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Structural Characteristics of Turbulent Diffusion Flame Combusted with Simulated Coal Syngas

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Abstracts — The present work determined the flame structure characteristics of coal syngas combusted inside swirl burners with various nozzle types. Fuel nozzle types are largely classified into two groups of axial and tangential. Experiments were carried out for investigating the effects of fuel nozzle geometry, fuel composition ratio, heating rate, excess air, and degree of swirl on the turbulent diffusion flame structure. To determine the characteristics of the flame structure, axial type fuel nozzle diameter of laboratory-scale combustor is varied to 1.23, 1.96, and 2.95 mm and the direction of tangential type nozzles are varied to radial, clockwise, and counter-clockwise. The comparison of the experimental results was performed to understand functional parameters relating the flame structure. Data analysis showed that the vertical straight flame height generally decreased with increasing swirl number and decreasing axial type nozzle diameter. Flame height established with tangential type nozzle is 3 times shorter than that with vertical type. The flame structures among the 3 different tangential fuel nozzles relatively showed no particular difference. By increasing the heating rate, the width of flame increased generally in both vertical and tangential flame. Within the present experimental parameters of the investigation, flame structure is mainly depends on the nozzle type of the combustor. The visually investigated flame lengths are confirmed through the analysis of temperature profile of each flame.

1. Introduction

Flames with swirl are often used in practical combustion systems because the swirl-induced recirculation zone stabilizes the flame. Many researchers have been concerned with the swirling flame, flow without flame, with flame, flame configuration, flame stability, and noise emission. For the formation/emission behavior of air pollutants such as NO_x, CO, and hydrocarbons in swirling flames, studies showed that the swirl has inconsistent effects of increasing or decreasing NO_x emission probably because of different flames structure. As a result, detailed measurements of gas species and temperature in swirling flames are necessary to reveal the interrelation between the flame structure and the formation and emission characteristics of air pollutants. For the case of coal syngas, emission behavior is hardly understandable because of complicated nature of mixture combustion, especially CO and H_2.

The H_2-CO mixtures that are mainly constituents in the coal syngas are encountered often in various industrial processes, for example, gasification process of various fuels and the steam reforming of fossil fuels for the production of hydrogen. Today, trend of the gas turbine combustor study is focused on a premixed flame with decreasing flame temperature to minimize NO_x emission rate[1][2]. However, modification of combustion parameter for NO_x reduction often results in increase of CO concentration[3][4]. Also, little attention has been paid to the processes of the emission of NO and flame temperature in relation to the flame structure of coal syngas. In the present study, detailed measurements of NO concentration and temperature were made in six different types of flames formed around a fuel jet surrounded by swirling air flow, and effects of a wide range of combustion parameters on pollutant emissions were examined in order to interpret the characteristics and processes of pollutant formation and emissions as they relate to

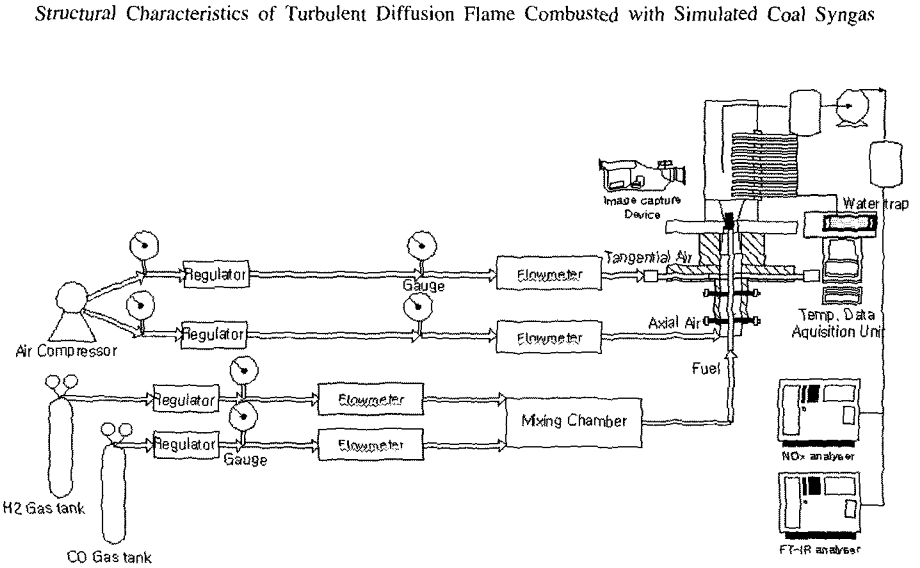

Fig. 1. Schematic diagram of the laboratory scale burner apparatus.

the flame.

