

Numerical simulation of flame instability induced by an in-line pre-heating effect

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1 Introduction

It is well known that the propagation of premixed flame in a combustion chamber has a great importance in the development of combustion devices because it gives rise to the variety of fundamental physical phenomena like instability which are often associated with the shapes of flame including curved, flat, cusped or cellular fronts [1-3]. The existence of these shapes of the flame front is usually very short and consequently, they follow each other with the variation of time during propagation [4]. The extensive investigations have been done on the flame propagation phenomenon, to address the transformation process of the shapes of flame front and their related basic physical phenomena, for a quite long time over various configurations accompanied by numerous conditions as well as assumptions. Recently, Tsuchimoto et al. [5] investigated experimentally the forced-deformed flame front propagation in a one-sided open tube. They deformed the shape of the flame front by imposing CO₂ laser beam along the center line of the tube and observed the oscillatory behavior of flame during the propagation subjected to the intensity of laser ray. However, the origin of the flame-oscillation process still remains to be explained in details under various possible aspects. This oscillation process is supposed to be induced by the simultaneous occurrence of several unknown factors which must be resolved precisely along with their individual roles to develop the complete mechanism for flame-oscillation in experiment [5]. The investigation of every small contribution of such unknowns by experiment is quite difficult. Therefore, in order to elucidate the laser induced flame oscillation mechanism [5], Hossain et al. [6] conducted a numerical investigation on the flame propagation in a two-dimensional channel where laser induced pre-heating effect in experiment [5] is modeled by imposing the uniform external high-temperature of width 1 mm along the center line of the channel. It is reported in [6] that the negative velocity distribution is developed, due to the deformed flame front caused by pre-heating treatment, in front of flame at the same direction of flame propagation which enhances the generation of a weak pair vortex in ahead of flame tip. But no flame oscillation is observed in their simulation.

The strong flame-vortex interaction often gives rise to flame oscillation during the propagation in the practical combustors. In this regards, the appearance of a pair vortex ahead of flame tip in the simulation [6] is a significant first ever observation which may assist in elucidating the flame instability in experiment [5]. Moreover, it is reported by Tsuchimoto et al. in their later studies [7-8] that the narrow laser beam diameter is sensitive to the generation of oscillation phenomenon. Motivated by these two issues, in this study, we have investigated numerically the influence of an in-line

pre-heating treatment, over the narrow zone of width 0.5 mm along the center line of the channel, on the propagation character of a laminar premixed flame.

2 Numerical conditions and their implementation

In this study, the effect of an in-line pre-heating zone of width 0.5 mm on flame character is investigated numerically under low Mach number assumption in a zero-gravity environment. The combustion chemistry is modelled by the single-step irreversible chemical reaction between ethylene and oxygen ($\text{C}_2\text{H}_4 + 3\text{O}_2 \rightarrow 2\text{CO}_2 + 2\text{H}_2\text{O}$) in a fuel-rich condition and the reaction rate is calculated by the Arrhenius Law as referred by Westbrook [9]. For simplicity, bulk viscosity, the Soret and Dufour effects, pressure gradient diffusion, and radiation process are neglected. The narrow pre-heating zone is generated following Hossain et al. [6] by imposing external uniform high-temperature of 600 K along the center line in a two-dimensional channel (shown in Fig. 1) with a width of 0.5 mm. The imposed external uniform high-temperature is maintained mainly in front of the flame tip along the center line during the propagation and this uniform temperature is termed here as the pre-heating temperature.

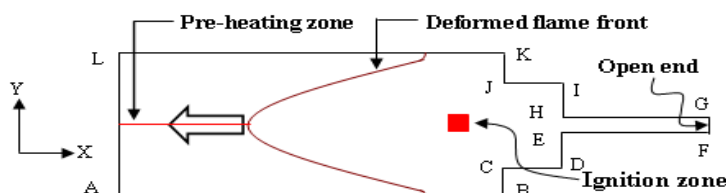


Fig. 1 Schematic view of calculation domain along with pre-heating zone [6].

The two-dimensional system of governing equations for reacting flows [6] is discretized using the finite volume method (FVM) on a hexahedral structure grid cells. The discretized equations are solved by adopting Front Flow Red [10], a multi-scale and -physics computational fluid dynamics (CFD) solver which is developed on the basis of SMAC/SIMPLE algorithm. No-slip condition at the walls for velocity, Neumann condition at open end (GF in Fig.1) and zero-flux conditions for scalars such as temperature and mass fractions are applied in this simulation. The convective terms are discretized by using 1st order upwind scheme and 2nd order central difference scheme is employed for other spatial derivative terms. The time integration is carried out by using the Euler implicit method. The effect of schemes on the results of flame propagation in a channel with and without pre-heating effect is examined by executing the simulation with the higher order schemes in both space and time [11]. The transport coefficients and thermo-chemical properties are estimated by using the approach of Smooke [12] and Gardiner [13] respectively.

