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FLAME STABILITY OF CO/H$_2$ SYNGAS IN THE DIFFUSION FLAME BY USING LAB-SCALE BURNER

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Abstract : The flame stability in lab-scale burner fired with coal-derived syngas has been investigated with the variation of combustion parameters. The tangential type swirl diffusion burner was designed to hold stable flame of coal-derived syngas in the fuel-lean combustion condition. The axial and tangential air flows are properly mixed inside combustor enclosure for the complete oxidization of coal-derived syngas within experimental condition. Parameters such as fuel bulk velocity, CO/H$_2$ ratio, excess air percent, swirl number, and nozzle type, are varied for investigating the effect of various experimental conditions on the flame stability. Experimental results represent that different CO/H$_2$ ratio of fuel did not show any effect on the stability limit of the flame. On the other hand, the fuel bulk velocity as well as the calorific value of fuel affected the flame stability limits. For the experiments with nozzle type variation, tangential type nozzles are more stable than the axial type nozzle within experimental conditions. For the experiment of swirl number variation, flame stability limit was increased with swirl number in the range of $S \leq 1$. Consequently, flame stability of swirl-stabilized burner within same type of nozzle is largely depends on the swirl number comparing to other combustion parameter.

Key Words : flame stability, diffusion flame, coal syngas, swirl

INTRODUCTION

According to recent energy consumption trends in Korea, the demand for electric power generation by gaseous fuel will be further increased in the future. However, with the finite outlook of natural gas resource, electricity generation utilities have to largely depend upon coal-derived syngas from IGCC (integrated gasification combined cycle) system since it ensures cost-effective and environmentally sound options for supplying future power generation needs. In IGCC system, coal is gasified inside high-temperature, high-pressure gasifier with oxygen and steam, then produced gas is transferred into gas cleaning unit, where fly ash and noxious gaseous products, such as H$_2$S and NH$_3$ are removed from the gas stream. Cleaned gas is burned at the gas turbine combustor with pressurized air, and then exhaust gas is transported to gas turbine to generate electricity. Cooled gas can be further utilized in the steam turbine with exhaust heat recovery boiler. For the performance improvement of IGCC power system, gas turbine combustor should be developed to satisfy the stability with various input combustion condition. Turbulent non-premixed flames are widely utilized in the practical combustion systems, principally because of the ease with which such flames can be controlled. Turbulent jet flames are usually characterized by flame luminosity and flame length according to their combustion parameters such as fuel types,

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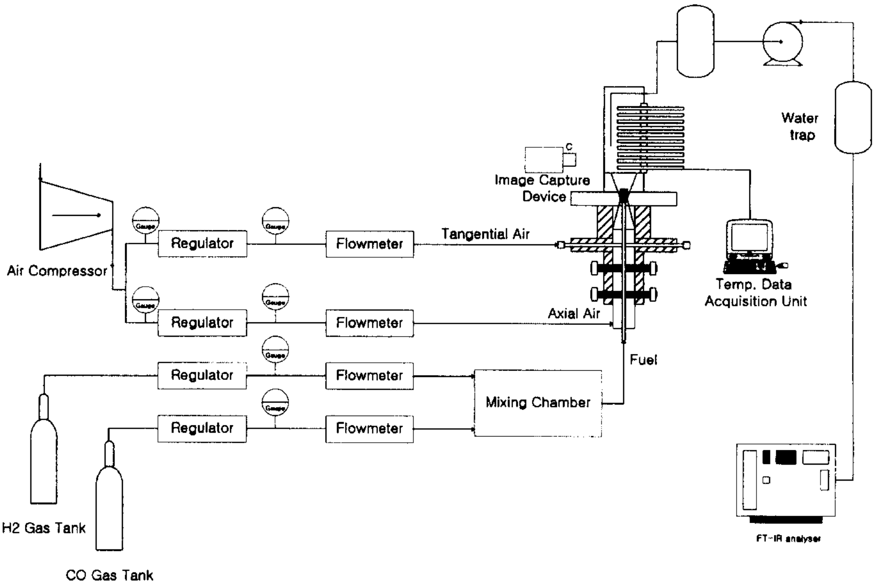

Figure 1. Schematic diagram of lab-scale burner system.

amount of swirl and input jet velocity. The shape of the flame represents visual image of brushy or fuzzy edges. However, the non-premixing usually increases the flame luminosity since some soot usually presents within the flame. Flame stability in the fuel-lean condition is important issue in these days since this condition produce temperature high enough to utilize for gas turbine as well as save the amount of the fuel used.