2. Experimental Apparatus and Procedure

A schematic of the laboratory scale swirl-stabilized diffusion burner apparatus is shown in Fig. 1. The burner specific configuration is shown Fig 2. Cylinder tank is used for producing predetermined composition of fuel gas and compressor is used for the delivery of air. Bottled coal syngas from 3 ton/day gasifier will be also fired for the comparison study with actual gas. Flashback safety device is installed upstream of fuel gas inlet point. Once the flame is established, temperature is monitored by thermocouples. Concentrations of NO_x and unburned hydrocarbon are also measured with chemiluminescent NO_x analyzer and FTIR. The shape of each flame is also recorded with Image Capture Device.

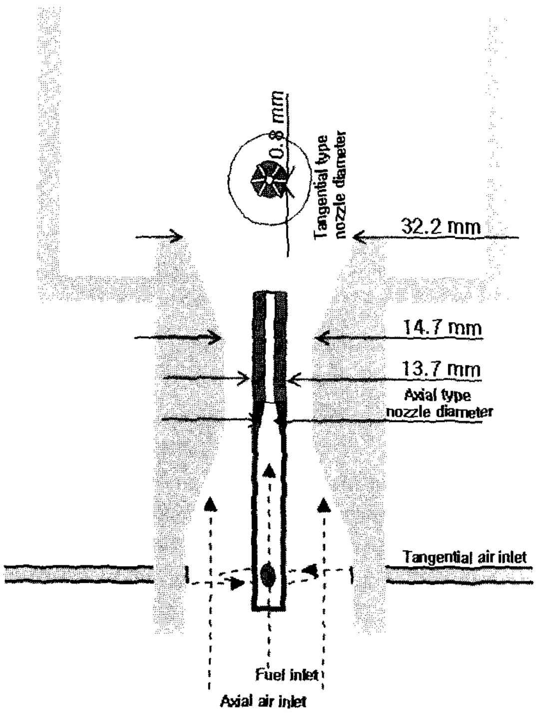

Fig. 2. Laboratory scale burner configuration.

The swirl generator consists of four tangential air inlets that mix tangential air with axial air upstream of the burner[5]. The swirling coaxial airflow surrounds a central fuel tube that injects fuel in the axial or tangential direction. However, axial fuel injection is preferred to study flame stability limit because when the tangential fuel injection is really complicated to analyze characteristics of flame with coal syngas. Also the swirl is gradually reduced to zero, one recovers the important case of a jet flame with coaxial air that is documented in the literature; thus the swirl and no-swirl cases can be properly compared. Six different shaped fuel nozzles were used; their shapes and dimensions are given in Fig. 3.

In these cases the ratio of the fuel tube inner diameter, denoted d_F, to the air tube diameter d_A at the

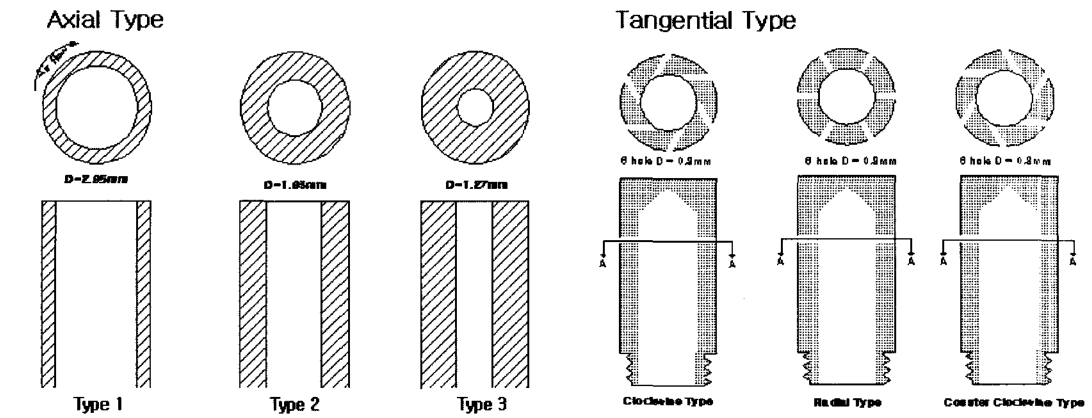

Fig. 3. The fuel nozzle types on different shapes.

