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NUMERICAL STUDY ON STABILIZATION OF A DIFFUSION FLAME OVER A FLAT PLATE

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ABSTRACT

A numerical study is performed of the effects on the stabilization of a diffusion flame in a flat plate boundary layer, into which fuel gas is injected vertically from the surface of the wall with a uniform velocity. A theoretical model is presented to couple fluid dynamics, chemistry and heat transfer on the surface of the flat plate. Governing equations of two-dimensional, compressible Navier-Stokes momentum, energy and chemical species are used and are numerically integrated by means of a finite difference method. Chemical reaction model is one-step, overall irreversible one with second-order, finite rate Arrhenius kinetics. Lots of computations are performed and five cases are discussed on understanding effects of Nusselt number, Damkohler numbers and free stream Reynolds number. By varying the Nusselt number, multiregion structures of mixing only, premixing- and diffusion-controlled reactions are observed near the leading edge of the flame. In the region of the premixing-controlled reaction, fuel lean and rich reactions can be found. As the flow velocity decreases, the flame tends to have a large stand-off distance and more fuel mass is transferred upstream of the burner to enforce the local reaction and to improve the stabilization of the flame.

1 INTRODUCTION

Laminar boundary layers over flat plates with chemical reaction are attracting much attentions because they are closely related not only to many practical problems such as combustion in hybrid rockets, fires over structures and liquid pools, but also to essential physical aspects of a system involving fluid dynamics, chemical kinetics and heat transfer. Understanding and controlling these problems relies on more accurately understanding the fundamental interactions among them. Sharing facets of this work, some experimental and numerical studies have been conducted. Using a boundary layer theory, Emmons [1] studied the burning rate of condensed fuel in an oxidizing stream, according to the theory, burning rate would become infinite at the leading edge of the condensed fuel

plate. To describe the transition of the diffusion flame, Hirano, et al.[2,3] investigated experimentally the flame stabilizing mechanism by changing injecting fuel and free stream velocity. But no details were reported on thermal and reacting zone structures when a diffusion flame underwent a transition. Miyashita et al.[4] made an experimental study of the effects of free stream velocity on flame stabilization and found that, at a low velocity, a recirculation flow formed upstream the burner could act as a stabilizer of the diffusion flame. Using a finite-rate Arrhenius kinetics, Chen and T'ien [5] investigated transition from an envelop to an open-tip flames when Damköhler number decreases. However, equal molecular weight of reactants and temperature-indenpendent diffusion coefficients were assumed with a constant wall temperature of the burner. Blasi et al.[6] constructed a model of pulsating flame spread across liquid fuels and predicted flame structure changing from a premixed type at the leading edge to a diffusive type downstream. But Bousinesq approximation was used and gas density is constant except for variations induced by buoyancy. In spite of these studies, there still remain some unknown mechanisms, for instance, on the local velocity anomaly, flame instability and sophisticated structures of the leading flame edges. Our previous numerical simulations have dealt with a diffusion flame established in a laminar boundary layers of a flat plate for an incompressible flow of nonexothermic chemical reaction[7] and for a compressible flow by using a flame sheet model and accounting for reaction heat release[8]. These works gave understandings about the mechanisms of the acceleration and deceleration of the flow across the flame zone which induces an anomaly in the velocity distribution, and the vortical generation which may disturb and wrinkle the flame sheet downstream. However, as fast chemistry was allowed, it is incapable of predicting behaviors of the leading flame edge and extinction, as observed in some related experiments.

