Springer

Journal of Mechanical Science and Technology 22 (2008) 2236~2244

Journal of Mechanical Science and Technology

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-008-0701-5

Prediction of flame formation in highly preheated air combustion †

Jang Sik Yang[1], Gyung-Min Choi[2,*], Duck-Jool Kim[2], Masashi Katsuki[3]

[1]*Research Institute of Mechanical Technology, Pusan National University 30, Jangjeon-dong, Geumjeong-gu, Busan 609-735, Republic of Korea*

[2]*Pusan Clean Coal Center, Pusan National University 30, Jangjeon-dong, Geumjeong-gu, Busan 609-735, Republic of Korea*

[3]*Department of Mechanical Engineering, Osaka University 2-1 Yamada-Oka, Suita, Osaka, 565-0871, Japan*

(Manuscript Received September 21, 2007; Revised June 2, 2008; Accepted July 2, 2008)

Abstract

Fundamental information about the ignition position and shape of a flame in highly preheated air combustion was obtained, and the suitability of the suggested reduced kinetic mechanism that reflects the characteristics of the highly preheated air combustion was demonstrated. Flame lift height and flame length with variations of premixed air temperature and oxygen concentration were measured by CH* chemiluminescence intensity, and were computed with a reduced kinetic mechanism. Flame attached near a fuel nozzle started to lift when preheated air temperature became close to auto-ignition temperature and/or oxygen concentration reduced. The flame lift height increased but the flame length decreased with decreasing preheated air temperature and flame length reversed after a minimum value. Calculated results showed good agreement with those of experiment within tolerable error. Flame shape shifted from diffusion flame shape to partial premixed flame shape with increasing lift height and this tendency was also observed in the computation results.

Keywords: Highly preheated air combustion; Flame lift height; Flame length; Reduced kinetic mechanism

1. Introduction

Low NOx combustion with highly preheated air can be accomplished by diluting the oxidant and fuel with recirculated burned gases prior to the reaction between pure fuel and air [1-3]. Since a combustion reaction occurs somewhere in a furnace when the temperature of the supplied air exceeds the self-ignition temperature of the fuel, it is important to prevent a local high temperature region and realize a uniform temperature reaction region for low NOx combustion [4, 5]. Because the flammable limit of highly preheated air combustion has been considerably extended beyond that of conventional combustion, the effects of the preheated air temperature range, dilution degree of air and fuel jet velocity on the flame shape and reaction characteristics have become more diverse [5]. The effect of lift-off on nitric oxide emission was investigated for the non-premixed jet flame in highly preheated air over 1450 K [6]. The influence of excess air ratio on the physical properties of a high-temperature air-LPG flame was investigated by numerical simulation [7].

The burning velocity of highly preheated air combustion is determined by a complicated relation between mixing velocity and chemical kinetic reaction rate. Since combustion in highly preheated air proceeds at low oxygen concentration as well as at high temperature that exceeds the self-ignition temperature of the fuel, the reaction zone is relatively wide and mild heat release occurs, resulting in a uniform temperature distribution. The combustion characteristics of highly preheated air combustion are quite different from those of conventional method. The conventional

† This paper was recommended for publication in revised form by Associate Editor Ohchae Kwon

*Corresponding author. Tel.: +82 51 510 2476, Fax.: +82 51 512 5236
E-mail address: choigm@pusan.ac.kr

combustion method does not involve highly preheated air temperature for auto-ignition and circumstances of low oxygen concentration etc. Experiences related to combustion methods for highly preheated air system have not been accumulated sufficiently and a practical database is not available for such a condition. Therefore, to design the optimum industrial furnace using alternating-flow regenerative combustion, numerical simulation has to be combined with appropriate experiments.

Recently, commercial software for analyzing reaction flow has become available. However, the software cannot predict whether combustion will start or not, that is, it only predicts the burned properties after combustion is ensured by forced ignition or a pilot flame. Since the onset of combustion in highly preheated air depends on the balance between chemical reaction and physical processes, no kinetic mechanism has been suitable for detail prediction.