Table 1. Physical properties on different composition fuels.

Gas	Purity/ Composition, %v	Molecular weight	Dynamic viscosity, μ, at 0°C, micropoises	Maximum burning velocity in air, S_u, m/s	Mass fraction in stoichiometric mixture with air, θ_s
Methane	99	16	102.7	0.39	0.055
Hydrogen	99	2	84.2	3.06	0.028
Carbon monoxide	99	28	166	0.136	0.289
H_2 : CO	(1 : 1), 99	15	182.5[6]	1.66[7]	0.179
H_2 : CO	(1 : 1.5), 99	17.6	184.8	1.41	0.204
H_2 : CO	(1 : 2), 99	19.42	185.7	1.23	0.220
H_2 : CO	(1.5 : 1), 99	12.4	178.7	2.02	0.153
H_2 : CO	(2 : 1), 99	10.58	174.7	2.20	0.133

throat was different on the fuel nozzle shapes; the ratio of the fuel tube inner diameter to the outer diameter denoted d_F/d_{F0}. Eights different fuel compositions were used in the experiment and their transport properties are given in Table 1, which is used in the theoretical investigation of flame length. Pure methane, pure hydrogen, pure carbon monoxide, a mixture of 0.5 hydrogen and 0.5 carbon monoxide by volume, a mixture of 0.4 hydrogen and 0.6 carbon monoxide by volume, a mixture of 0.34 hydrogen and 0.66 carbon monoxide by volume, a mixture of 0.6 hydrogen and 0.4 carbon monoxide by volume, and a mixture of 0.66 hydrogen and 0.34 carbon monoxide by volume, as listed in Table 1.

Flow rates were metered using a system of calibrated gas meter and 4 rotameters. Flow rates were metered within the accuracy of 10%. Control of fuel velocity was calculated for experimental conditions and compressibility effects on system are considered. That is, for most cases fuel velocity U_F is determined by dividing measured fuel mass flow by the fuel tube area and by the standard density of the fuel gas. For the data, the exit Mach number of the fuel that was used was determined from standard compressible flow tables and the known stagnation pressure and temperature. To obtain recirculation vortex on combustion environmental, a diverging metal quarl section is placed downstream of the cylindrical throat. Upstream of the tangential air inlets, the axial air profile was assumed uniform flow. The principal experimental parameters are fuel heating rate, swirl number, fuel composition, nozzle type, primary air, and secondary air. The primary air is defined by subtracted secondary air flow rate from the total air flow rate, respectively. Total air flow rate is the sum of the primary and secondary air flow rate. Detailed profiles of concentrations of NO and temperature in typical flames and exhausted gas species concentrations are measured. The combusted gases are sampled with a quartz probe (1 mm in inner diameter). The probe is made as thin as possible to be 6 mm in outer diameter, in order to minimize the disturbance of the flow, especially in the recirculation zone. The sampled gases are cooled with the condensing unit before analyzing concentration measurement unit. NO and NO_x are detected by a chemiluninescence detector equipped with an NO_2-NO converter. Other gas species noted above are analyzed by a FT-IR. Gas temperature is measured by a thermocouple (Pt.-Pt. Rh. 13%, 0.3 mm in diameter) coated with MgO. Radiation loss is not considered in the temperature measurement.

3. Results and Discussions

3-1. Flame Configuration of Axial Type Nozzle

The flame characteristics of axial nozzle type are investigated while the swirl numbers and nozzle type are varied and keeping the fuel heating rate, the fuel composition and total air flow rate constant[8]. The flame shape images are shown in Figs. 4~6. The experimental conditions of Figs. 4~6 are constant fuel heating rate (1,000 kcal/hr), fuel volume compositions ($CO:H_2=1:1$), and total air flow rate (13 l/min: stoichiometric condition). The varied combustion parameters are noted in the figure caption. The decrease of the flame length is notified with increasing input fuel bulk velocity.

