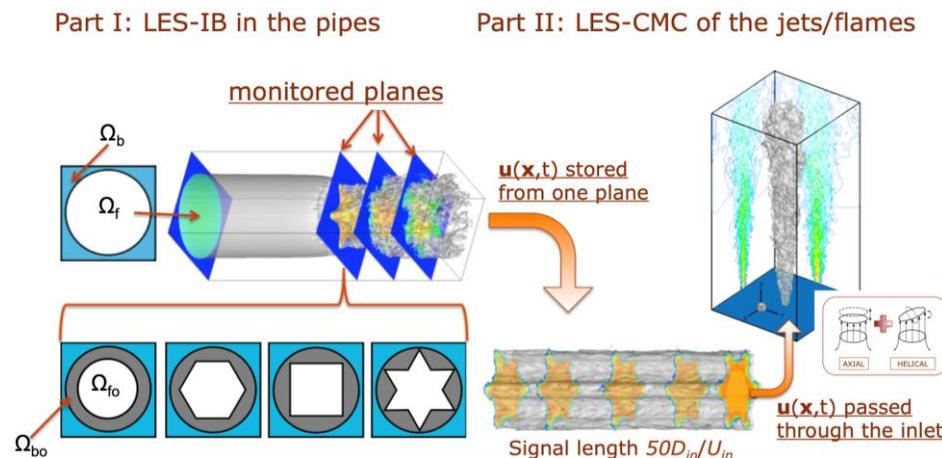

Figure 1: Schematic view of the computational procedure and orifices geometries

5 Results of Simulations

Fig. 2 shows the time-averaged contours of the temperature in the main cross-section plane. The most left subfigure shows the solution for original Cabra configuration, while the remaining subfigures refer to modified configurations. As can be seen compared to the original case the flame are anchored closer to the nozzle, however differences between particular solutions are small. Fig. 3 shows the axial profiles of the

time-averaged values of the mixture fraction, temperature and OH species and their fluctuations. It can be seen that in modified cases the temperature maxima are shifted to the nozzle, they are more or less on the same level. The same can be said regarding the OH species and fluctuations of the temperature and mixture fractions, their maxima are visible closer to the inlet. It is somewhat surprising that the fluctuations of temperature are smaller than in the original configuration, whereas the fluctuations of OH are definitely higher.
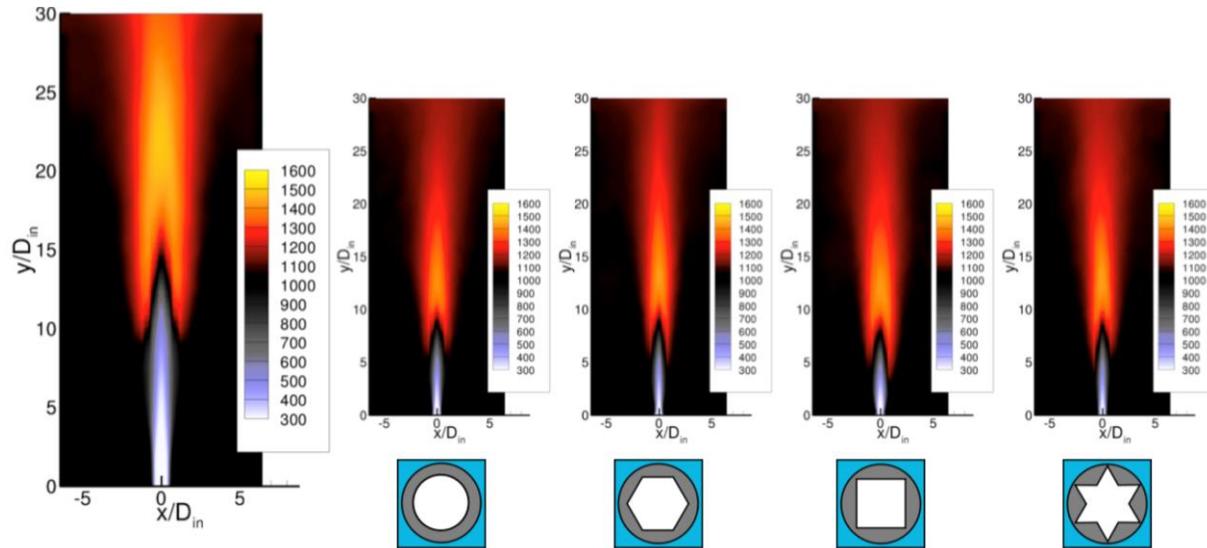