To accurately simulate highly preheated air combustion, a detailed kinetic mechanism is indispensable for considering both minor and major species. However, a practical simulation incorporating a detailed kinetic mechanism is far beyond the capability of the present computer. Therefore, the most realistic solution would result from the application of a reduced kinetic mechanism. A simulation of a realistic furnace of complex geometry would only allow comparisons of the resultant temperature and major species concentration in the furnace. Thus, it would be difficult to verify the validity of the model without a comparison of the simulation results with those obtained from experiments as they become available. A simpler flow system is reasonably useful to examine the potential and applicability of combustion reaction models to numerical simulation.

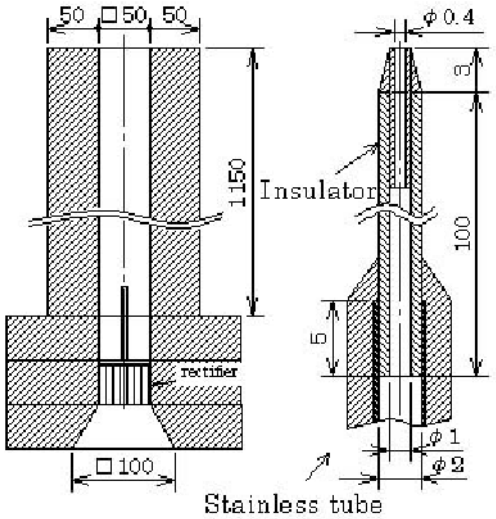
Therefore, detailed information such as flame ignition position and its shape is essential for designing an effective industrial furnace and to establish a kinetic mechanism of highly preheated air combustion. The objectives of the present study are to obtain basic and detailed information about the ignition position and shape of a flame in highly preheated air combustion and to demonstrate the feasibility of the suggested reduced kinetic mechanism, which reflects the characteristics of the highly preheated air combustion.

In the present study, we measured the flame lift height and flame length in the coaxial highly preheated air stream and conducted a numerical simulation applying the reduced kinetic mechanism to predict the influence of highly preheated air and oxygen concentration on the flame characteristics.

2. Experimental method

Fig. 1 shows the combustor used in the present experiment to measure the lift height and length of a flame and to observe the change of the flame shape with variation of preheated air temperature and oxygen concentration. Preheated air was supplied through a square duct of 100 mm x 100 mm with a contraction of 50 mm x 50 mm and length of 1150 mm. A coaxial fuel nozzle of 0.4 mm inner diameter and 100 mm in length was installed at the center of the duct, as shown in Fig. 1. The flow rate of the preheated air was set to 1.5 L_N/s and that of the injection fuel ranged from 6 to 12 mL_N/s.

Preheated air was generated by a modified alternating-flow regenerative system. This system, which is described in detail by previous study [8], consists of two sets of main burner, pilot burner and ceramic heat regenerator. Switching a four-way valve can operate either of the sets. In the middle of the combustion duct, there is an escape duct for the burned gas, and the end of this duct has another ceramic heat regenerator supplying preheated air. To generate highly preheated air, two sets of burners are operated alternately by switching the valves every 30 seconds until the temperature of the third heat regenerator reaches a



(a) Combustor (b) Fuel nozzle

Fig. 1. Schematic of combustor and detail of fuel nozzle.

specified temperature to produce a preheated air stream at the required temperature. Then, if air is supplied after the fuel feed is shut off, a highly preheated air stream is produced easily through the escape duct. The combustor is connected at the downstream of this duct.

Utilizing the characteristics of a preheated air generator, experiments were carried out from high temperature, and measurements were taken during natural cooling. By measuring CH band chemiluminescence intensity passing through the interference filter (central wavelength: 430.5 nm, bandwidth : 1.0 nm), the flame lift height and flame length were measured. The image of CH chemiluminescence was intensified by an image-intensifier (Hamamatsu Photonics C6653MOD) and recorded to a personal computer through a CCD camera (Kodak, MEGAPLUS camera model ES 1.0, shutter speed 32 ms). The solid-radiation from the combustor walls was eliminated by subtracting the background image intensity from the measured image intensity. And then, the flame length and lift height were obtained from the binary image.

