Numerical Study on Ultra-Lean Combustion by Using Stagnation Flow Swirl Burner

Akane Uemichi, Hiroki Aizawa, Takumi Hattori, Makihito Nishioka
University of Tsukuta
Tsukuba, Ibaraki, Japan

1 Introduction

Lean combustion in swirling flow has been attracting attentions because of its high efficiency and reduction of NOx emissions [1]. However, since the turbulent combustion with swirl is a very complicated phenomenon, the mechanism has not been explained completely. In order to reveal the combustion mechanism, analysis of a swirl flame using a simple-shaped flame model is needed.

So far, we have been conducting numerical studies focusing on the ultra-lean swirling flame whose equivalence ratio is out of the lean flammability limit [2, 3]. In the case of the calculation of rotating counterflow twin flame which can be treated one-dimensionally, the flame structures were investigated for methane-air and hydrogen-air premixed flame. As a result, we confirmed that the leanest extinction limits for both fuels are beyond the lean flammability limit [2, 3]. Rotating counterflow twin flame is the simplest swirling flame model, so it is suitable for theoretical analysis. Nevertheless, it is impossible to realize the flame keeping its the one dimensional flame structure is in an experimental way. Therefore, whether the mechanism which we revealed using the 1-D model is valid or not for multidimensional flames is very important. Thus we performed an axisymmetric two-dimensional swirl flame calculation which is thought to be realized experimentally [4]. In the previous study, it was found that the flame structure of methane-air swirl flame around the tip under ultra-lean condition, $\phi = 0.35$, is the same as that of rotating counterflow twin flame. However, the ultra-lean two-dimensional swirl flame can be formed only temporarily; they were unsteady and unstable.

In this study, we designed a "stagnation swirl burner" that may be able to realize a steady and stable ultra-lean axisymmetric two-dimensional flame and performed a detailed calculation. We also compared the ultra-lean flame structures of stagnation swirl flame with that of a rotating counterflow twin flame, and checked whether the flame structures are the same or not.

2 Concept for Design of Stagnation Flow Swirl Burner

In the previous study, we adopted a model in which premixed gas was injected into a truncated-cone-shaped burner with swirling and a flame is formed in the swirl flow. By using this swirl burner, we could obtain a flame whose structure is similar to that of a rotating counterflow twin flame under ultra-lean condition, $\phi = 0.35$. However, the flame existed only temporarily and reached extinction as time passed. This extinction is caused by a backward flow of unburned gas. As for the mechanism of combustion in swirl flow, it has been thought that the backward flow region is formed within flame

Correspondence to: akane@uemichi.net

and hot burned gas plays a role as a heat and radical source, so its flame surface is enhanced. However, in the case of the truncated-cone-shaped burner, since not only hot burned gas but also cold unburned gas comes into the flame surface, the flame reaches extinction.

Therefore, in this study, a stagnation swirl burner, in which the backward flow of only burned gas comes toward the flame surface, is designed. This burner is composed of a burning section and a stagnation plate. The burning section has a straight tube section with a 20 mm-width slit from which premixed gas comes in and it generates swirl flow. Next to the straight section, there is a bugle-shaped wall whose curvature radius is 40 mm in which a flame is formed. The stagnation plate has a cilinder-shaped cavity of radius 30 mm and depth 10 mm. The purpose of setting the stagnation plate is to prevent unburned gas from flowing backward by separating the unburned gas from the burned gas. The width of the annular exit passage is 10 mm.

3 Numerical Method

Figure 1 shows the calculation domain and the boundary conditions. In this study, we assume an ax-isymmetric two-dimensional flow. Governing equations to be solved are the equation of continuity, Naviar-Stokes equation, and conservation equations for energy and concentrations of all species. These equations were discretized and solved computationally with the equation of state for ideal gas. At the side wall of the straight tube section, we give the upstream boundary conditions of unburned gas: temperature T_0 = 300 K, the species mass fraction $Y_{k,0}$, the axial velocity U, and the circumferential velocity W. Table 1 shows the calculation conditions. All of the calculation results shown in this paper were conducted in accordance with these conditions.

The adapted chemical kinetics scheme is somewhat simplified C1 chemistry obtained by deleting all NOx-related reactions from GRI-mech3.0 [5]. The resultant scheme involves 23 species and 119 elementary reactions. The numerical code is based on SIMPLE scheme and CHEMKIN subroutine libraries [6–8] for evaluating chemical reaction rates, thermochemical properties and transport properties. For comparison, we will also show the results of 1-D planer flame calculated using PREMIX and the rotating counterflow twin flame using RCTF code which is a modified version of PREMIX [2].