Because of the relatively rapid fuel bulk velocity contributed to fuel mixing with air. The right side images of the Figs. 4~6 are flames with higher primary air flow rate than that of the left side. Generally, the recirculation bubble plays an important role in flame stabilization by providing a hot flow of recirculated combustion products and a reduced velocity region where flame speed and flow velocity can be matched. Toshimi et al reported that the swirling primary air serves to form a recirculation zone and the position and the size of the recirculation zone of the reversed cone shape is drawn back into the primary air nozzle and extends downstream from the primary air nozzle tip for the flame[9]. However our experimental quarl equipment in combustor diminished in flame width expansion. In other words, the position of recirculation zone is relatively smaller than that by

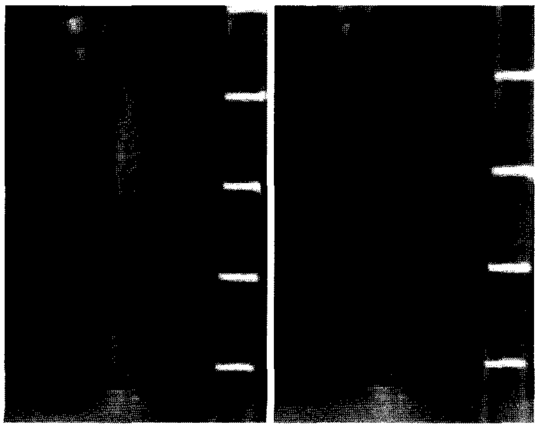

Fig. 4. Photographs of the axial type 1 (Left Side: Swirl number=0, Right Side: Swirl number=1).

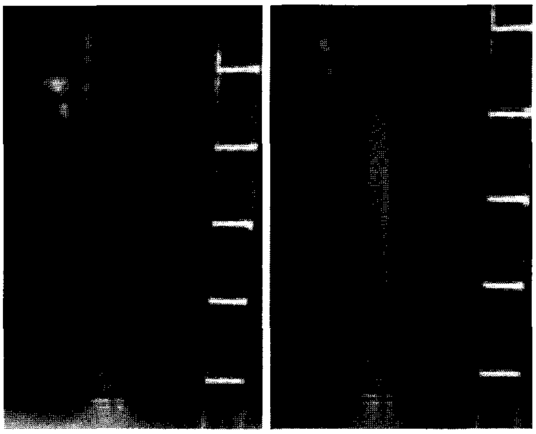

Fig. 5. Photographs of the axial type 2 (Left Side: Swirl number=0, Right Side: Swirl number=1).

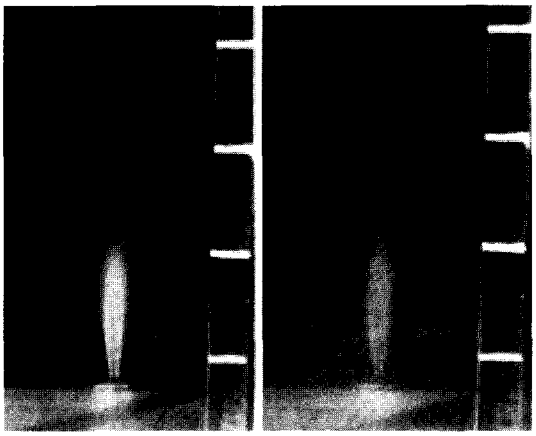

Fig. 6. Photographs of the axial type 3 (Left Side: Swirl number=0, Right Side: Swirl number=1).

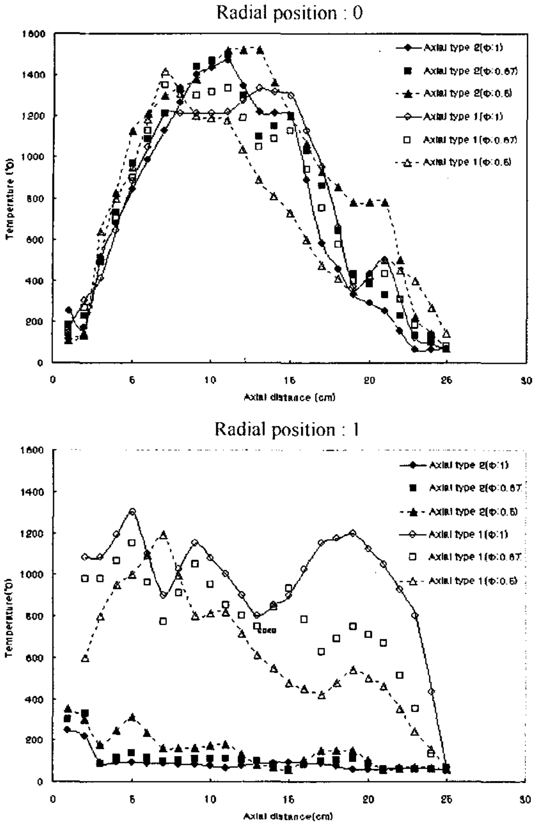

Fig. 7. Temperature profiles for axial type nozzles (1,000 kcal/hr, S: 0).