3. Numerical method

3.1 Combustion and turbulence model

Though combustion reaction calculation with a detailed kinetic mechanism [9, 10] can give precise predictions, a powerful computer is needed for practical field computation because of the many kinds of species and elementary reactions. A detailed kinetic mechanism includes many elementary reactions whose rates differ from one another. Since these differences among elementary reactions may cause the loss of balance in the production rate of species, a simulation with a detailed kinetic mechanism is not realistic for a practical combustion furnace.

From this viewpoint, many research groups have developed various reduced kinetic mechanisms [11]. Since most of the reduced kinetic mechanisms consider only the chemical reaction rate, it is necessary to include the influence of turbulent mixing on the combustion reaction to simulate a practical furnace with accuracy. However, there is no model that adequately represents production and destruction of intermediate species. Here, we have modified the reduced kinetic mechanism [12] based on GRI-Mech 2.1 [9] by combining eddy-dissipation-concept proposed by Magnussen [13, 14].

In this study, a reduced kinetic mechanism consists of 9 steps and 13 species reaction mechanism, and is given by:

$$O_2 + CH_4 \Leftrightarrow H_2 + H_2O + CO \quad (1)$$

$$O_2 + 2CO \Leftrightarrow 2CO_2 \quad (2)$$

$$2H_2 + O_2 \Leftrightarrow 2H_2O \quad (3)$$

$$2O + CH_3 \Leftrightarrow 3H + CO_2 \quad (4)$$

$$O + CH_3 \Leftrightarrow H + CH_2O \quad (5)$$

$$H + OH \Leftrightarrow H_2O \quad (6)$$

$$H + O \Leftrightarrow OH \quad (7)$$

$$H_2 + O \Leftrightarrow H + OH \quad (8)$$

$$H + HO_2 \Leftrightarrow 2OH \quad (9)$$

The mixing is assumed to obey the ideal gas law. The viscosity, the thermal conductivity and the specific heat of the mixture are computed from the properties of individual species, and the properties of individual species are all functions of temperature [9, 15].

The turbulence is modeled by using the standard k-ε turbulence model and radiation is neglected.

3.2 Governing equation and numerical method

The governing equations for combustion analysis are the conservation equations of mass, momentum, energy, turbulence kinetic energy and dissipation rate of turbulent kinetic energy. Density-weighted (Favre) averaging is used to account for the effects of the density change. The steady two-dimensional Favre-averaged conservation equations can be expressed in radial coordinates as follows:

$$\frac{\partial}{\partial x}(\bar{\rho}\tilde{u}\phi) + \frac{1}{r}\frac{\partial}{\partial r}(r\bar{\rho}\tilde{u}\phi) - \frac{\partial}{\partial x}(\Gamma\frac{\partial \phi}{\partial x}) - \frac{1}{r}\frac{\partial}{\partial r}(r\Gamma\frac{\partial \phi}{\partial r}) = S_\phi \quad (10)$$

where, Γ and S_Φ indicate the turbulent transport coefficient and source term, respectively.

The combustion analysis program was developed by modifying the STARPIC code produced by Lilly [16], and a control volume approach [17] was used in which a staggered grid arrangement is employed to discretize the differential governing equation. The interpolations between the grid points and the calculation of the derivatives of the dependent variables were carried out with the first-order power law scheme. The velocity and pressure fields were linked by the SIMPLE algorithm.

4. Result and discussion

4.1 Observation of flames in the highly preheated air stream

Fig. 2 is a direct photograph of lifted flames in the highly preheated air stream. An experiment was carried out from a preheated air temperature of 1350 K and photographs were obtained as the preheated air temperature decreased. When oxygen concentration is high, flame stabilizes at the fuel injection nozzle until the preheated air temperature reaches the limit of blow-out. On the other hand, the stabilized flame can be blown off from the fuel nozzle by increasing the fuel injection velocity and/or air stream velocity. And then, when the fuel injection velocity and/or air stream velocity return to the primary condition, the flame stabilizes again near the fuel injection nozzle if the preheated air temperature is higher than the threshold temperature, but lifted flame is formed when the preheated air temperature is lower than the threshold temperature. Fig. 2 shows photographs of a forced lifted flame formed by the method explained above. The lifted height increased gradually with decreasing preheated air temperature, and the flame shape also changed. For relatively high temperatures of preheated air, a diffusion flame of jet type with relatively long flame length was formed. Flame length became shorter with increasing lift height, and the flame color changed to blue.

