FLAT FLAME STRUCTURE WITH STRAIN RATE IN IMPINGING JET FLAMES OF SYNGAS FUEL

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ABSTRACT

A study has been conducted numerically to investigate the lifted flat flame structure in impinging jet configuration of syngas fuel with the global strain rates in 10% hydrogen content. In this study, the effect of strain rate was major parameters on chemistry kinetics, and a main focus is to investigate flame structure at stagnation point. The numerical results were calculated by SPIN application of the CHEMKIN package. The strain rates were adjusted with Reynolds numbers of premixed syngas-air mixture. As strain rate has increased, flame temperature and axial velocity have decreased due to the flame heat loss increment. A reversal phenomenon of H_2O according to increasing strain rate appeared at near stagnation point. This phenomenon is attributed to the rapid production of reaction such as the R12 ($H + O_2 (+M) = HO_2 (+M)$) and R16 ($HO_2 + H = OH + OH$), which makes the R18 ($HO_2 + OH = O_2 + H_2O$) reaction increment.

KEYWORDS: Impinging jet flame, Flat flame, Syngas fuel, Strain rate, Flame structure

1. INTRODUCTION

Impingement jet combustion has been widely used in both industrial and domestic applications such as scrap metal melting, glass shaping, and fabric drying and indoor cooking and heating, because of excellent heat transfer performance. Conventional hydrocarbon fuels have been used for uniform heating in the process using impinging jet flame. But, syngas is used to alternative energy because of energy depletion problem [1]. Main components of syngas are hydrogen (hereafter, H_2) and carbon monoxide (hereafter, CO). Syngas is more excellent than pure hydrocarbon fuel in the combustion efficiency, exhaust emission performance and burning velocity [2, 3]. However, these advantages have problems such as auto-ignition, flashback and flame instability at the same time [4, 5].

We have been studied syngas fuel including various H_2 content to investigate the combustion and heat transfer characteristics such as laminar burning velocity, heat flux and temperature profiles in the impinging jet combustion system [4-7]. The coupling that occurs between fluid mechanics and chemical kinetics at the stagnation point is important in impinging jet flames, but it is difficult to confirm experimentally.

Numerical studies according to the equivalence ratio, impinging distance, Reynolds number and strain rate, which represent main parameters of impinging jet flame, are needed to study detail flame structure, especially at stagnation point. It seems that strain rate has a significant impact on flame structure of lifted impinging jet flame. In this case, the effects of strain rate are necessary to understand the combustion reaction and heat transfer that are practical interest. To understand the impinging jet flame structure, numerical studies by strain rate should be preceded. The purpose of this study is investigation about the detail structure of impinging jet flame according to strain rate with hydrogen 10% content in lifted flat flame having one-dimensional shape in numerical terms. Numerical analysis was conducted using SPIN code of CHEMKIN package at one-dimensional stagnation flow [8]. The results are calculated along the vertical position, i.e., x-direction to stagnation point from nozzle exit because of one dimensional analysis.

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2. NUMERICAL APPROACH

2.1 Numerical Models

Fig. 1 shows the schematics of lifted flat flame in impinging jet configuration. Mixtures with velocity V_{inlet} and temperature T_{inlet} exit from contraction nozzle. Impinging plate with temperature T_{wall} positioned at a separation distance H/d. The radial dimension of impinging plate in numerical system is presumed to be large compared with H/d. This geometry exhibits a similarity behavior that can be exploited mathematically 3D shape flame into a system of one-dimensional approach. Hence, the temperature and composition fields only become a function of the vertical position x on the basis of stagnation point.
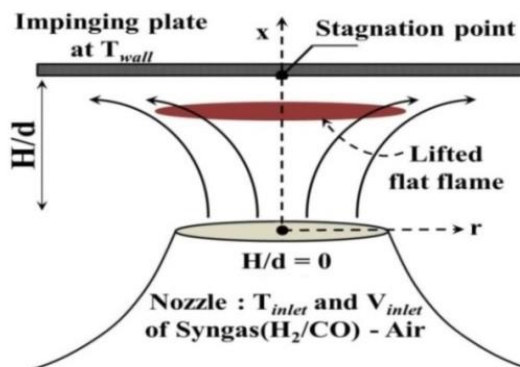