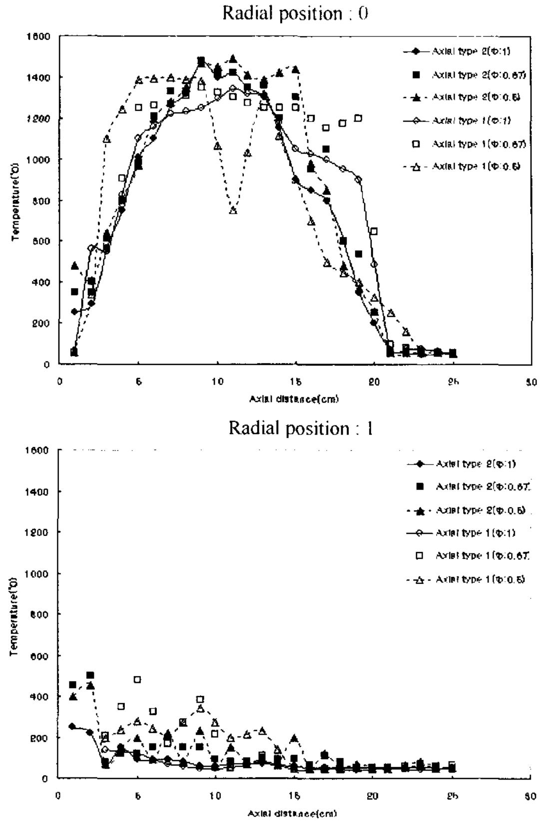

Fig. 8. Temperature profiles for axial type nozzles (1,000 kcal/hr, S: 1).

Toshimi *et al*'s experiment. Again, our flame recirculation zone was located in the divergent quarl. The recirculation zone is filled with high-temperature burnt gas to anchor the flame and the fuel flows mainly around the recirculation zone forming a fuel. Considering swirl number effects in Figs. 4~6, increasing swirl number affected decreasing flame length and increasing flame width. Figures. 7~10 showed temperature profile of the flames with equivalence ratio, Φ, fuel heating rate, and swirl number, S variation for axial type nozzle experiments. The radial position was defined by the radial distance from the nozzle tip centerline that was divided by the quarl radius, 16.1 mm. The temperature measurement for the axial type 3 was excluded. Because the flame of the axial type 3 nozzle was not formed stable flame within some kinds of experimental conditions. But a tendency of the axial type 3 temperature profile is nearly similar to other axial type temperature profile. The variation of equivalence ratio in Figs. 7~10 was cited on a parenthesized passage in figures. Considering the equivalence ratio variations, change of the equivalence ratio was relatively small affected the flame structure. Considering the swirl number, increasing the swirl number is accompanied with decreasing the flame height and expanding the flame width. Increasing the fuel bulk velocity, the flame domain gradually got small. Considering radial temperature profiles, the fuel layer burns to form flame around the recirculation zone that causes the sudden drop of the flame temperature in below radial position 1.

Comparing the radial position, 0 of Fig. 7 with Fig. 8, the centerline flame temperature profile not showed specific difference regardless of the variation of swirl intensity. Figures. 9 and 10 showed same temperature profile. However, considering over the domain of