In the present paper, we are particularly concerned with a air stream flowing parallely over a flat plate, from a part surface of which (known as burner) fuel is vertically injected into the oxidizing stream and is reacted chemically. Under certain conditions, a diffusion flame may be

established and stabilized near the front end of the burner. Chemical reaction interacts closely with the flow and thermal states, for instance, the velocity of the free stream and the rate of heat transfer on the wall surface, which may be represented by the Reynolds, the Damkohler and the Nusselt numbers. Objectives of the study are to access multiregion structures of the leading flame edges and their dependence on the free stream velocity.
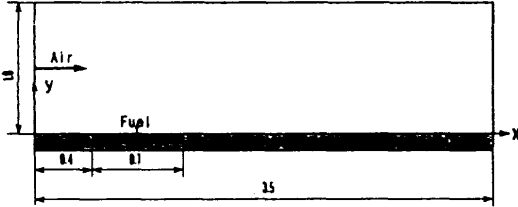

Fig.1 Configuration of the computation model

2 PHYSICAL MODEL AND GOVERNING EQUATIONS

Computational domain of the present study is shown in Fig.1, with 350mm in length and 100mm in width. The fuel of gaseous methane is injected from a porous plate within a region from $x=40$mm to 110mm with uniform velocity, formed a burner with 70mm in length. The governing partial differential equations of mass, momentum, energy, and species are deduced for a two-dimensional laminar reacting boundary layer flow with the following assumptions:

a) the flow is two-dimensional and laminar with stokes' hypothesis,

b) chemical reaction is one-step, irreversible with second-order, finite rate Arrhenius kinetics.

c) the reactants and product are perfect gases with equal and constant specific heats, equal diffusion coefficients. The diffusion coefficients are assumed temperature-dependent obeying the law given by Strehlow[9]: $\mu \propto T^{0.7}$ 、 $D \propto T^{1.7}$、 $\alpha \propto T^{1.7}$.

d) the Soret and Dufour effects, along with pressure diffusion, work done by pressure and body force are neglected,

d) Lewis number is unity,

To normalize the governing equations, height of the computational domain is chosen as the characteristic length and the state of air main stream at $T_{\infty} = 300K$ and one atmospheric pressure is specified as the reference. According to the above assumptions, the nondimensional governing equations can be written as follows:

Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0, \tag{1}$$

Momentum equation

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u u)}{\partial x} + \frac{\partial(\rho u v)}{\partial y} = -\frac{\partial p}{\partial x} +$$

$$\frac{\partial}{\partial x}\frac{\mu}{R_e}[2\frac{\partial u}{\partial x} - \frac{2}{3}(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y})] + \frac{\partial}{\partial y}[\frac{\mu}{R_e}(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})], \tag{2}$$

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho v u)}{\partial x} + \frac{\partial(\rho v v)}{\partial y} = -\frac{\partial p}{\partial y} +$$

$$\frac{\partial}{\partial x}[\frac{\mu}{R_e}(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})] + \frac{\partial}{\partial y}\frac{\mu}{R_e}[2\frac{\partial v}{\partial y} - \frac{2}{3}(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y})], \tag{3}$$

Energy equation

$$\frac{\partial(\rho T)}{\partial t} + \frac{\partial(\rho u T)}{\partial x} + \frac{\partial(\rho v T)}{\partial y} = \frac{\partial}{\partial x}(\frac{\mu}{R_e P_r}\frac{\partial T}{\partial x}) +$$

$$\frac{\partial}{\partial y}(\frac{\mu}{R_e P_r}\frac{\partial T}{\partial y}) + Q w_{fu}, \tag{4}$$

Chemical species

$$\frac{\partial(\rho Y_i)}{\partial t} + \frac{\partial(\rho u Y_i)}{\partial x} + \frac{\partial(\rho v Y_i)}{\partial y} = \frac{\partial}{\partial x}(\frac{\mu}{R_e S_c}\frac{\partial Y_i}{\partial x}) +$$

$$\frac{\partial}{\partial y}(\frac{\mu}{R_e S_c}\frac{\partial Y_i}{\partial y}) + w_i, \tag{5}$$

where the consumption rate of fuel is

$$w_{fu} = -D_a \rho \rho Y_{fu} Y_{ox} exp(-Z/T), \tag{6}$$

and ρ, u, v, p, T, Y_i, are the density, velocity components of x and y-directions, pressure, temperature and mass fraction of ith chemical species for the mixture gas, respectively. B_f is the preexponent coefficient.Four species of fuel, oxidizer, inert and product are taken into account. The equation of thermodynamic state is