Detailed photographs of the lifted flame are shown in Fig. 3. With increasing lift height, the bottom region of the flame, considered as the lean premixed flame, became larger and the region inside of the jet flame, considered as the rich premixed flame, started to diminish in size. The mechanism of flame shape change will be explained later.

Fig. 4 shows the changes of lift height and flame length as a function of preheated air temperature in various oxygen concentration conditions. These measurements were taken from the flame in natural lift pattern, that is, a stabilized flame near the fuel injection nozzle lifts naturally by decreasing the preheated air temperature and oxygen concentration. For oxygen concentration of 21%, the flame stabilized near the fuel injection nozzle but the flame never lifted until it blew out at 1040 K. For oxygen concentration of 18%, the flame detached from the fuel nozzle and changed to a lift flame when the preheated air temperature decreased below the threshold temperature. Flame length kept constant for the attached flame regardless of the decrease in the preheated air temperature, but decreased after detachment.

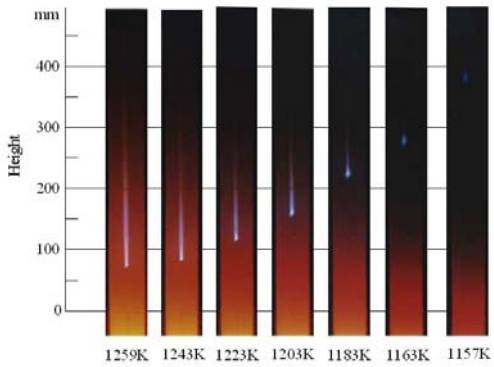
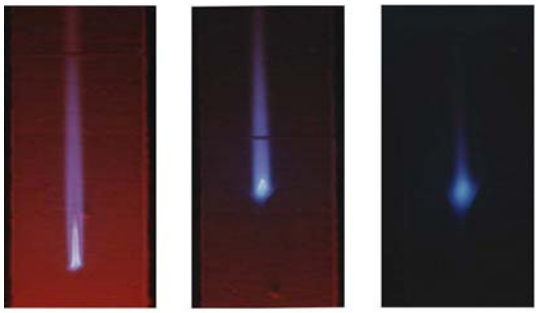


Fig. 2. Effect of preheated air temperature on lift height of flames (Fuel flow rate: 10 mLN/s, O_2 : 21%).

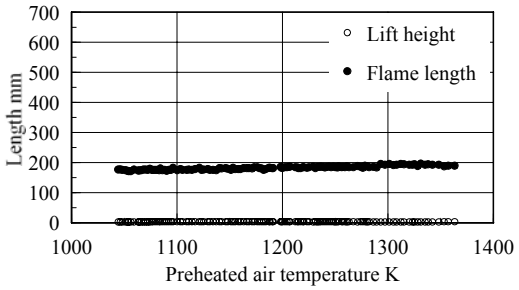


(a) 1235K (b) 1194K (c) 1165K

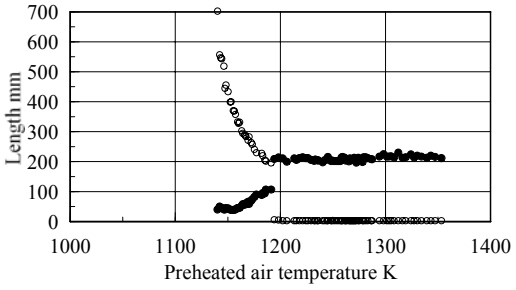
Fig. 3. Flame shape change with preheated air temperature (Fuel flow rate: 10 mLN/s, O_2 : 21%).