Fig. 1 Schematic diagram of the lifted flat flame in impinging jet configuration

This approach has been followed in the development of the SPIN code of the CHEMKIN package. In this code, the species, temperatures and velocity profiles are calculated for steady-state one-dimensional stagnation flow while accounting for finite-rate gas-phase chemical kinetics and multicomponent molecular transport. The detailed flame structures of impinging jet flames were numerically investigated by employing the Davis chemical kinetics mechanism (14 species, 38 reactions) for syngas (H_2/CO) with 10% H_2 content.

2.2 Numerical Methods

Main parameters that could potentially control burning velocities and flame structures include: Reynolds number (hereafter, Re), dimensionless separation distance (hereafter, H/d), equivalence ratio (hereafter, Φ) and composition ratio. However, the main parameters in present study were Reynolds numbers and global strain rates while others are fixed. These parameters are listed in Table 1 along with others relevant.

Table 1 Numerical conditions

Mixture(syngas-air)	High purified H_2, CO, Air
Composition ratio	H_2 : CO = 10 : 90
Equivalence ratio (Φ)	0.9
Impinging distance (H/d)	2.0
Reynolds number (Re)	600 - 2200
Strain rate(a_g)	$48.5 \sim 179.0 s^{-1}$ (with Re)

In this study, the global strain rate, hereafter known as the strain rate (hereafter, a_g), was defined as following equation (1):

$$a_g = \frac{du}{dh}, \ du \equiv Re, \ dh \equiv H/d \tag{1}$$

Therefore, this paper used a_g instead of Re, H/d for calculating strain rate. To exclude the effects of H/d and Φ, the conditions were fixed with $H/d = 2.0$, $\Phi = 0.9$, respectively. To investigate a_g dependent, computations were conducted the impinging jet flames of syngas at increasing Re from 600 to 2200. In simulation, the surface temperature of impinging plate was 323.15 K and the mixture temperature of syngas-air was 300 K.