$$\rho = \frac{p}{C_1 T}, \tag{7}$$

where $C_1 = RT_{\infty}^*/U_{\infty}^*/U_{\infty}^* = 1/kM^2$, k is the specific heat ratio of the mixture gas and M is the Mach number of free stream flow. R is the gas constant of the mixture and is estimated by

$$R = \sum_{i=1}^{n} \frac{Y_i}{W_i} R_u. \tag{8}$$

R_u is the universal gas constant and W_i is the molecular weight for ith species. Referencing Lee's work[10] on the gas phase chemical reaction where the fuel is taken as methane (CH_4), the value of related properties are specified: $P_r = 0.714$, $Q^* = 116.8$. The governing equations are numerically integrated by SIMPLE procedure and lots of numerical experiments have been done to properly specify the size of the computational domain and the mesh. A nonuniform mesh is adopted with grid nodes 401×146.

Table 1 Computed Cases

Case No.	Re No.	$Nu_{(\delta y)}$	Da No.
Case 1	6234	0.05	1.85×10^8
Case 2	6234	0.062	1.85×10^8
Case 3	6234	0.07	1.85×10^8
Case 4	3117	$0.05 * \sqrt{U_{\infty}}$	$1.85 \times 10^8/U_{\infty}$
Case 5	8104	$0.05 * \sqrt{U_{\infty}}$	$1.85 \times 10^8/U_{\infty}$

3 RESULTS AND DISCUSSION

Five computation cases are listed in Table 1 and inject-ing velocity of the fuel is set $0.07m/s$ in all of the five cases. In the first three cases, the free stream velocity is fixed at $1m/s$ with variation of the Nu number. Effects of varying free stream velocity are reflected in cases 4 and 5. The determination of those velocities are based on our exper-imental study in which stabilized and transient diffusion flames have been observed[11].
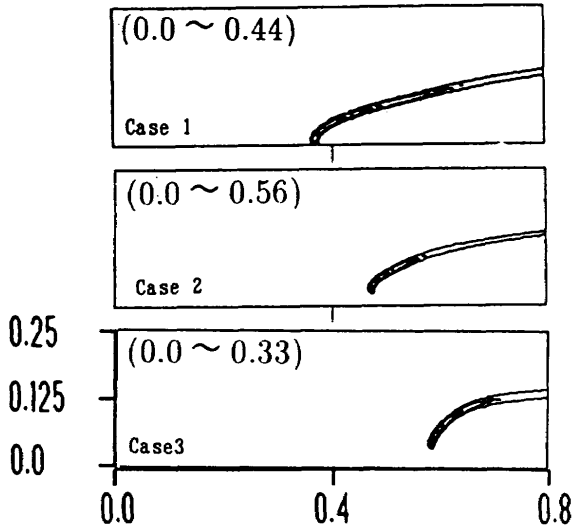

Fig.2 Contours of the fuel reaction rate for Cases 1, 2 and 3.

