Influence of the Coflow on the Structure of Premixed Turbulent Flames in a Stagnation Point Flow

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Introduction

Premixed turbulent flames stabilised in stagnation point flow have been the subject of various experimental studies [1]-[5] as well as theoretical 1 - D calculations on the symmetry axis [6, 7, 8], or 2 - Dnumerical calculations [9]-[12], because of the simplicity of theirs geometries. In the experiments, the effects on the flame structure of such quantities as the turbulence in the reactants, the turbulent length scale, the equivalence ratio and the mean strain rate have been investigated. Some of these results have been used in the modeling of the mean chemical production rate [11, 13]. In most experiments however, the flow of reactants is shielded from ambient still air by a coflowing stream of air, but the effect of this coflow is not taken into account in the assessment of the mean chemical reaction rate closure.

The attention of theoretical and numerical studies was focused on the results on the symmetry axis. However, recently Karmed et al.[13] have presented a comparison between experimental results (isocountour of \bar{c}) of Cheng and Shepherd [4] and their numerical results in the central core of the flow, obtained by using the isenthalpic BML model. The combustion process was described by means of a unique progress variable c that does not allow one to distinguish between ambient air and diluted burnt gases. Consequently, in such earlier 2-D calculations it was assumed that the reactants are discharging into an ambient atmosphere of fully burnt products. Despite this assumption, Karmed et al.[13] have shown that non-gradient transports of the progress variable prevail for flames stabilised far from the wall as is suggested in experiments.

Thus, the aim of this study is to use a recent turbulent combustion model developed by Lahjaily et al.[12] to evidence the effects of the coflow on the structure of impinging premixed turbulent flames and that takes into account the dilution by air of both the unburnt and burnt gases. This combustion model, together with a full low-Reynolds number second moment turbulence closure for turbulent transports of both velocity and progress variable, is applied to the case of a premixed turbulent flame stabilised in stagnation point flow.

Modeling

The turbulent combustion model of Lahjaily et al.[12] developed for lean-mixture premixed flames is considered with a one-step fast chemical reaction $R \longrightarrow B$. The mean heat expansion parameter $\tilde{\tau}$ is expressed as [12] $\tilde{\tau} = \tau_e \tilde{f}$ and the mean rate of production by: $\bar{\omega} = \eta D_T a \rho^R \bar{c} (1 - \bar{c})$ where $\eta = \int_{f=f_{\min}}^{f=1} \widetilde{\mathcal{P}^R}(f) df$, D_T is a turbulent Damköhler number, a is the mean rate of strain defined by $a = V_e/H$, V_e is the velocity at the burner exit, H is the distance from this exit to the stagnation plate, and ρ^R is the density of the reactants. The Damköhler number D_T is assumed to depend on \tilde{c} with the objective of improving the predictive abilities of the combustion model. To this end, we use the form $D_T(\tilde{c}) = (D_{T,0} + D_{T,1}\tilde{c}^2)$ [11, 13]. The modeling of the progress variable turbulent fluxes and the Reynolds stresses considered here is the same as the one used by Karmed and Champion [11] and Karmed et al.[13] in the case of isenthalpic flames except that terms of the form $\overline{\Phi''}$ appearing in the various equations are modeled as: $\overline{\Phi''} \approx \frac{\tau_e}{\rho^R} \left(\tilde{f} \ \overline{\rho c'' \Phi''} + \tilde{c} \ \overline{\rho f'' \Phi''} \right)$ instead of $\overline{\Phi''} = \tau_e / \rho^R \overline{\rho c'' \Phi''}$.

This set of equations is supplemented by the classical equations of the mean mixture fraction f and its variance $\widetilde{f''^2}$. These quantities are used in the calculation of the characteristics of the pdf $\mathcal{P}^R(f)$ which is assumed to obey a statistical distribution beta function.



Figure 1: Geometry of the flow.



Figure 2: Evolution of the mean rate of production $\bar{\omega}$ field as a function of V_c/V_e .

Results and discussion

The system that includes balance equations for total mass, mean momentum axial and radial components, Reynolds stresses, turbulence dissipation rate, mean progress variable, the mean mixture fraction and its variance and the progress variable turbulent fluxes is solved by using a staggered finite-volume solver based on a SIMPLE procedure [14]. The geometry of the flow is shown in figure (Fig. 1). The computational domain $(7d_e x 2d_e)$ is a non-uniform mesh of 150x150 grid points. The calculations were performed for conditions corresponding to the case S9 of Cheng and Shepherd [4] experiment ($\tau = 6.84$, H = 0.1 m, d = 0.05 m, $l_{t,e} = 0.003 m$, $V_e = 4.2 m s^{-1}$ and $V_e' = 0.4 m s^{-1}$). The Damköhler number constants $D_{T,0}$ (related to the turbulent burning velocity [13]) and $D_{T,1}$ are assigned the arbitrary values 2 and 120 respectively. They can be tuned in order to obtain the best agreement with experimental data. The lean-limit extinction equivalence ratio ϕ is taken equal to 0.5. Preliminary results in the case of non-reactive flow (not presented here) have shown that the axial velocity decreases more rapidly when the coflowing velocity stream is increased. We expect that this trend can be encountered in the case of reactive flows. Shapes of the flame brush in terms of mean chemical rate production calculated for various ratio V_c/V_e (1/8; 1/4; 1/2 and 1) are presented in figure 2. For low values of the coflow velocities $(V_c/V_e = 1/8; 1/4)$ the same flame brush shape with a concave rim is obtained. This flame brush remotes from the wall when the ratio V_c/V_e increases and becomes more plate for $V_c/V_e = 1$. The mean axial velocity and the mean progress variable profiles calculated on the symmetry axis show superposed profiles for $(V_c/V_e = 1/8; 1/4)$ indicating that the flame brush is located at the same place. This flame brush moves towards the exit burner when this ratio is increases (Fig. 3-(a)). The radial gradient of the mean radial velocity profile (Fig. 3-(a)) shows that the flame brush moves far from the wall when the mean strain rate in the vicinity of the stagnation point decreases in agreement with earlier calculations[6, 9].



Figure 3: Influence of the coflowing air velocity on mean quantities along the symmetry axis: (a) - axial velocity and progress variable; (b)- radial gradient of the radial velocity.

Conclusion

A turbulent combustion model developed recently for lean-mixture premixed flames was used together with a full second order closure to study the influence of the coflowing air stream on the structure of premixed turbulent flame stabilised in a stagnation point flow. Only the influence of the coflowing air stream velocity was considered. It was clearly shown that the flame moves towards the burner exit when the coflow velocity is increased. This displacement is attributed to the variation of the mean strain rate. This result shows that the main flow is modified and, depending on the coflowing air stream velocity, the flow properties on the symmetry can be affected and consequently, this effect cannot be neglected and should be taken into account in further assessment of the mean chemical rate production for quantitative comparison with avalaible experimental data.

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