Figure 2: Time averaged contours of the temperature. Left figure shows the solution for original Cabra configuration
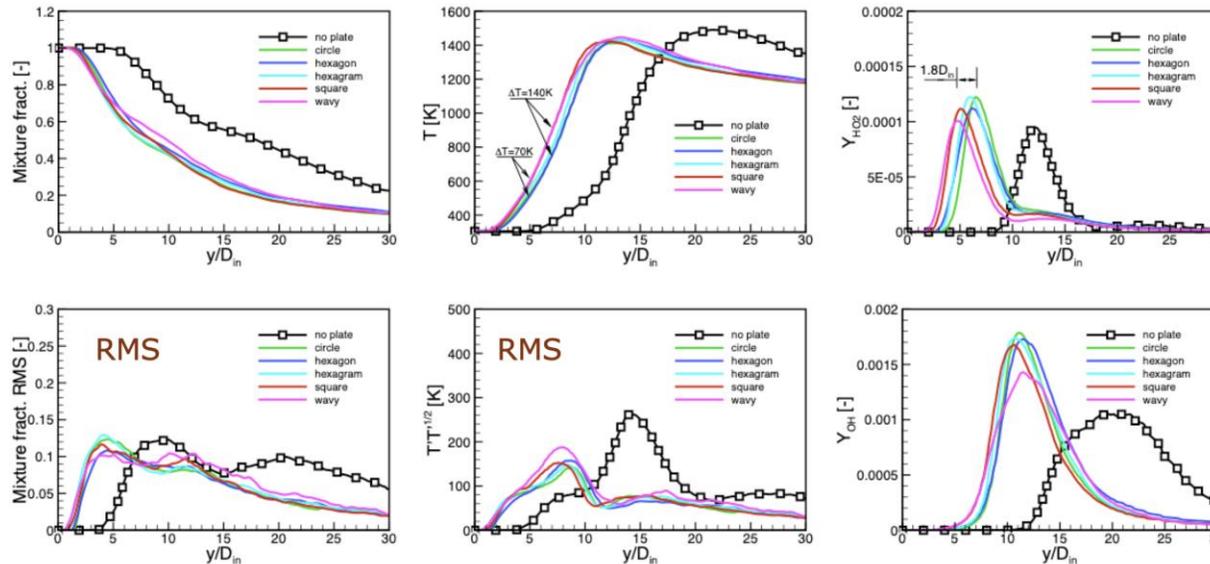
Figure 3: Axial profiles of the time-averaged values of the mixture fraction, temperature and OH species and their fluctuations

Fig. 4 shows instantaneous and time averaged contours of the temperature in the excited configurations. It can be seen that the excitation changes the flame shape but it has practically no impact on its position with respect to the nozzle. Increasing the oscillation frequency cases that the flame becomes wider. We found that for $St = 0.5$ the flame was the widest.

| *St = 0.3* | *St = 0.45* | *St = 0.3* | *St = 0.45* |
| *(instantaneous)* | *(instantaneous)* | | |
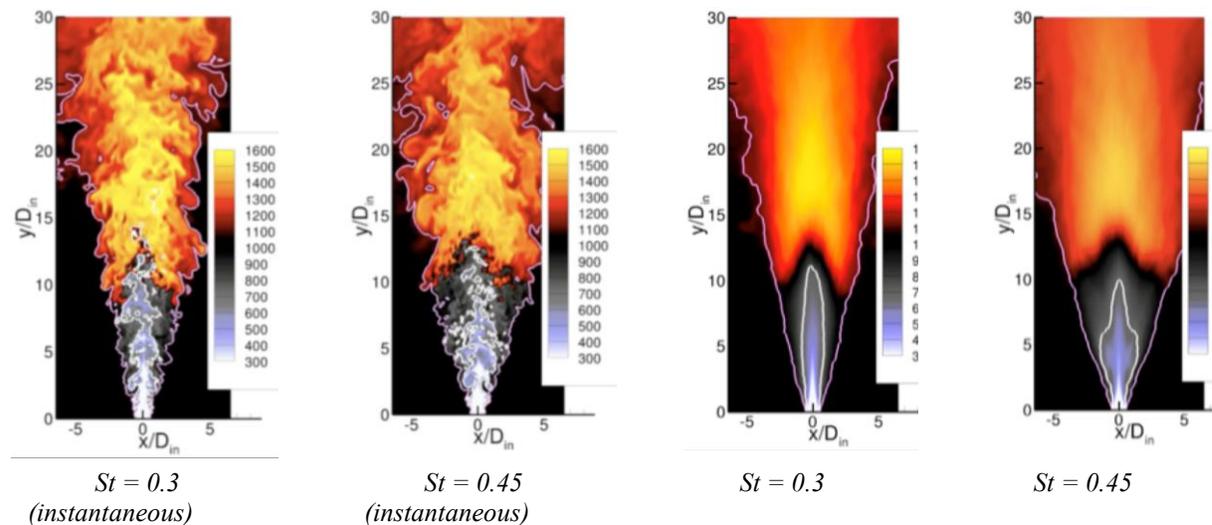
Figure 4: Instantaneous and time averaged contours of the temperature in the excited configurations

6 Conclusions

The paper presented results of applications of two methods for flame control based on passive and active techniques. The numerical simulations were performed using LES-CMC model combined with the immersed boundary method, which was applied to compute the solution in the complex shape pipe. The results showed that by modifications of the fuel nozzle geometry one can significantly influence the flame dynamics including the lift-off height and location of the maximum temperature. It was observed that the application of the active control as the combination of axial and flapping excitation added to the inlet velocity profile changes the flame shape significantly by widening it in the direction of the flapping motion. An increase of the oscillation frequency causes that the flames become wider.

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