3.1 Varying Nusselt number

The Nusselt number, Nu, defined by $h\Delta y/\lambda$, is propor-tional to the heat transfer rate h from the gas phase to the solid flat plate. The effect of varying Nusselt num-ber is investigated by fixed the free stream velocity and by changing the h for a wide range for Cases 1, 2 and 3. Contours are depicted in Fig.2 for the fuel reaction rate of the three cases. In all of the three cases, concentrated reaction occurs in the apex of the reaction zone, meaning a highly exothermic reaction zone and serving as a holder of the diffusion flame. At $Nu=0.05$ for Case 1, the reac-tion zone originates from upstream of the leading end of the burner, forming an enveloped flame and hindering the cold oxidizing stream penetrating into the fuel side. When the heat transfer rate to the wall increases for Cases 2 and 3, chemical reaction zones are retreated toward down-stream and their apexes become open, no longer anchoring on the surface of the flat plate. This indicates a genera-tion of a low temperature, nonreactive zone between the leading edge of the flame and the wall and is consistent with many experimental observations that at certain con-ditions, only premixing of the fuel and the oxidizer occur near the leading flame edge. Corresponding contours of the temperature are shown in Fig.3. For Case 1, the con-tours of high temperature enclose upstream of the leading end of the burner and there appear a concentrated stream-wise gradient, by which a large heat flux can be conducted
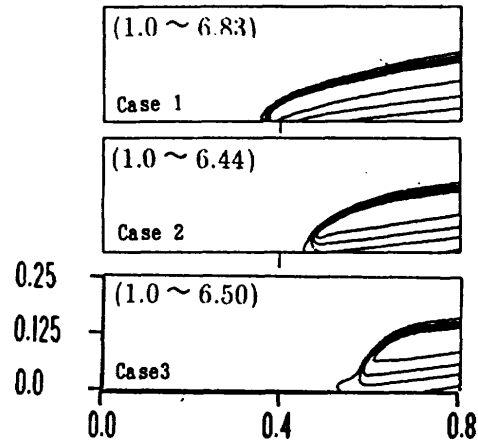

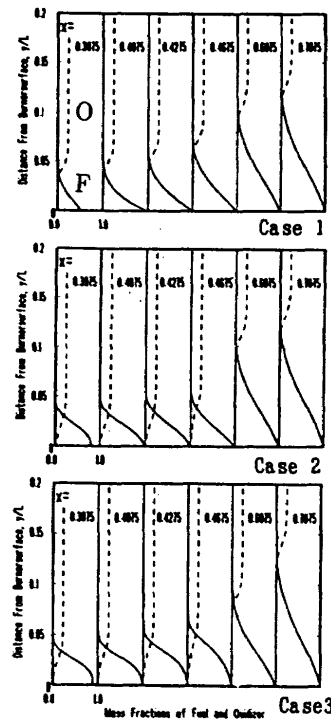Fig.3 Contours of the temperature for Cases 1, 2 and 3.

Fig.4 Profiles of the oxidizer and fuel mass fractions along y-direction at six positions for Cases 1, 2 and 3.

upstream to preheat the cold oxidizing stream and to sta-bilize the enveloped flame. With the increase of Nu for Cases 2 and 3, however, high temperature zones are lifted off and blown downstream. This results in less heat con-duction toward upstream and low temperature zones near the apexes of these contours. Thus, chemical reaction is hard to sustain there as shown in Fig.2 and stabilization of the flames is weakened. Further decreasing in Nu will bring about the flame stabilization at the rear end of the burner or the flame disappearance in the computational zone. This implies a transition process of the flame from an enveloped to an open-tip ones, affected by variation of the heat loss rate on the wall.

To clarify the structures of the leading flame, it is impor-tant to understand the details on processes of the species mixing and the chemical reaction arising there. Fig.4 gives