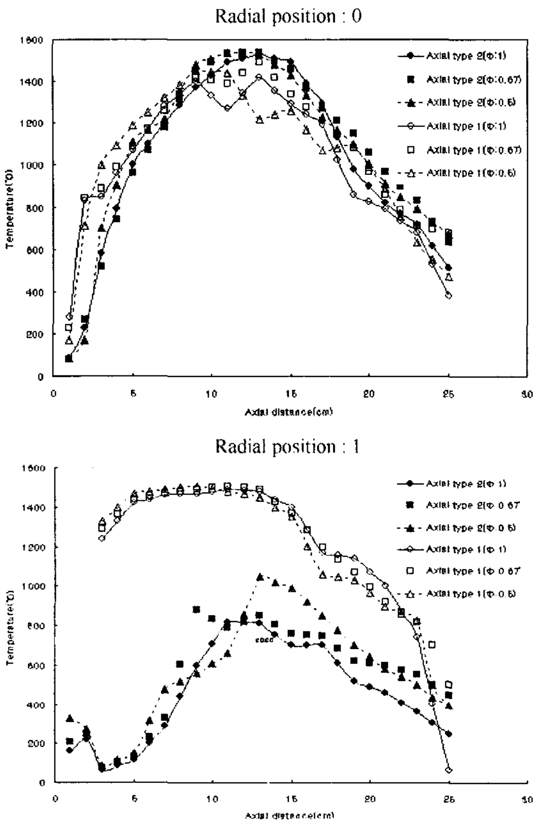

Fig. 9. Temperature profiles for axial type nozzles (2,000 kcal/hr, S: 0).

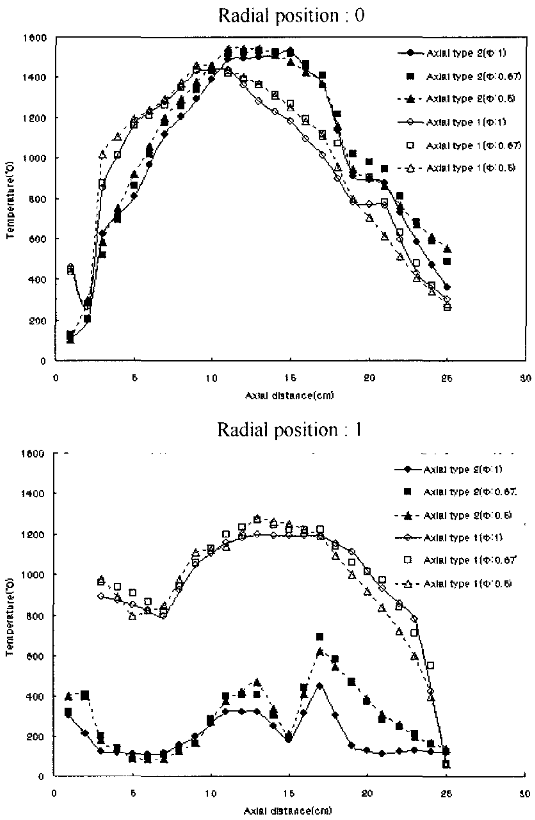

Fig. 10. Temperature profiles for axial type nozzles (2,000 kcal/hr, S: 1).

1,000℃ on the radial position, 0 among the Figs. 7~10, Figs. 8 and 10 that operated at 2,000 kcal/hr have relatively large flame width. Also the temperature profiles of the radial position, 1, showed the same tendency except the Fig. 8. Because the heating rate of Fig. 8 case is too small, the flame was located in the quarl section. So the recirculation zone was strongly formed in quarl section. For the reasons of these tendencies, the fuel layer around the recirculation zone in quarl section burns at the downstream section after dilution by the excess air.

3-2. Flame Configuration of Tangential Type Nozzle

The radial types of flame shape on the variation of axial position in quarl section are shown in Fig. 11. The radial nozzle tip was set quarl angle start position, whose position value is 0. The position value is defined by nozzle tip length from the angle start position divided by the quarl vertical length, 15 mm. The position value in Fig. 11 was cited below each figure.

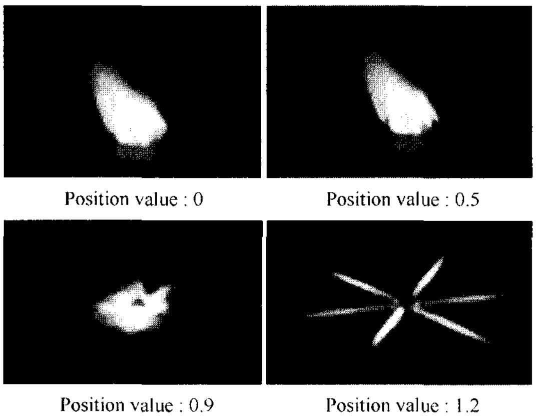

Fig. 11. Flame shapes of radial type nozzles (equivalence ratio: 1, swirl number: 1).