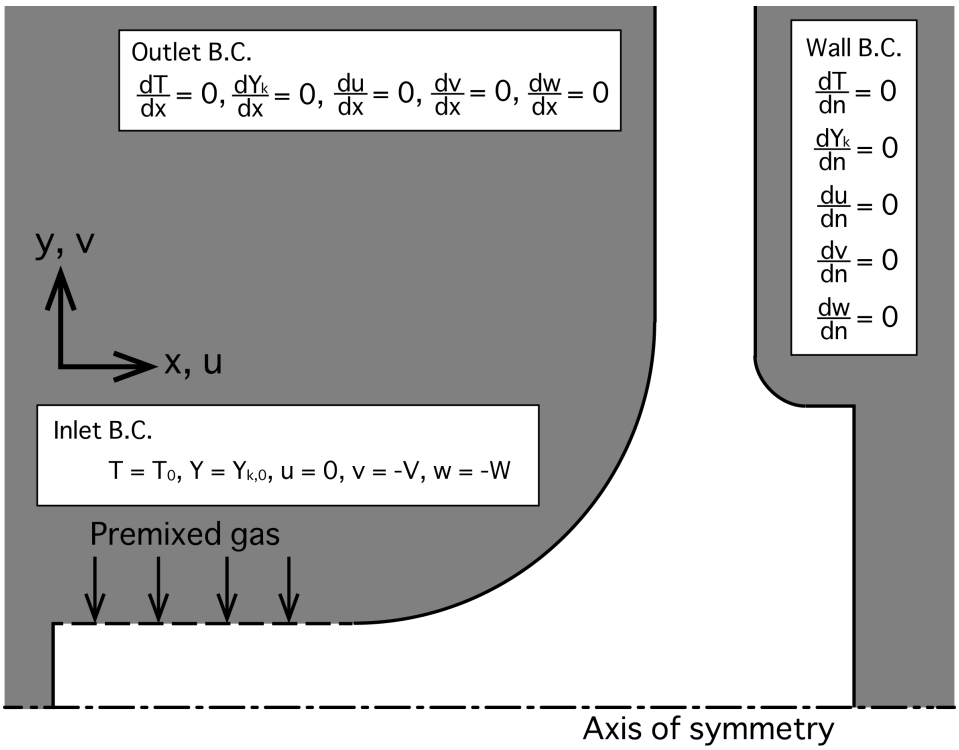
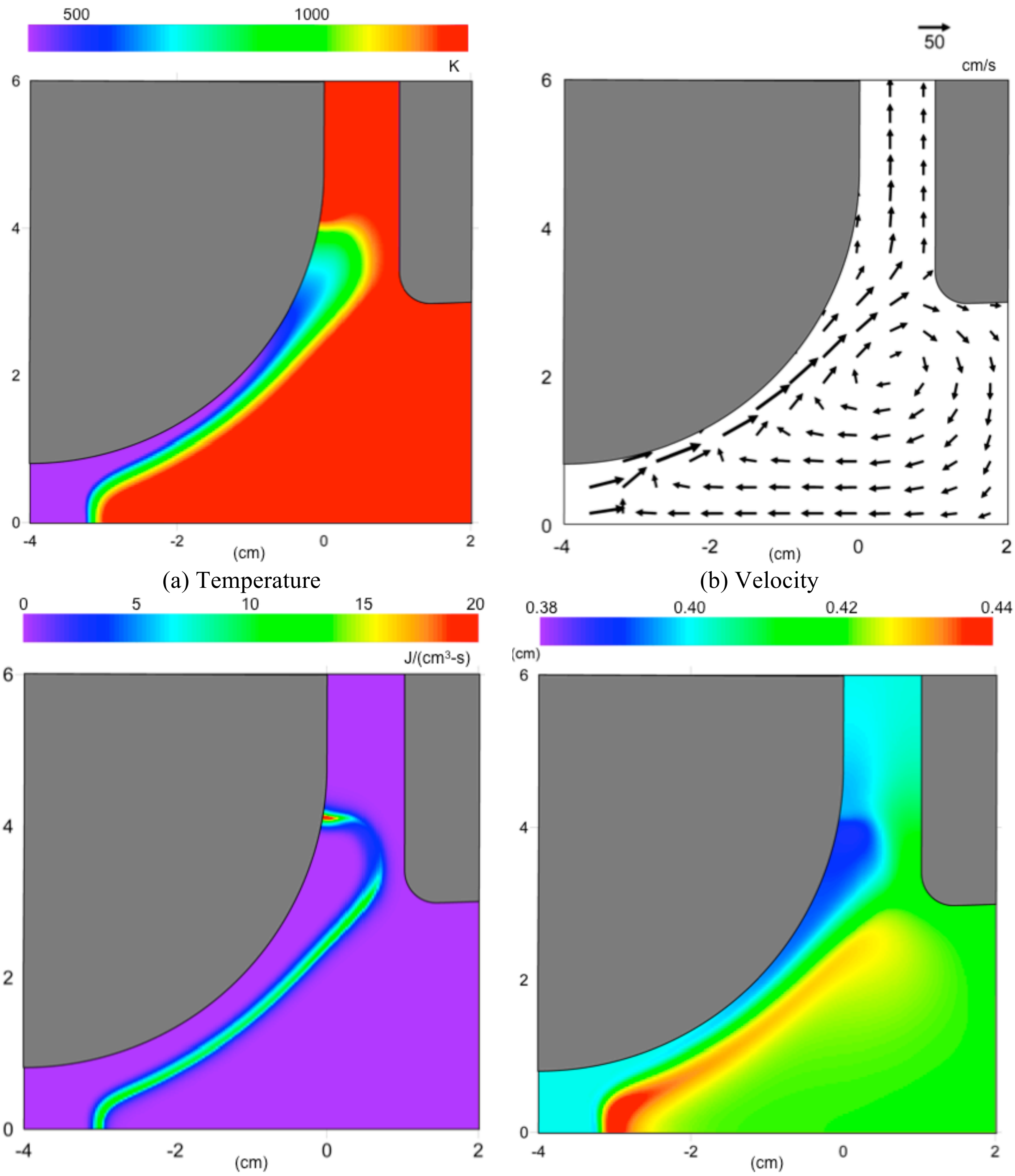