profiles of oxidizer and fuel mass fractions along y-direction at six positions around the leading end of the burner at $x=0.4$ for Cases 1, 2 and 3. Profiles for oxidizer and fuel mass fraction are indicated by dashed and solid lines respectively. For Case 1, because an enveloped flame is stabilized on the upstream of the leading end of the burner, mass fractions of fuel and oxidizer reach zero almost at the same spatial positions, meaning the establishment of a diffusion-controlled type of flame. For Cases 2 and 3, a coexisting zone of oxidizer and fuel, that is, a premixed zone of the two species can be clearly recognized. Considering the fact that locations of the apexes of the reaction zones are $x_{Case2}=0.4635$ and $x_{Case3}=0.5607$, as shown in Fig.2, three stages can be divided along x-direction. First of all, fuel and oxidizer are mixed by diffusion and convection and no chemical reaction takes place, thus premixed zone of the reactants are formed until x_{Case2} and x_{Case3}. Downstream the x_{Case2} and x_{Case3}, chemical reaction takes place and premixed flames are expected to generate. Premixed zones, however, can still be found at $x=0.4675$ for Case 2 and $x=0.6075$ for Case 3 because of the low temperature and the low reaction rate there. At $x=0.7075$, diffusion flames are achieved since the mass fractions of fuel and oxidizer come to zero at the same spatial positions. It is reasonably to inference that there exist transition flames from a premixed one, through a comparably predominated one by both chemical kinetics and diffusion, to a diffusing one. Furthermore, fuel lean and fuel rich chemical reactions are found in the upper and lower parts of the premixed reaction region. Gradient of the profiles for the fuel near the wall decreases when Nu number increases, especially at the leading part of the burner at $x=0.4$. This tendency diminishes toward downstream for the three cases. There are no obvious distinction in the diffusion height (distance off the wall when mass fraction of fuel comes to zero).

To get an insight into the heat transfer between the flowing fluid and the wall, it is necessary to understand thermal status on the surface of the wall. Distributions of the wall temperature and its gradient of y−direction are shown in Fig.5 along x−direction. A similitude on the profiles can be seen that, the profiles increase very quickly and peak
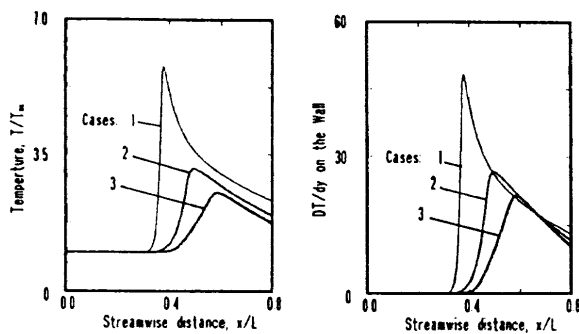

Fig.5 Distributions of the wall temperature and its gradient along x−direction.

in fronts of the leading flames, then become small toward downstream. The trend of temperature change is consistent with many experimental measures. With the increase of Nu number, the maximum of the profile decreases and moves downstream.

3.2 Varying free stream velocity

To examine the effect of varying free stream velocity, results for Cases 1, 4 and 5 are chosen with three different velocities. Results for Case 1 are used as the based data to compare throughout the present paper and most of its results have been given in section 3.1. Our discussion is covering the three cases but results for Cases 4 and 5 are mainly given in this section.
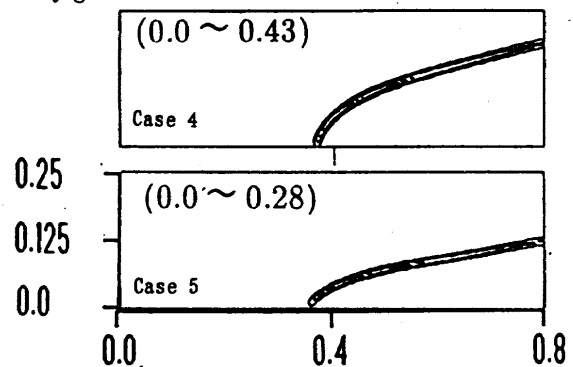

Fig.6 Contours of the fuel reaction rate for Cases 4 and 5.

Contours are depicted in Fig.6 for the fuel reaction rate of fuel for Cases 4 and 5. By comparing with the result of Case 1 in Fig.2, the chemical reaction takes place upstream of the burner and the reaction zones enclose on the wall of the plate for the three cases. However, with decrease of the velocity, the reaction zone becomes full and its rear part is lifted off the wall significantly, because the thickness of boundary layer increases when the velocity decreases. Maximum of the reaction rate has no big distinction for Cases 1 and 4, but decreases quickly when the velocity goes up to $1.3 m/s$. Further increase of velocity results in blow-off flame or extinction.