3 Results and discussion

The typical computed results for present study are displayed in Figs. 1-3. It is clear in Fig. 1 that flame tip radius of curvature decreases with the reduction of pre-heating width (PHW) from 1 mm to 0.5 mm. The propagation speed for PHW of 1 mm along the center line is higher than that of the propagation speed for PHW of 0.5 mm as the radial propagation is faster at narrow PHW. Fig. 2 represents the negative velocity distribution at 1 mm ahead of each flame tips. When flame front is curved, the stream lines across the curved flame front diverge tangentially [14]. The extremely curved flame front is achieved by the pre-heating treatment and consequently, a thin vortex sheet is generated which is attached ahead on the curved flame front. Once vortex sheet is generated which enhances the generation of negative velocity distribution in ahead of flame front. The high deformation in flame front is observed in Fig.1 for PHW of 0.5 mm compared to PHW of 1 mm. This deformation generates about two and half times higher negative velocity in ahead of tip along the center line at

the prescribed locations and time (showed in Fig. 2). This high negative velocity gives rise to a strong pair vortex in unburnt gases along center line of the channel.

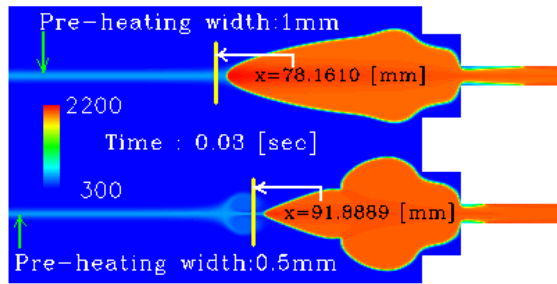


Fig. 1 Instantaneous temperature distribution at time 0.03 sec for pre-heating temperature of 600 K.

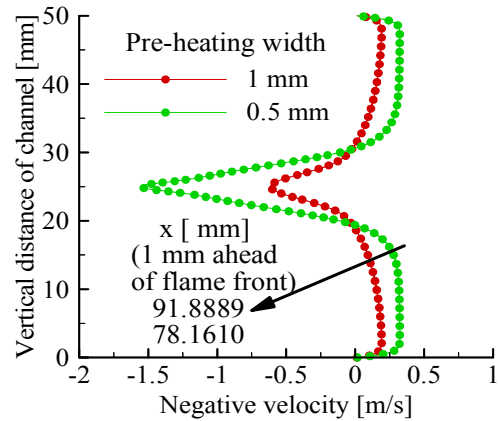


Fig. 2 Negative velocity profile at 0.03 sec for pre-heating temperature of 600 K at 1 mm ahead of flame tip.

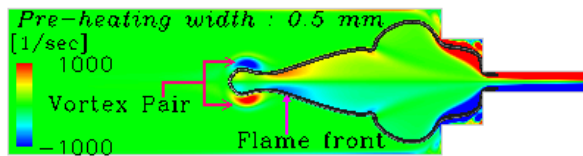


Fig. 3 Instantaneous vorticity distribution at time 0.036 sec along with deformed flame front (black contour) for pre-heating temperature of 600 K.

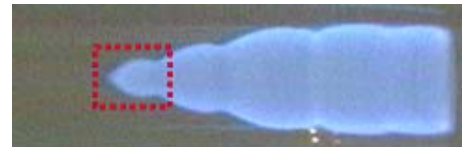


Fig. 4 The shape of deformed flame front in experiment (Tsuchimoto et al.)

The distribution of vorticity along with the deformed flame front is displayed in Fig. 3. It is observed in Fig. 3 that the pair vortex interacts with the flame front and slips down on the flame surface towards the upstream of the channel and flame exhibits oscillation during the propagation with the progress of time. However, in this study, after the first mode of oscillation, the vortex pair in ahead of flame tip becomes weak and eventually no oscillation is appeared as before. But the weak pair vortex is found to be sustained in ahead of flame tip during propagation. The comparison between Fig. 3 and 4 reveals that the flame tips are very similar, with respect to the level of deformation in the shape of flame front along the center line, even though the overall shapes are different. Therefore, it is thought that the appearance of a strong vortex pair in ahead of flame tip due to pre-heating effect could be one of the possible trigger of flame oscillation observed in experiment [5].

4 Concluding remarks

In this study, the influence of narrow pre-heating zone on the propagation character of a flame is investigated numerically. The following conclusions can be derived from the present investigation:

- The narrow pre-heating zone deforms the flame front extremely along the center line of the channel.
- The strong deformation in flame induces a high negative velocity in front of flame tip along

the center line and this negative velocity distribution gives rise to a strong pair vortex in unburnt gases ahead of the flame tip.

- The pair vortex interacts with the flame front and slips down on the flame surface towards the upstream of the channel, and shows flame oscillation during the propagation.
- The comparison between the result of simulation and experiment in terms of flame tip, along the center line, shows a good qualitative agreement.

Acknowledgements

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