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# Model of flame dynamics of laminar premixed flame subject to the low frequency equivalence ratio oscillations☆

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ABSTRACT

The effect of the non-uniform profile of scalar variables, such a fuel at the upstream and temperature at the downstream of the flame zone was discussed theoretically to elucidate; (1) the deviation of motion from the steady state case and (2) the hysteresis of premixed flames response to the equivalence ratio oscillations seen in an experimental and numerical works. One-dimensional integral model for the non-uniform scalar variable profile with low frequency equivalence ratio oscillation has been developed. Here, the wavelength of the oscillation is assumed to be larger than the nominal flame thickness. Through the integral analysis, we obtained the relation of the flame propagation speed for steady and unsteady cases depending on the non-uniform scalar profile at the upstream and downstream of the flame zone. Hysteresis of the flame propagation speed is found due to the transport of fuel and heat by the non-uniform scalar profile at the upstream and downstream of the flame zone. This result qualitatively agreed with the numerical results of a response of the stagnation laminar $CH_4$/air premixed flames for a low equivalence ratio oscillation frequency.



## 1. Introduction

The environmental problem is one of the key issues to be solved in this century. Air pollution, specifically NOx production, is mainly due to combustion activities. One candidate to reduce NOx is a lean premixed combustion. The low NOx premixed combustor with lean premixed combustion, has been used in power plants and jet engines. However, it faces problems of instability due to the operating condition in the lean fuel air ratio. Several researchers have conducted studies on this field and concluded that this instability is mainly due to the velocity and fuel concentration perturbations, which results in the thermal acoustic fluctuation in the combustor [1]. Research on the effect of velocity perturbation has been performed in well controlled conditions and data were used to develop the models while the effect of equivalence ratio perturbation has been less well investigated [1,2]. Research on the effect of the equivalence ratio perturbation can be divided into two cases, one is the stratified case and the other is the equivalence ratio oscillation case. The stratified case is considered as a spatial equivalence ratio perturbation and the oscillation case is a temporal and spatial perturbation case. Although researches for both cases have been done rigorously [2–15], some fundamental mechanisms are still not well understood.

The flame motion under the influence of the equivalence ratio perturbation was supposed to be affected by a back support effect. The back support effect introduced in Ref. [3] has been used to discuss in detail on the stratified case. They found that the flame propagation speed and burning rate increased due to the back support effect and the model was developed in stratified case [8–10]. Moreover, the non-uniform scalar value profile at the downstream of the flame zone affected the flame response in the lean $CH_4$/air premixed flames [4,8–10]. They observed the propagation speed from stoichiometric to lean flammability limit was enhanced by the heat and composition fluxes from the burned gas compared to the steady state case at the specific equivalence ratio [4]. Additionally, it was found that the mathematical model using Frank-Kamenetskii approach for the lean $CH_4$/air mixture clarified that the cumulative heat from the burned gas enhances the flame propagation [8–10]. On the other hand, Ref. [11] observes that the species fluxes play an important role than the heat flux in an increase in flame propagation speed in lean case. Despite the single dominated mechanism of thermal or species diffusion, both mechanisms found dominated in help the flame propagates beyond the lean or rich flammability limit compared to steady state case [12].

In the equivalence ratio oscillation case, the back support effect is known to modify the flame responses [11,13], though no mathematical model has yet been developed to explain. Numerical work [13] showed that both scalar values at the upstream and the downstream of the flame zone vary in response to an incoming equivalence ratio oscillation but no detailed analysis has been done with both effects. An asymptotic

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**Nomenclature**

| | |
|---|---|
| *A, B* | constant |
| $c_p$ | specific heat at constant pressure (kJ kg$^{-1}$ K$^{-1}$) |
| *D* | mass diffusivity (kJ kg$^{-1}$) |
| *F* | frequency (Hz) |
| *M* | mass flux (kg m$^2$ s$^{-1}$) |
| *S* | flame propagation speed (ms$^{-1}$) |
| *T* | temperature (K) |
| *T* | time (s) |
| *X* | x-direction |
| *Y* | mass fraction |

*Greek letters*

| | |
|---|---|
| $\delta$ | thickness (mm) |
| $\lambda$ | thermal conductivity (kJ m$^{-1}$ s$^{-1}$ K$^{-1}$) |
| $\rho$ | density (kg m$^{-3}$) |
| $\omega$ | angular velocity (rad$^{-1}$) |

*Subscript*

| | |
|---|---|
| *A* | activation energy |
| *Ad* | adiabatic |
| *B* | burned |
| *F* | fuel |
| *M* | flame zone |
| *O* | non-dimensional |
| *R* | reaction zone |
| *T* | thermal-diffusive zone |
| *U* | unburned |

analysis was performed for the oscillation of the incoming mixture case and found that the local flame propagation speed varies, although, the back support effect was not considered [14]. The objective of this study is, therefore to introduce a concept of the non-uniform scalar value profiles in upstream and downstream regions of the flame zone into a one-dimensional simplified qualitative mathematical model and analyze it under equivalence ratio oscillation at a frequency wavelength larger than that the nominal flame thickness.