The coal-derived gas produced from the O_2 blown, entrained-type coal gasifier has a calorific value as low as 1/5 of natural gas, so that its combustion behavior is different from that of natural gas. The most important parameter of gas turbine combustor operation is to maintain stable flame with variation of air and fuel flow rate. In the present investigation, combustion stability of coal-derived syngas is examined with lab-scale combustor while varying CO/H_2 ratio, percentage of excess air, swirl number, ratio of axial and tangential air, and type of the nozzle. The amount of air for combustion is first calculated by stoichiometric mixing ratio, and then total amount of air is also varied from 100 to 200 percent of stoichiometric amount. Therefore, stability study of coal-derived syngas in fuel lean condition is established. During the experiments, blow-off and flash-back points are determined with varying swirl and excess air percent. The large variety of flame types reflects the wide range of research needs in practical devices. For any particular application, combustion parameters such as flame shape and size, flame holding and stability, heat transfer and pollutant emissions should be studied. The experimental results are compared with characteristic of pure hydrogen and methane flame by using previous experimental data of flame stability limit.

Theory and Experiments

Various compositions of coal-derived syngas are manufactured by mixing the CO and H_2 from the gas cylinder tank and air is delivered through commercial air compressor. Predetermined flow rates of fuel and air passed through flowmeter and introduced into burner arrangement. The entire experimental system is illustrated in Figure 1. The goal of the burner design was to incorporate realistic industrial burner characteristics while maintaining experimental

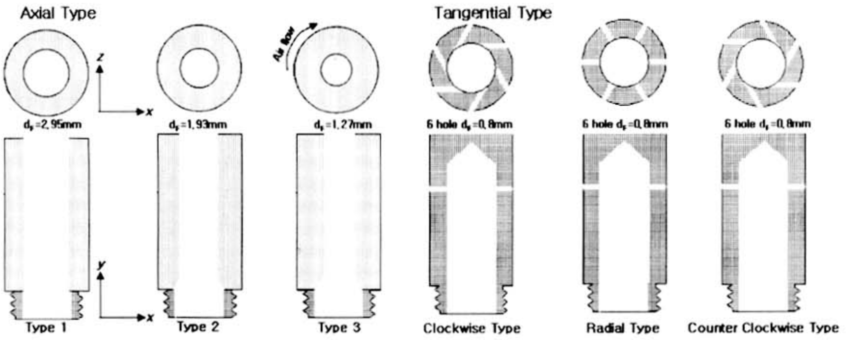

Figure 2. Specific configuration of nozzles.

Table 1. Area and bulk velocity on the variations of nozzle diameter

Condition [477.7 kJ/hr]	Axial type 1	Axial type 2	Axial type 3	Tangential types
Area [m^2]	6.8E-04	2.9E-04	1.3E-04	3E-04
Bulk velocity, U_F [m/sec]	26.8	62.5	144.4	48

flexibility in regard to the burner geometry and input flow parameters. The burner was designed to be upfired, coaxial, and fueled by pure methane as well as simulated coal syngas. The burner consists of five components: the axial air plenum, the swirl module, the air contraction, the quarl, and the fuel injector. All of these components are threaded and changeable such that different geometries can be installed and investigated. This was done for maximum flexibility in addressing interesting research ideas as well as responding to the directions proposed by industry.

The components of burner swirl module, air contraction, quarl, and fuel nozzles are arranged into one unit and the burner specific configuration with installed fuel nozzles is shown Figure 2. While changing the fuel nozzle of the burner, fuel is also varied with different ratio of CO and H_2. Eights different mixtures of fuel were used for the experiment of flame stability and their physical properties are given in Table 2. Flashback safety device is also installed upstream of fuel gas inlet point since flame velocity of H_2 represents high value of about 0.3m/sec [1]. The swirl generator consists of four tangential air inlets that mix tangential air with axial air upstream of the tip of fuel nozzle. The swirling coaxial airflow surrounds a central fuel tube that injects fuel in the axial direction. During the experiment, swirl is also gradually reduced to zero, so that one recovers the important case of a jet flame with coaxial air that is documented in the literature [2]; thus the swirl and no-swirl cases can be properly compared. Two types of fuel injection nozzles were chosen for the initial burner facility tests: axial, tangential jet injectors. A schematic diagram of the nozzles used in the experiment is presented in Figure 3. The axial injectors were chosen for the flames which have low swirl and a closed, off-axis recirculation zone; these flames have characteristic of higher fuel velocity comparing to air velocity [3]. The selection of nozzle diameter of axial type nozzles was based on the design operating conditions. The variations of fuel nozzle diameter are represented in Table 1. With axial nozzles, most of the experiments were carried out because axial nozzles produce rather simple flame shape that can be analyzed through the variation of experimental parameter. The tangential nozzles were