The nozzle tip position really affected flame structure. The position values of 0.9 and 1.2 minimized flame height but flame width suddenly expanded. So our tangential type nozzle position was set position value 0.5. The tangential types of flame temperature profiles are formed when the swirl numbers, fuel heating rate, and nozzle type are changed on keeping the fuel composition and stoichiometric air flow rate. The flame temperature profiles are shown in Figs. 12~15. In Fig. 12, the symbols colors were classified nozzle type: the white symbols are radial type, the black symbols are clockwise type, and the gray symbols are counter-clockwise type. Also symbol shapes were described the radial position: the diamond shapes are radial distance, 0 mm, the rectangular shapes are radial distance, 5 mm, triangular shapes are radial distance, 8 mm, and circular shapes are radial distance, 16.1 mm. The changed other flame conditions are noted in the figure caption. Considering flame temperature profiles, the flame heights of the tangential type nozzles are about 3 times smaller than those of the axial type. The flame heights deviations of CO/H_2 ratio on the same fuel nozzles are not showed specific difference and the variation of tangential type nozzles show the same tendency as before. The increasing swirl numbers affected decreased flame height and broaden the flame width. The increasing heating rates affected increased flame height and broaden the flame width.

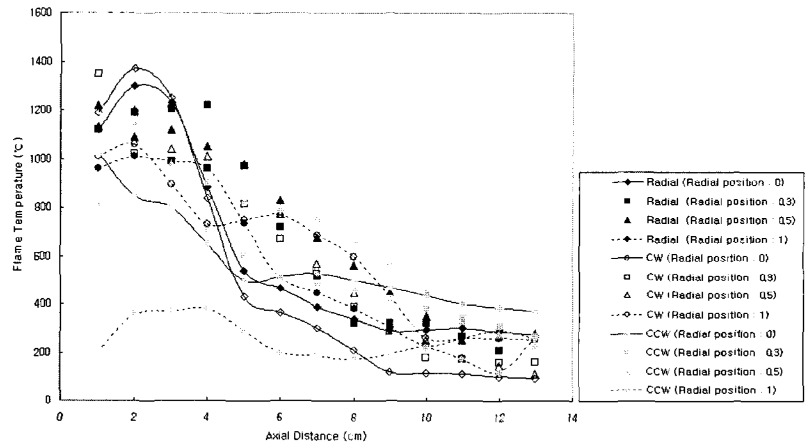

Fig. 12. Temperature profiles for tangential type nozzles (1,000 kcal/hr, Swirl number: 0).

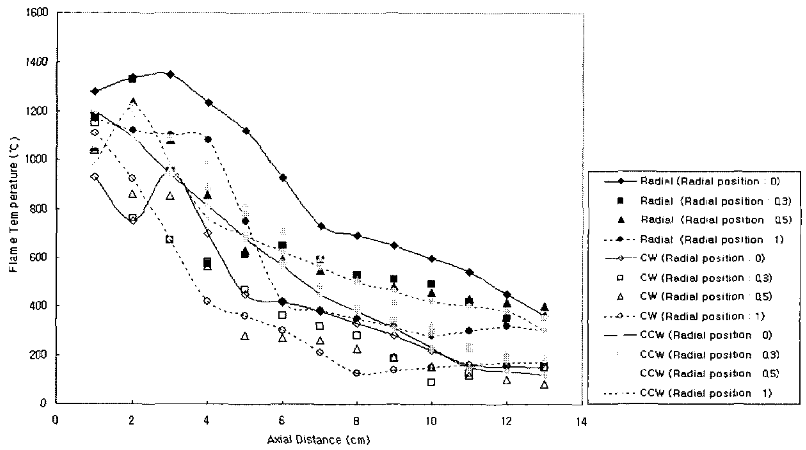

Fig. 13. Temperature profiles for tangential type nozzles (1,000 kcal/hr, Swirl number: 1).