## 2. Concept of the non-uniform scalar

### 2.1. Physical consideration

Deviation and hysteresis of the flame movement from the steady state case are seen in both the numerical [11,13,15] and experimental [16] works. Detailed analysis of the numerical work showed that the scalar value profile of the reactant and temperature at the upstream and downstream regions of the flame zone is non-uniform. Thus, it can be considered the fuel molecular diffusion toward the flame zone in the upstream region of the flame zone similar to the back support effect [3,8–10]. A concept of the non-uniform scalar value profile of the reactant and temperature at the upstream and the downstream of the flame zone is, then, introduced. Here, the model is simplified by assuming that the flame temperature reaches the maximum value at the equivalence ratio, $\varnothing = 1.0$.

Fig. 1 shows the variation in the equivalence ratio at upstream of the flame preheat zone. Following the variation in the equivalence ratio, reactant of mass, $Y_f$ and burned gas temperature, $T_f$ varies for lean (Fig. 2(i)), rich (Fig. 3(i)) and lean rich crossover (Fig. 4(i)) cases respectively. In Figs. 2(i), 3(i) and 4(i), upstream and downstream sides of the flame zone are the right and left sides of the flame zone as shown in Fig. 2(i)(a). Gradient of non-uniform scalar profiles, fuel profile at the

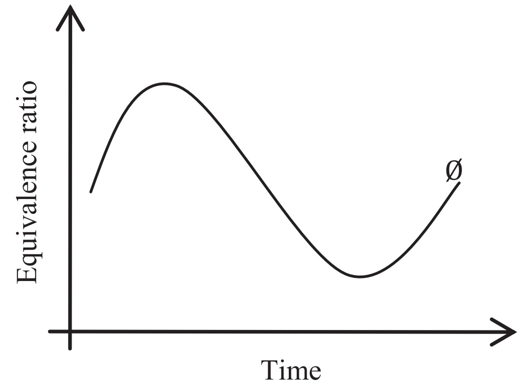


**Fig. 1.** Variations in the equivalence ratio at the upstream of the flame preheat zone.

upstream (left side) and temperature profile at the downstream (right side), of the flame zone can be illustrated in Fig. 2(ii), Fig. 3(ii) and Fig. 4(ii) for the lean, rich and lean rich crossover cases respectively. In the lean case (Fig. 2(i)), the flame temperature increases when the equivalence ratio is increased. Furthermore, Fig. 2(ii) shows the gradient of scalar variables at the position of the flame zone in lean case of each equivalence ratio (a)–(d) in Fig. 2(i). As the flame is located at the top of the fuel concentration (near stoichiometric), (a) in Fig. 2(ii), the reactant diffuses toward upstream direction due to decreasing fuel concentration profile toward the upstream direction and the heat diffuses toward the downstream direction due to the decreasing temperature profile toward the downstream direction. These losses of reactant and heat weaken the flame which results in a decrease in the flame propagation speed decreases. When the flame is located intermediate (Fig. 2(ii) (b)), the reactant diffuses toward the reaction zone from the upstream direction due to the increasing reactant profile toward the upstream direction, while the heat diffuses downstream direction as well as in the case (a) in Fig. 2(ii). It means that the intensification of the flame due to the diffusion of fuel toward the reaction zone is canceled by the diffusion of heat from the reaction zone. When the flame is located at the bottom of the fuel concentration (near leaner region) (Fig. 2(ii) (c)), both fuel and heat diffuse toward the reaction zone. As a result, the flame is intensified and the flame propagation speed increases. As the flame is another intermediate (Fig. 2(ii) (d)), a loss of heat from the flame zone is balanced by incoming fuel diffused to the flame zone as well as the intermediate (b) in Fig. 2. Fundamentally, both cases (Fig. 2(ii) (b)) and (Fig. 2(ii) (d)) are the same except case (Fig. 2(ii) (b)) is supported by heat and case (Fig. 2(ii) (d)) is by fuel. Therefore, the flame propagation speed shows deviation from the steady state case, following variations in equivalence ratio.

Fig. 3(i) shows the variations in the reactant mass fraction at the upstream and burned gas temperature at the downstream of the flame zone following the equivalence ratio variation (Fig. 1) in rich case respectively. In the rich case (Fig. 3(i)), the flame temperature decreases when equivalence ratio is increased. Fig. 3(ii) shows the gradient of scalar variables at the position of the flame zone in rich case of equivalence ratio (a)–(d) in Fig. 3(i). As the flame is located at the rich fuel, (a) in Fig. 3(ii), the reactant diffuses toward upstream direction due to decreasing fuel concentration profile toward the upstream direction and the heat diffuses into the flame zone due to the increasing temperature profile toward the downstream direction. The loss of reactant is compensated by the heat from the burned gas. When the flame propagates toward the stoichiometric condition (Fig. 3(i) (b)), the reactant diffuses out from the flame due to the decreasing reactant profile toward the upstream direction and the heat diffuses out toward the downstream direction as well (Fig. 3(ii) (b)). As a result, the flame is weakened. When the flame is located near to the stoichiometric region (Fig. 3(ii)(c)) the loss of heat from the flame zone is compensated by incoming fuel into the flame zone. Case (Fig. 3(ii) (a)) and (Fig. 3(ii) (c))