Table 2. Physical properties of fuel gaseous used in the flame stability experiment

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
CH_4	99	16	102.7	0.39	0.055
H_2	99	2	84.2	3.06	0.028
CO	99	28	166	0.136	0.289
H_2 : CO	99/ (1:1)	15	182.5	1.66	0.179
H_2 : CO	99/ (1:1.5)	17.6	184.8	1.41	0.204
H_2 : CO	99/ (1:2)	19.42	185.7	1.23	0.220
H_2 : CO	99/ (1.5:1)	12.4	178.7	2.02	0.153
H_2 : CO	99/ (2:1)	10.58	174.7	2.20	0.133

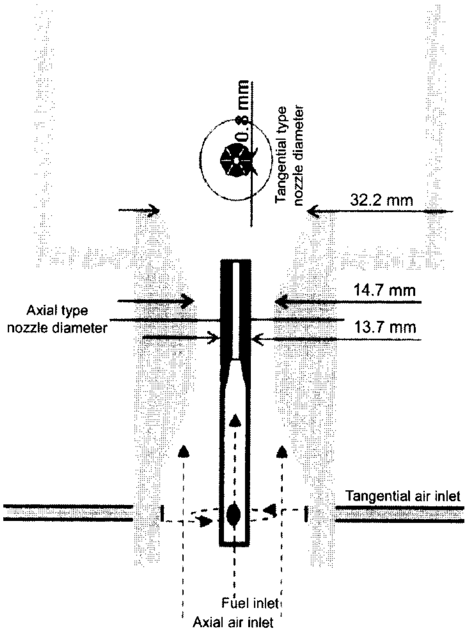

Figure 3. Laboratory scale burner configuration.

chosen to match the quarl angle and it used to determine the flame shape and stability only.

Flow rates of gas streams were metered using a system of calibrated gas meter with rotameter so that flow rates were delivered within the accuracy of ± 5%. Fuel velocity was calculated with different experimental conditions of flow rate and compressibility effects of the flow system are considered. 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. To obtain recirculation vortex inside combustor, a diverging metal quarl section is placed downstream of the cylindrical nozzle throat. Upstream of the tangential air inlets, the axial air profile was assumed uniform flow. The swirl number (S) in the study is identical to the conventional definition [4] i.e., S is the ratio of the flux of angular momentum passing through the nozzle throat to the flux of axial momentum, divided by the throat radius as in Eq. (1)

$$S=\int_{d_{F,0}/2}^{d_A/2}(\rho r u_\theta u_z)2\pi r dr \Big/ \left[\int_{d_{F,0}/2}^{d_A/2}\rho(u_z^2-u_\theta^2/2)2\pi r dr\cdot(d_A/2)\right] \tag{1}$$

Determination method of swirl by Eq. (1) eliminates the need to measure static pressure. However, the measurement of u_θ and u_z within the metal throat are really difficult. Since, it was found that a convenient way to determine S is introduced such as monitoring the mass flow rates of the axial air (m_A) and tangential air (m_T) respectively. Thus, a geometric swirl number (S_g) is determined as in Eq. (2). In this Equation, A_t is the total area of the four tangential air inlets and r_0 is the radius of the tangential air tube. By using this method, it is possible to deduce S directly from the mass flow measurements as in Eq. (3).

$$S_g=\frac{\pi r_0 d_A}{2A_t}\left(\frac{m_\theta}{m_\theta+m_A}\right)^2 \tag{2}$$

$$S'=\left(\frac{Q_{swirl}}{Q_{swirl}+Q_{axial}}\right)^2=\frac{S_g}{\pi_0 d_A}2A_t \tag{3}$$

In the present investigation, the swirl intensity (S'), which is essentially the mass ratio of tangential air to the total air input, was used to provide a more easily understanding of swirl. Eventually, S' value of 1.0 represents 100% swirl intensity and a value of 0.44 represents twice as much swirl as axial air. S_g only is depends on the geometric parameters. The relationship between swirl intensity and swirl number with different tangential air flow rate is illustrated in Figure 4.