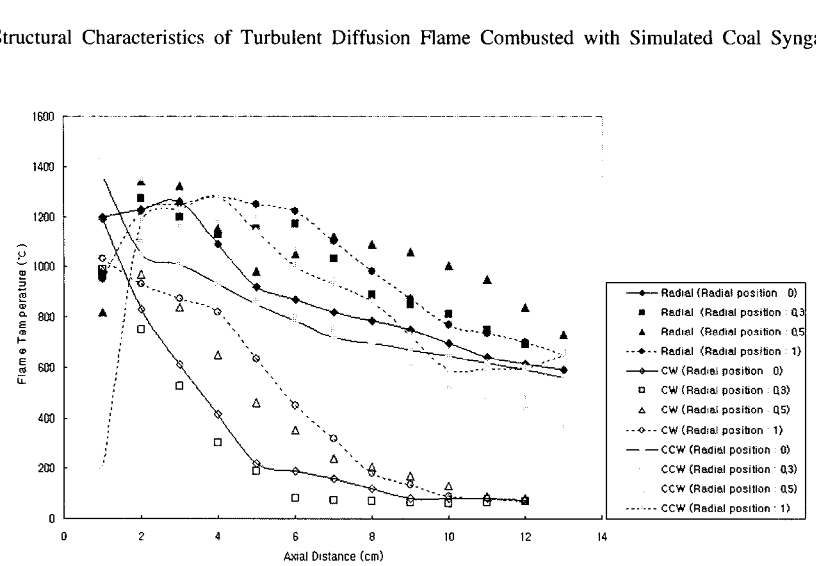

Fig. 14. Temperature profiles for tangential type nozzles (2,000 kcal/hr, Swirl number: 0).

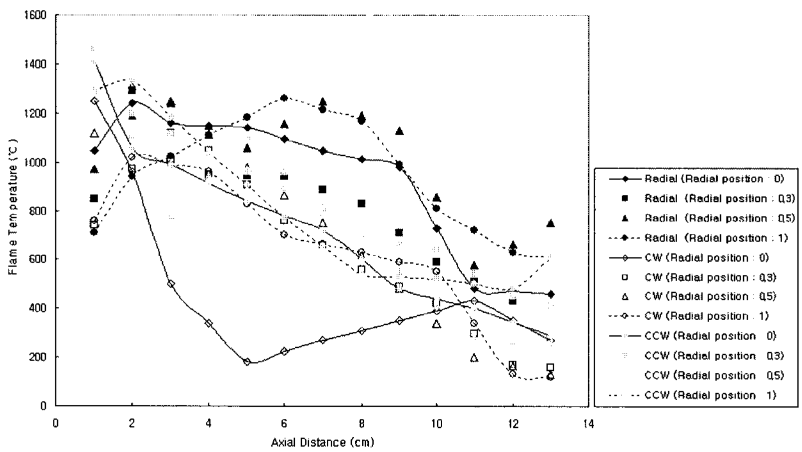

Fig. 15. Temperature profiles for tangential type nozzles (2,000 kcal/hr, Swirl number: 1).

But the swirl number variation effect on the flame structure relatively lower than the fuel heating rate variations. Considering the radial temperature profiles, the radial temperature variations of the tangential type relatively lower changed than axial types. Because the fuel layer burns to intersect the air stream, which was formed by swirl number variation. Therefore the flame structure mainly depends on the nozzle shape and nozzle tip position. Also the fuel heating rate and air flow rate can affected the flame structure within same nozzle shape and tip position. The fuel composition and swirl number are relatively minor factor on the flame structure limited in our experimental conditions.

4. Conclusions

A study of flame structure was using conducted simulated coal-derived syngas. The experiments were performed using selected nozzles with different diameters and shapes, and operation conditions. The following conclusions were made: 1) The structure of the flame formed around a fuel jet surrounded by swirling air is characterized by the mixing and combustion of the fuel layer flowing around the high-temperature recirculation zone. The flame configurations arise according to the nozzle shapes. 2) In axial type nozzles, the flame heights of smaller diameter nozzles were longer and the flame widths relatively narrowed.

Accordingly, the nozzle diameter would appear to be the key parameter determining the flame structure. 3) In tangential type nozzles, the flame structure is depended on the fuel heating rate and air flow rate. The swirl number variation affected the flame structure more or less. Accordingly, the fuel flow rate would appear to be the key parameter determining the flame structure. 4) Compared to nozzle types, the flame heights of the tangential type nozzles are about 3 times smaller than those of the axial type. The radial temperature profiles of the tangential type are more uniform than the axial type. The swirl effects on the flame structure are minor factor in our experimental conditions.

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