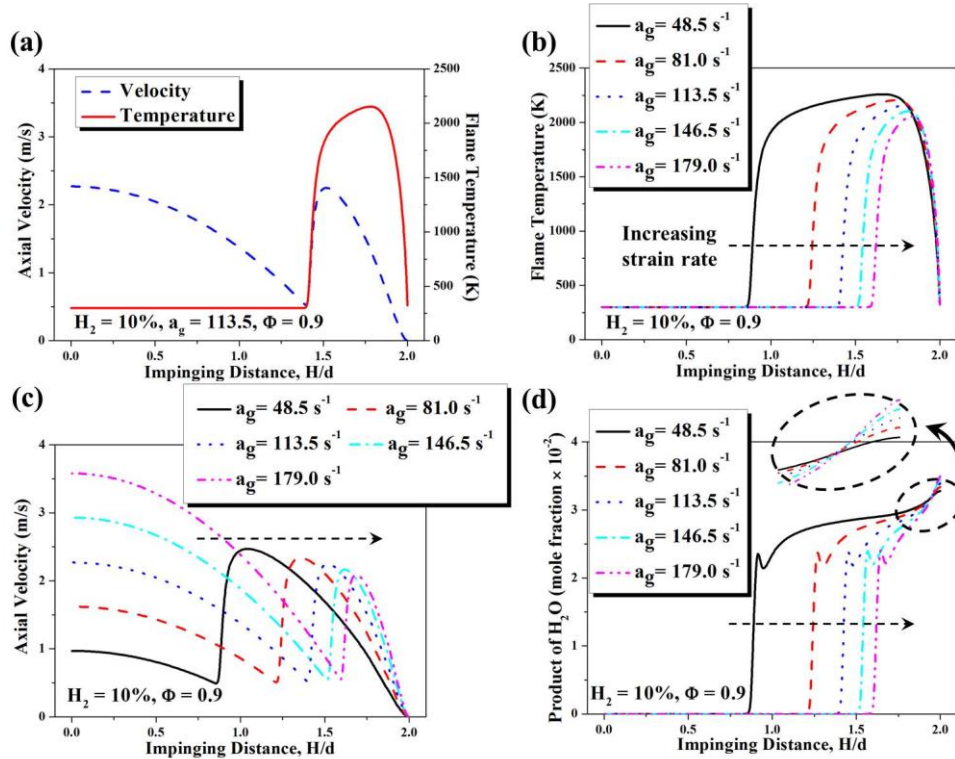## 3. RESULT AND DISCUSSION

3.1 Effect of Strain Rate

Fig. 2 Profiles for 10% H_2 and $\Phi = 0.9$ with the strain rate of 4.85, 81.0, 113.5, 146.5 and 179.0 s^{-1} : (a) axial velocity and flame temperature for $a_g = 113.5$ s^{-1}, (b) temperature, (c) velocity, (d) H_2O mole fraction

Fig. 2-(a) shows the simulated variation of axial velocity and flame temperature at $a_g = 113.5$s^{-1}, $H/d = 2.0$, $\Phi = 0.9$ and $H_2 = 10\%$. The axial velocity profile continuously declines till the reaction zone. A dip in the velocity occurred before attaining the peak at the reaction zone due to divergence of the mixture. The axial velocity profile increased again at the reaction zone and then decreased due to the stagnation point, while the temperature presented with a sudden increase after constant profile of ambient temperature. This peak in the axial velocity was due to high temperature of the burn gases resulting in decreased density and increased velocity. The flame temperature increased sharply because of combustion heat release. Hereafter, the flame temperature profile increased continuously because of burning of H_2 and CO at reaction zone. After the peak point, the flame temperature profile decreased sharply due to the cooling effect of the fixed T_{wall}.

The temperature and axial velocity profiles at a_g of 48.5, 81.0, 113.5, 146.5 and 179.0 s^{-1} are shown in Fig. 2 -(b), (c). It is observed that increasing a_g moves the flame reaction zone to stagnation point. Flame temperature and axial velocity declined when the reaction zone approached closer to the impingement plate. This was because of greater heat loss to the surface from the flame when it was closer to impinging plate.

Fig. 2-(d) shows the simulated variation of H_2O mole fraction at a_g of 4.85, 81.0, 113.5, 146.5 and 179.0 s^{-1}. The product of H_2O increased twice sharply because of reactant combustion. The 1´st peak in the product of H_2O appeared due to active combustion reaction in the reaction zone. It is observed that increasing a_g moved along the flame reaction zone to stagnation point. A reversal phenomenon of 2´nd peak point according to increasing a_g appeared at near stagnation point.
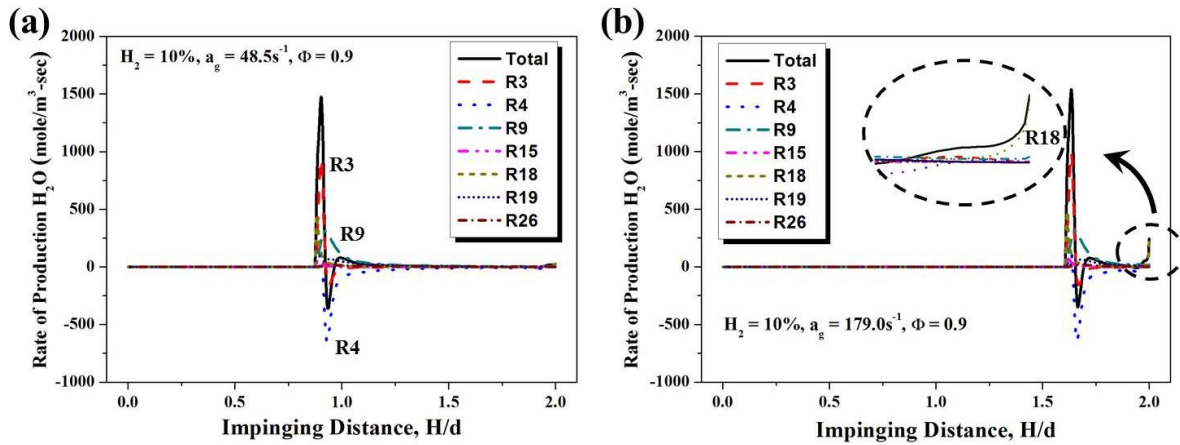
(a)