For oxygen concentration of 15%, we can observe an overall tendency in which the flame length decreased with increasing lift height, but the minimum value of the flame length was reached at 1175 K. Since the combustion reaction progressed quickly after the mixing of fuel and air in the lifted region, the flame length decreased with increase of lift height. However, with excessive mixing, a lean premixed mixture was formed, and hence became slow reaction rate. Thus, the minimum flame length is the result of excessive mixing between fuel and air. These phenomena were visualized by photographs, as shown in Fig. 3

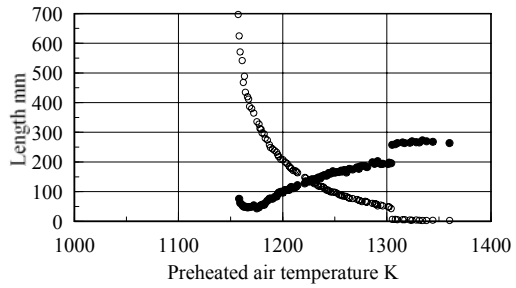
Fig. 5 shows the change of lift height and flame length of a forced lifted flame as a function of preheated air temperature under various oxygen concentration conditions. As shown in Fig. 5(a), the flame detached from the fuel nozzle and became a lifted



(a) 21% O_2

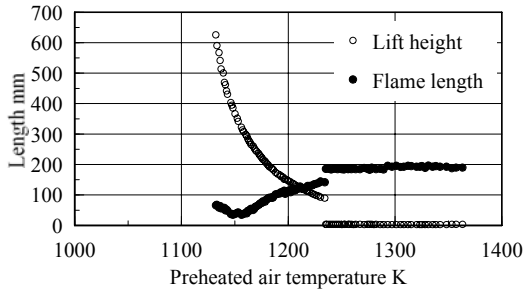


(b) 18% O_2

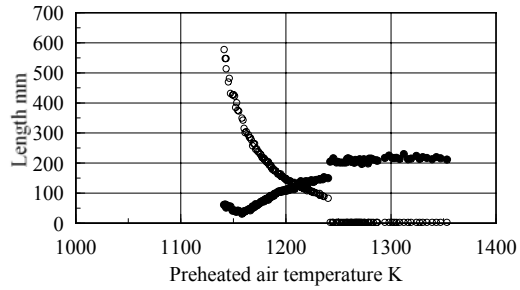


(c) 15% O_2

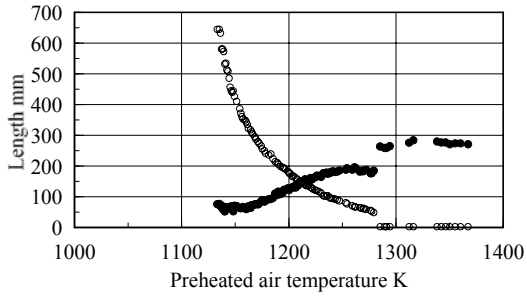
Fig. 4. Change of lift height and flame length as a function of preheated air temperature with natural lift pattern.



(a) 21% O_2



(b) 18% O_2



(c) 15% O_2

Fig. 5. Change of lift height and flame length as a function of preheated air temperature with forced lift pattern.

flame at the preheated air temperature of 1235 K. This tendency is similar to that of the natural lift pattern. The flame length decreased with the increase of the lift height, but increased after the minimum value of 1150 K. If a flame detaches from the fuel nozzle due to strong shear stress or ignition delay, mixing may be promoted with the increase of lift height. Since this mixing may increase the reaction rate in the flame base, the flame length may become shorter due to large fraction of fuel consumed in the flame base. However, if the lift height exceeds a certain level, a lean premixed mixture would be formed in the flame base and would decrease the reaction rate; hence, a longer flame length would result again.

Flame lift height with variation of oxygen concentration for various fuel injection velocities is shown in Fig. 6. Since the fuel injection velocity decreased by mixing with air, the fuel injection velocity had little influence on the lift height. Here, only the results obtained from the natural lift pattern were described. The oxygen concentration at which the attached flame starts to detach from the fuel injection nozzle increased with increasing fuel injection flow rate. The lift height also increased slightly with increasing fuel injection flow rate.