Figure 1. Calcuration domain and boundary conditions

Table 1 Conditions of calculation

Fuel	CH_4
Oxydiser	Air
Equivalence ratio ϕ	0.40
Radial velocity at the inlet V	10 cm/s
Circumferential velocity at the inlet W	80 cm/s
Gas temperature at the inlet T_0	300 K



(a) Temperature (b) Velocity

(c) Heat release rate (d) Pseudo local equivalence ratio

Figure 2. Structure of a ultra-lean flame. ϕ = 0.40.

4 Results and Discussions

4.1 Formation of Ultra-Lean Swirl Flame

Figure 2 shows the flame structure under an ultra-lean condition, ϕ = 0.40. Focusing on the heat release rate, large heat release rate zone reaches the burner wall without extinction, so the flame surface is ”closed” within the burner. As for the velocity distribution, it is seen that the flow collides with the stagnation plane and is separated into two directions: the axial direction and the radial direction. The axial split flow turns back due to the cavity settled on the stagnation plate. Around the cavity, comparing the velocity distribution with the temperature distribution, it is found that only hot burned gas flows backward to the flame surface within this region. Therefore, the stagnation plate plays an important role for forming the ultra-lean swirl flame.

Figure 2 (d) shows the distribution of “pseudo local equivalence ratio”, which is defined by; ϕ_{PL} = (0.5[H]+2.0[C])/[O]. For the atom concentrations, all species including reactants, intermediates, and the final products are considered. It is noted that although the equivalence ratio of unburned mixture is 0.40, the pseudo local equivalence ratio is more than ϕ = 0.40 around the flame tip. It is thought to be because of the plenty of fuel species CH_4 at the region due to the preferential diffusion whose mechanism is similar to that of ultra-lean rotating counterflow twin flame.

In the previous numerical study using the truncated-cone-shaped burner, steady ultra-lean flame could not be obtained. In addition, we could not realize the formation of ultra-lean flame in an experimental way. However, since we ascertained that this flame is almost steady, using the stagnation swirl burner, we expect the ultra-lean flame to be realized experimentally.

