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HYDROGEN JET FLAME CONTROL BY GLOBAL MODE

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INTRODUCTION

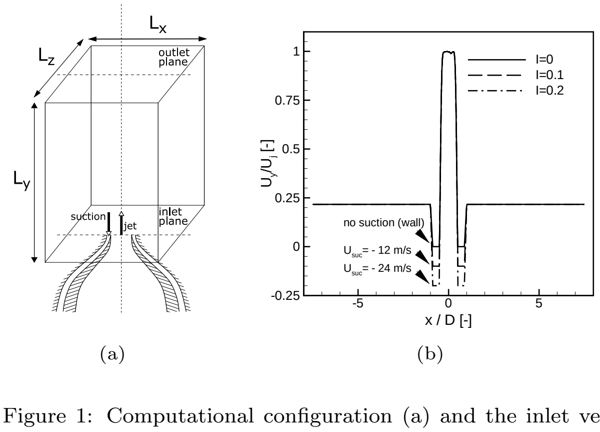
Flame control has been in the centre of interest for decades and constitutes a subject of intensive research as it may lead to considerable improvement in efficiency and safety of various technical devices. Numerous industrial applications, such as aeroplane engines, involve jet-type flames with fuel issuing from a nozzle into an oxidizer stream. An interesting phenomenon emerging in round jets, which could be considered as a flow control technique, is self-excited global instability triggered by absolutely unstable local flow regions [1]. The theoretical predictions of Monkewitz and Sohn [2] and Jendoubi and Strykowski [3] showed that absolute instability can be triggered in variable density and counter-current jet configurations. Two absolutely unstable modes called Mode I and Mode II have been analytically identified [3] and additionally confirmed by experimental and numerical works [4, 5, 6, 8]. However, there are no investigations devoted to global instability in jet flames, despite their significance for practical solutions. In the present paper the effect of counter-current co-axial flow on the emergence of the global instability in the hydrogen jet flame is studied with the help of large-eddy simulations (LES).

COMPUTATIONS

The test case configuration is presented schematically in Fig. 1(a). It corresponds to the experimental set-up of Markides and Mastorakos [7] used for hydrogen autoignition in a turbulent co-flow of heated air. Mixture of hydrogen and nitrogen with the mass fractions Y_{H_2}=0.13 and Y_{N_2}=0.87 is injected into a heated air through a 2.25 mm (D) internal diameter pipe. Table 1 shows details of the temperature and velocity of the fuel jet as well as the co-flow stream. The density ratio $S = \rho_j/\rho_{cf}$, where ρ_j and ρ_{cf} denote density of the jet and co-flow, is slightly above the critical density ratio for which global oscillations emerge in a jet without counterflow for a given shear layer thickness characterized by the parameter $D/\theta = 40$ (θ - momentum thickness) [8]. The suction is applied through the annular nozzle which is placed around the main nozzle. It produces a counter-current region in the direct vicinity of the main jet. The strength of the counterflow is controlled by the velocity ratio $I = -U_{suc}/U_j$ (U_j - velocity of the jet, U_{suc} - velocity of the counter-current). The effect of the counterflows characterised by I= 0.1 and 0.2 is assessed in relation to the flame without suction ($I = 0$).

In the present work we do not consider the inner geometry of the nozzles and the computational domain is a rectangular box with dimensions $L_y = 30D, L_x = L_z = 15D$, where '$y$' is the axial direction. The applied mesh counts N_y=288, $N_x = N_z$=192 nodes in the axial and radial directions, respectively. The inlet boundary conditions are specified in terms of the instantaneous velocity profile. The velocity fluctuations are computed according to method proposed by Klein et al. [9] whereas the inlet mean velocity is described by the Blasius profile. Sample profiles of the mean axial velocity at the inlet plane of the computational domain are displayed in Fig. 1(b).

The LES solver used in this study is an in-house high-order solver based on the low Mach number approximation. The Navier-Stokes and continuity equations are discretised using the sixth order compact difference method on half-staggered meshes [10]. A sub-grid model of Vreman [11] is used to compute the sub-grid viscosity for SGS-stress tensor. The chemical reactions are computed using the CHEMKIN interpreter with the help of a detailed mechanism of hydrogen oxidation [12] involving 9 species and 21 reactions. The calculations are conducted without any closure for turbulence/combustion interactions at the sub-grid level. Correspondingly, the filtered reaction rates of species were obtained directly from the Arrhenius formula.