The above results showed that flame lift height was greatly influenced by the preheated air temperature and oxygen concentration and that a lifted flame was

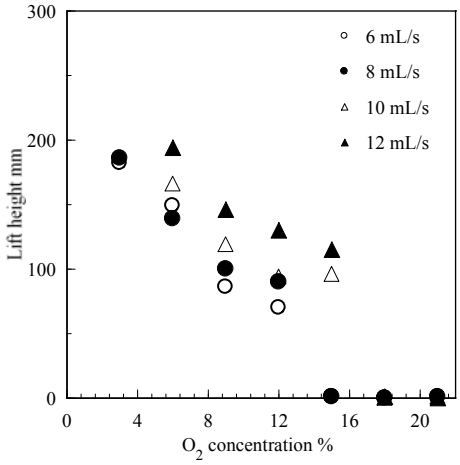


Fig. 6. Effect of oxygen concentration on lift height with changing fuel injection velocity (T_{air}=1250 K).

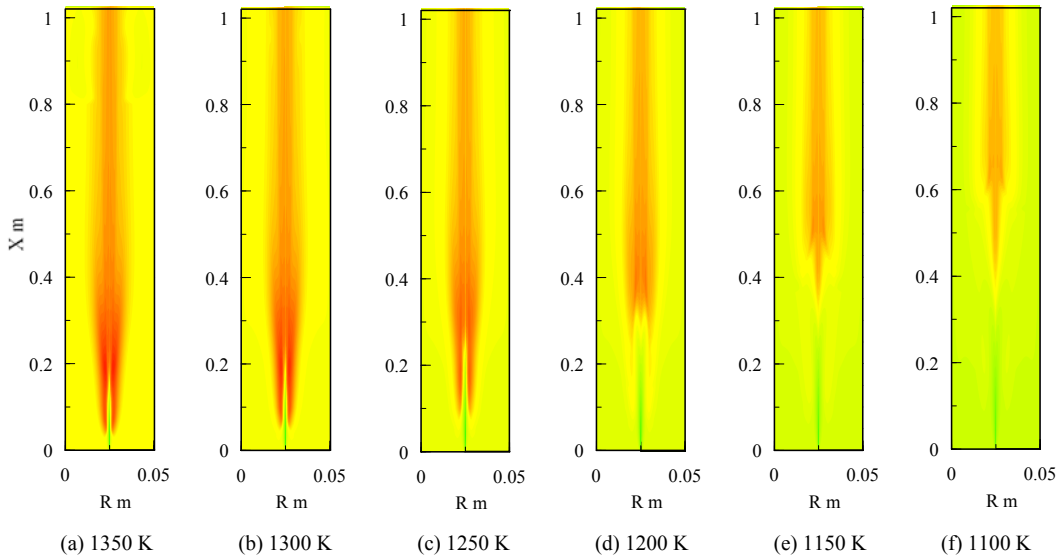


Fig. 7. Calculated temperature distribution as a function of preheated air temperature.

formed when the preheated air temperature was close to auto-ignition temperature and/or the oxygen concentration was low. The flame shape was shifted from diffusion flame shape to partially premixed flame shape with increasing lift height.

4.2 Prediction of flame lift height and flame length in highly preheated air combustion

Fig. 7 shows the flame temperature distribution obtained by computation with the reduced kinetic mechanism as a function of preheated air temperature. The high temperature region considered as the flame base moved to downstream with decreasing preheated air temperature. This phenomenon is ascribed to the elongated ignition delay with decreasing preheated air temperature. From the region of 1250 K to 1350 K, a diffusion flame, in which the fuel in the central region reacts with the surrounding air, is formed and this flame type keeps to downstream. However, the diffusion flame near the central axis moved downstream at the preheated air temperature of 1200 K. When the preheated air temperature decreased further, a combustion reaction occurred as the premixed flame on the central axis and the remaining fuel burned as the diffusion flame after mixing with the surrounding air. This tendency is quite similar to that of the flame

shape change shown in Figs. 2 and 3.

Because the flame lift height and length are measured by the CH chemiluminescence intensity, it is desirable to estimate the flame length and lift height with the calculated CH concentration. However, because it is impossible to obtain CH chemiluminescence intensity from the present reduced kinetic mechanism, the lift height was defined as the distance between the nozzle tip and the cross-section where the temperature rises by 5% of the difference between adiabatic flame temperature and preheated air temperature. And, the flame length was defined as the distance between the estimated lift height and the cross-section where CH_4 consumption ceased.