(b)

Fig. 3 Production rate of H_2O concentration with the strain rates (a) $a_g = 48.5s^{-1}$, (b) $a_g = 179.0s^{-1}$

Fig.3 shows the top 7 reaction rates of H_2O product at a_g 48.5s^{-1} (Fig. 2-(a)) and 179.0s^{-1} (Fig. 2-(b)). The 1´st peak in Fig.2-(d) appeared cause by R3 (OH + H_2 = H + H_2O) reaction that H_2O generation rate is the biggest. Thereafter it declined by R4 (OH + OH = H + H_2O) reaction and increased by continuous R9 (H + OH + M = H_2O + M) reaction. A reversal phenomenon of Fig.2-(d) caused by increasing R18 (HO_2 + OH = O_2 + H_2O) reaction at near stagnation point.
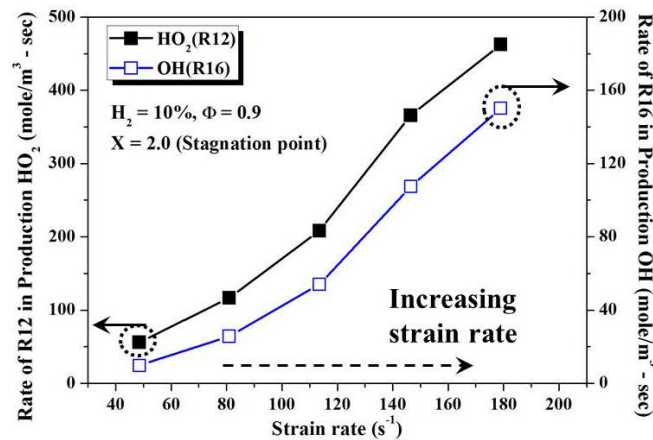

Fig. 4 Production rate of HO_2 (R12) and OH (R16) with the strain rates of 4.85, 81.0, 113.5, 146.5 and 179.0 s^{-1}

Fig.4 shows R12 and R16 reactions with the a_g (48.5 ~ 179.0 s^{-1}) at stagnation point. The R12 and R18 reactions become active according to increasing a_g, because the mixture flow is compressed at stagnation point. HO_2 is generated by third body (+M) reaction R12 (H + O_2 (+M) = HO_2 (+M)) that occurs in compression flows. It increases OH through R16 (HO_2 + H = OH + OH) reaction. Finally, it seems that a reversal phenomenon of H_2O occurs through R18 (HO_2 + OH = O_2 + H_2O) reaction.

Table 2 Reaction equation of major reaction

Reaction number	Reaction equations
R3	OH + H_2 = H + H_2O
R4	OH + OH = H + H_2O
R9	H + OH + M = H_2O + M
R12	H + O_2 (+M) = HO_2 (+M)
R16	HO_2 + H = OH + OH
R18	HO_2 + OH = O_2 + H_2O

4. CONCLUSIONS

This study has been conducted numerically to investigate the lifted flat flame structure in impinging jet flame of syngas of 10% H_2 with various global strain rates. The conclusion was derived as follows: Axial velocity is affected by the flame temperature. When the global strain rate (a_g) increase, the flame reaction zone is narrower and moves to stagnation point. At this time, flame temperature and axial velocity declined due to heat loss increased. R12 (H + O_2 (+M) = HO_2 (+M)) reaction appears actively when the more a_g increases, the more pressure increases at stagnation point. It is verified that the reversal phenomenon of H_2O caused by increasing R18 (HO_2 + OH = O_2 + H_2O) reaction at stagnation point.

ACKNOWLEDGMENT

NOMENCLATURE

SI Units

H/d	dimensionless impinging distance	
Φ	fuel/air equivalence	
Re	Reynolds number	
a_g	global strain rate	(s^{-1})

V_{inlet}	mixture velocity	(m/s)
T_{inlet}	mixture temperature	(K)
T_{wall}	impinging plate temperature	(K)

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