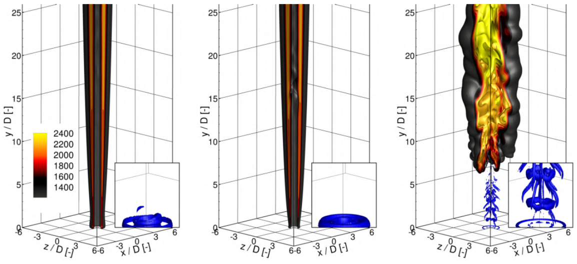


(a) (b)

Figure 1: Computational configuration (a) and the inlet velocity profiles (b) for the cases considered.

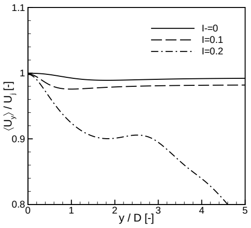
Fuel (jet)	Oxidiser (co-flow)	T_j [K]	T_{cf} [K]	S [-]	U_j [m/s]	I [-]	U_{cf} [m/s]
0.13 H_2/0.87 N_2	0.23 O_2/0.77 N_2	691	1010	0.53	120	0, 0.1, 0.2	26

Table 1: Summary of test cases considered.

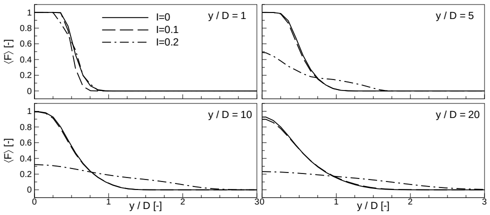


(a) I-00 (b) I-01 (c) I-02

Figure 2: Instantaneous iso-surfaces of the Q-parameter ($Q = 0.05$ s^{-2}, blue) and temperature inside the flames.



(a)



(b)

Figure 3: Profiles of the time averaged mean axial velocity along the jet axis (a) and the radial distributions of the time averaged mixture fraction at different axial locations (b).

RESULTS

Figure 2 displays fully developed flames visualised by the instantaneous iso-surfaces of the temperature inside the flame and the Q-parameter close to the inlet plane. It appears that the flow pattern is similar for I=0 and I=0.1 while significant differences emerge when the strongest suction is applied, i.e., for the case with $I = 0.2$. As can be seen in Fig. 2, the flame in the original configuration ($I = 0$) is attached to the nozzle, whereas strong counterflow stabilizes the lifted flame. Increasing the suction triggers global instability before autoignition occurs. In fact, at strong suction the velocity field drastically changes revealing the formation of strong coherent structures close to the nozzle. These structures pair and subsequently break up further downstream (see the blue iso-surfaces in Fig. 2). As can be seen in Fig. 3 showing velocity profiles along the jet axis the velocity decay appears close to the nozzle exit. In this case, mixing is drastically intensified directly behind the inlet plane as the mixture fraction is reduced. A large amount of fluid taken from the surroundings becomes mixed with the fuel to make the mixture leaner. This even prevents an upstream flame propagation and the flame lifts off. The lift-off height as well as the radial size of the flame can be deduced from the results presented in Figs. 2-3. One can see that the flame is nearly two times wider and stabilises at a distance of $6D$ from the nozzle. Moreover, in the case with $I = 0.2$ the temperature inside the flame is 120 K higher compared to the cases with $I = 0.0$ and $I = 0.1$ where the global mode does not appear.

CONCLUSIONS

The present study showed that the critical velocity ratio for which global instability is triggered in the considered jet flame is between 0.1 and 0.2. The global mode observed at sufficiently strong counter-current flow (I=0.2) causes qualitative changes of the flame characteristics. It was demonstrated that the position, global size and temperature of the flame can be effectively modified by the application of suction around the fuel jet. This may be desirable from a practical point of view since a suitable alteration of the flame would lead to considerable improvement of efficiency, safety or pollution reduction. Further calculations for a wider range of velocity ratios as well as different density ratios are planned to investigate whether the flame can be effectively controlled by the global mode.

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