In Fig. 8, the calculated lift height and flame length were compared with those obtained by measurements. In Fig. 8(a), the attached flame detached from 1300 K and the lift height increased with decreasing preheated air temperature while the flame lift occurred from 1230 K in measurement. Generally, calculated flame lift heights showed good agreement with measured flame heights, although there were some discrepancies in estimating the flame-lifting temperature.

In Fig. 8(b), the calculated flame length slightly increased with decreasing preheated air temperature until 1200 K while the measured one remained constant. However, both types of flame height showed a minimum value at 1150 K and then the flame lengths began to increase after the minimum point. The calculated flame length showed similar qualitative tendency with measured flame length, although additional improvement is needed in estimating the flame length over preheated air temperature of 1200 K. From the above results, the reduced kinetic mechanism proposed in the present study can be applied to predict highly preheated air combustion, although some discrepancy was found in the estimation of the flame lift height and flame length with variation of preheated air temperature.

Fig. 9 shows the comparison of lift height and

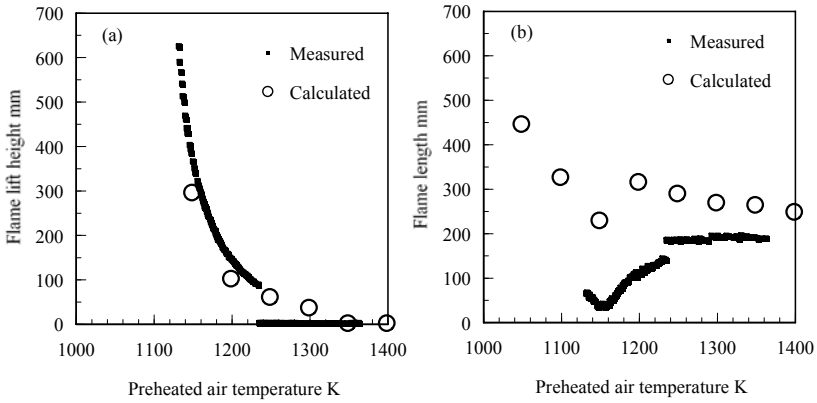


Fig. 8. Comparison of lift height and flame length obtained by experiments and computations with changing preheated air temperature.

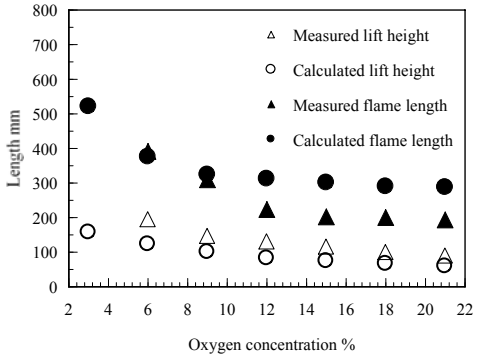


Fig. 9. Comparison of lift height and flame length obtained by experiments and computations with changing oxygen concentration (1250 K, 12 mL).

flame length obtained from experiments and computations with variation of oxygen concentration. The calculated flame lift heights showed good agreement with the measured ones, although the calculated values were slightly smaller than the measured ones. On the other hand, the calculated flame lengths were about 100mm longer than the measured ones for oxygen concentration of 12-21%, but good agreements were observed for low oxygen concentrations. Even with the difference in the definitions of lift height and flame length between experiment and computation, we can see that the reduced kinetic mechanism used in the present study can reflect the influence of oxygen concentration in highly preheated air combustion within a tolerable error range.

5. Conclusions

Flame lift height and flame length were measured, and change of flame shape was observed in the highly preheated air stream. They were also computed with the reduced kinetic mechanism proposed in this study and compared with measured results.