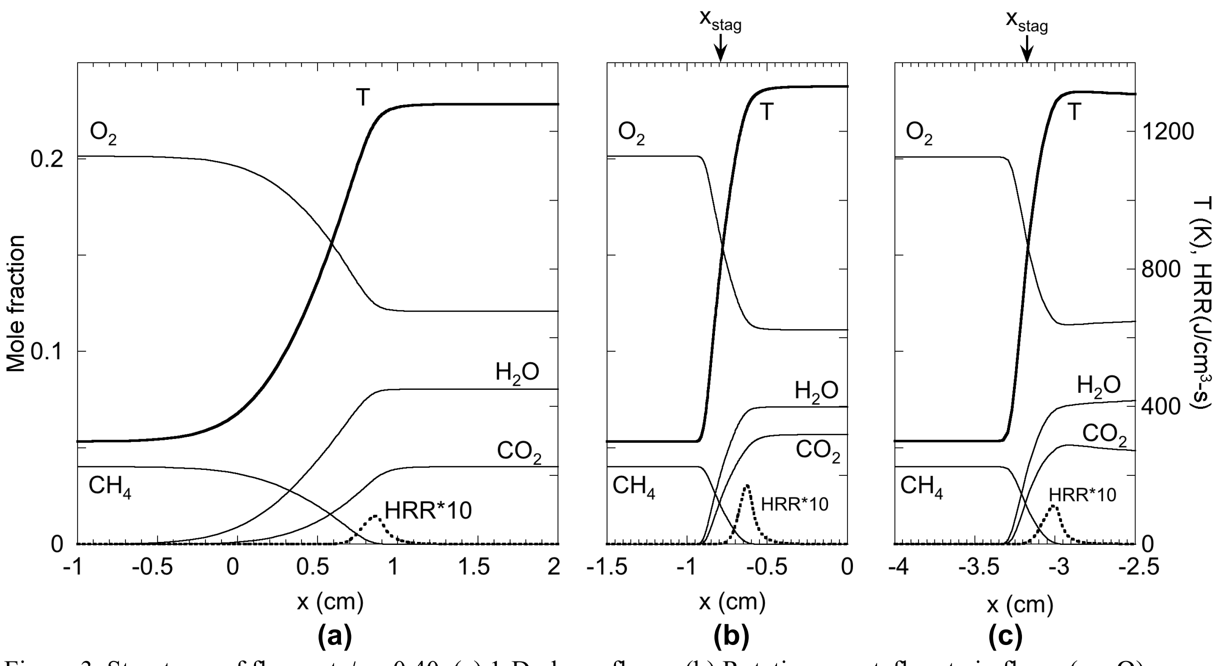


Figure 3. Structures of flame at ϕ = 0.40. (a) 1-D planer flame. (b) Rotating counteflow twin flame (u_R, Ω) = (400 cm/s, 150 rps). (c) Stagnation swirl flame.

4.2 Structure of Flame Tip

It is noted that unburned gas and burned gas are facing each other around the flame tip (x = 3.0 cm). This is the same ultra-lean flame structure as that of rotating counterflow twin flame. Figure 3 (a), (b), (c) show the flame structures of 1-D planer flame, rotating counterflow twin flame of (u_R, Ω) = (400 cm/s, 150 rps), and stagnation swirl flame on the center axis, respectively. For the rotating counterflow twin flame and the stagnation swirl flame, the stagnation point x_{stag} in which the axial velocity is zero are shown by the arrows. It is noted that x_{stag} exists within the flame zones. When the flame surface is defined as the maximum heat release rate position, x_{stag} is located at the upstream of the flame surface. It is seen that, in the case of stagnation swirl flame, the reactant species is transported by diffusion against the convection similarly to the rotating counterflow twin flame. The flame thickness of 1-D planer flame is approximately 1.5 cm. On the other hand, those of other two of flames with swirling flow are approximately 0.5 cm, so this is thin enough to be realized in ordinary scale combustors.

As mentioned above, we compared the flame structures between the stagnation swirl flame and the rotating counterflow twin flame under ultra-lean conditions. The numerical result of stagnation swirl flame agrees with that of rotating counterflow twin flame very well. Thus, it seems that the stagnation swirl flame and the rotating counterflow twin flame share the same characteristics, so their mechanisms of ultra-lean combustion are the same. This ultra-lean combustion mechanism could be extended other combustion system like swirl burner combustion or turbulent combustion [9] in which burned gas and unburned gas are countered.

5 Concluding Remarks

In this study, we designed the stagnation swirl burner and we performed a detailed kinetics calculation of ultra-lean axisymmetric stagnation swirl flame, and we could obtain a virtually steady ultra-lean premixed flame. Using the swirl burner, it is noted that the only burned gas can be flowed backward as we expected. In this case, large heat release rate region reaches the burner without extinction, so it is seen that unburned gas cannot be flow backward. In the case of the ultra-lean flame obtained in this study, reactants and burned gas species are facing each other at the flame tip, so the stagnation point is formed within the flame zone. This is the same feature as that of rotating counterflow twin flame.

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