Profiles of the oxidizer and fuel mass fractions are given in Fig.7 at six positions for Cases 4, and 5. Premixed zones of the reactants can not be found clearly for the three cases and similar to the reaction zones in Fig.6, the flame height increases with decrease of the velocity.

Profiles of the temperature at the six positions are shown in Fig.8 for Cases 4 and 5. Common trends in the profiles are found that the maximum temperature has less change with the variation of x, and that the temperature close to the wall decreases monotonously toward downstream for the three cases. When the velocity decreases, temperature gradient in the fuel side becomes mild because the thermal boundary layer increases. Corresponding distributions of the wall temperature and its gradient are shown in Fig.9. In the three cases, the wall temperature and its gradient are the largest for Case 1 and the smallest for Case 4. The temperature rises up in the most upstream position for Case 5 and almost at a same point for Cases 1 and 4,
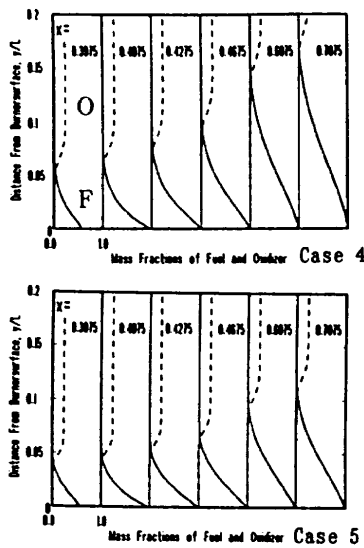
Fig.7 Profiles of the oxidizer and fuel mass fractions along y-direction at six positions for Cases 4 and 5.
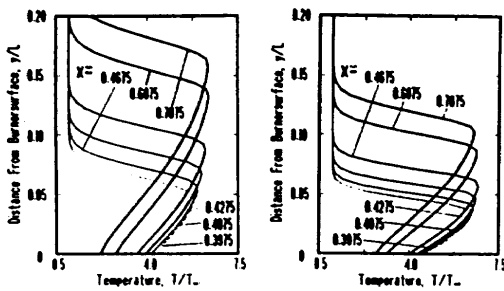

Fig.8 Profiles of the temperature at six positions in x−direction for Cases 4 and 5.

meaning much more heat is transferred toward upstream for Case 5 than for Cases 1 and 4.

CONCLUSIONS

(1) The leading flame edge anchors and stabilizes at the front end of the burner at the low Nusselt number, and is lifted off the wall with increase in the Nusselt number. This means a transient process of the leading flame edge dependent on the heat loss from the surface of the wall.

(2) In the case of lifted off flame, multiregion structures of the leading flame edge are found. Towards downstream, there are regions of mixing only, premixed and diffused flame and fuel lean and rich flames exist in the region of premixed flame.

(3) As the free stream velocity decreases, the flame has a large stand-off distance and more fuel mass is transferred upstream of the burner, showing a stabilizing tendency of the flame.

(4) For stabilized flames, the temperature and its gradient on the wall surface maximize nearly the front end, decrease quickly toward downstream of it.

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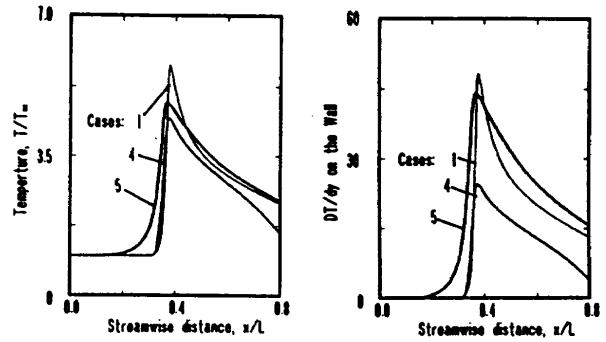1.   H. Emmons, 'The film combustion of liquid fuel,

Fig.9 Distributions of the wall temperature and its gradient along x−direction.

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