(1) The flame attached near the fuel nozzle lifted when the preheated air temperature became close to auto-ignition and/or oxygen concentration became low. The flame lift height increased with decrease of preheated air temperature, but the flame length decreased with the decrease of preheated air temperature and started to increase after the minimum value.
(2) The calculated flame lift height and flame length showed good agreement with the measured ones within a tolerable error.
(3) The flame shape was shifted from diffusion flame to partial premixed flame with the increase of lift height, and this tendency was also observed in the computation results.
(4) The reduced kinetic mechanism proposed in this present study can be applied to highly preheated air combustion.

Acknowledgement

This work was supported by the research project [2007-C-CD12-P-01-3-010] of the Korea Energy Management Coorporation.

References

[1] S. Michida and T. Hasegawa, Heat transfer characteristics of an industrial furnaces using high-temperature air combustion, *International Joint Power Generation Conference,* Miami Beach, Florida. (2000) Paper IJPGC2000/FACT-15040.

[2] Y. Suzukawa, Y. Sugiyama, Y. Hino, M. Ishioka and I. Mori, Heat transfer improvement and NOx reduction by highly preheated air combustion, *Energy Conversion and Management*, 38(10-13) (1997) 1061-1071.

[3] J. A. Wunning and J. G.. Wunning, Flameless oxidation to reduce thermal NO-formation, *Prog. Energy Combust. Sci.*, 29 (1997) 81~94.

[4] P. J. Coelho and N. Peters, Numerical simulation of a mild combustion burner, *Combust. Flame*, 124 (2001) 503-518.

[5] M. Katsuki and T. Hasegawa, The science and technology of combustion in highly preheated air, *Proc. Combust. Inst*., 27 (1998) 3135-3146.

[6] T. Fujimori, D. Riechelmann and J. Sato, Effect of liftoff on NOx emission of turbulent jet flame in high-temperature coflowing air, *Proc. Combust. Inst*., 27 (1998) 1149-1155.

[7] W. Yang and W. Blasiak, Numerical simulation of properties of a LPG flame with high-temperature air, *Int. J. Thermal Sci.,* 44 (2005) 973-985.

[8] G-M. Choi and M. Katsuki, New approach to low emission of nitric oxides from burnaces using highly pre-heated air combustion, *J. Inst. Energy*, 73 (2000) 18-25.

[9] R. J. Kee, F. M. Rupley and J. A. Miller, The CHEMKIN Thermodynamic Data Base, *Sandia Report SAND 87-8215*, (1987).

[10] R. J. Kee, F. M. Rupley and J. A. Miller, CHEMKIN-II; A Fortran Chemical Kinetics Package for Analysis of Gas-Phase Chemical Kinetics, *Sandia Report SAND 89-8009*, (1989).

[11] N. Peter and R. J. Kee, The computation of stretched laminar methane-air diffusion flames using a reduced four-step mechanism, *Combust. Flame*, 68 (1987) 17-29.

[12] J. Y. Chen, A general Procedure for Constructing Reduced Reaction Mechanisms with Given Independent Relations, *Sandia Report, SAND87-8782*, (1989).

[13] P. Glarborg, P., N. I. Lilleheie, S. Byggstoyl, B. J. Magnussen, P. Kilpinen and M. Hupa, A Reduced Mechanism for Nitrogen Chemistry in Methane Combustion, *Proc. Combust. Inst*, 24 (1992) 889-898.

[14] B. F. Magnussen and H. Hjertager, On Mathe-

matical Modeling of Turbulent Combustion With Special Emphasis on Soot Formation and Combustion, *Proc. Combust. Inst*, 16 (1976) 719-729.

[15] JSME, Handbook of Combustion Engineering, (1995).

[16] D. G. Lilly and D. L. Rhode, A Computer Code for Swirling Turbulent Axisymmetric Recirculating Flow in Practical Isothermal Combustion Geometries, *NASA Report*, CR-3442, (1982).

[17] S. V. Patankar, Numerical Heat Transfer and Fluid Flow, Hemisphere, New York, USA, (1980).

Gyung-Min Choi studied the areas of combustion engineering, heat recirculating combustion, and solid fuel gasification, receiving his Ph.D. degree in engineering from Osaka University in 2001. He served as a researcher at Japan Aerospace Exploration Agency and is now an associate professor in the School of Mechanical Engineering at Pusan National University.