In order to ensure fully turbulent conditions, the experimented flames were operated with the control of burner pipe exit Reynolds numbers in the range of 10,000 to 30,000, whose value is higher than the transitional Reynolds number of about 3200 for a free jet flame. Most of the experimental conditions studied ensure turbulent behavior of fuel/air mixture. The calculated Reynolds numbers are shown in the Figure 5, with various nozzle type and fuel composition. Combustion diminishes the Reynolds number based on local conditions through its direct effect on the density and viscosity and enhances it indirectly through buoyancy. The flame tip Reynolds number (ReL) proposed by Becker and Liang [5] seem to offer the best guidance for characterizing the overall downstream state of the flow. Flame tip Reynolds number is defined as in Eq. (4).

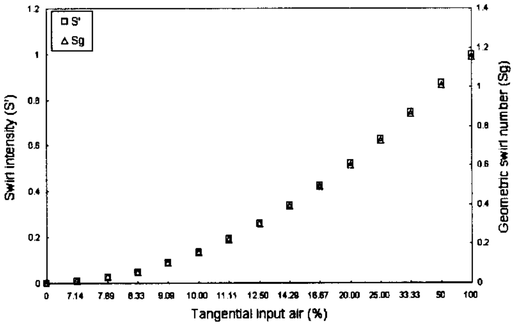

Figure 4. Variation of swirl intensity and geometric swirl number increase with tangential input air.

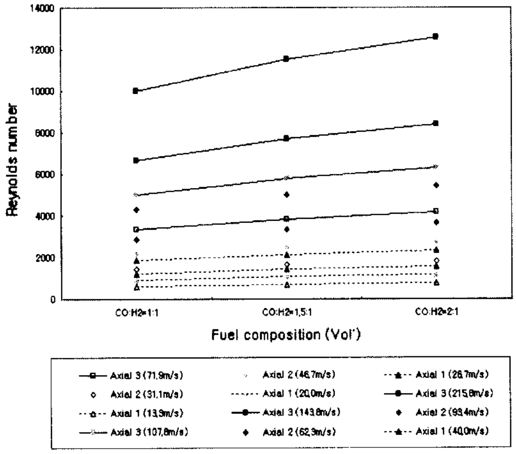

Figure 5. Reynolds numbers with the variations of the fuel composition and the nozzle type.

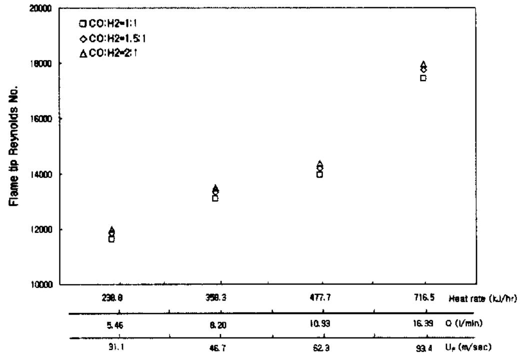

Figure 6. Flame tip Reynolds numbers with the variations of the fuel composition and the fuel bulk velocity (Axial type 2).

$$\mathrm{Re}_L = \frac{14\dot{m}_0\beta}{\mu_\infty W_1 L} \tag{4}$$

In Eq. (4), μ_∞ is the surrounding gas viscosity in kg/msec, L is the visible flame length and $\dot{m}_0$ is the input mass flow rate in kg/sec. Turbulent characteristic of the flame is established for Re value of about 8000. This value is well below those for the present flames, as in Figure 6, so that turbulent condition is ensured for entire experimental condition.

RESULTS AND DISCUSSION

Prior to investigate flame stability limit, different characteristics of flames were observed,

1) lifted flames, which look like lifted simple jet flames, 2) jet-like flames, which look like long, attached jet flames but blow out suddenly without lifting off, and 3) short flames, which also blow out suddenly without rising. However, these flames didn't accurately divide with different experimental parameters. The stability limit for each nozzle was determined as follows. A low flow rate of fuel was delivered to the nozzle for start-up. An ignitor was used to ignite the fuel such that a diffusion type flame resulted. The fuel and the swirl air flow rates were slowly and alternately increased until the desired firing rate and excess air percentage were achieved or the flame blow out. If the flame was stable at the desired excess air percentage, the swirl air was decreased as the axial air was increased by an equivalence amount such that the total air flow rate to the burner remaining constant. As the axial air was increased, the amount of swirl decreased. The point at which the flame extinguished indicated the blow off or stability limits of the flame at that excess air percentage and swirl ratio. These experiments were continued for increasing excess air ratios until a flame was no longer achievable under any swirl conditions.

The flame stability limits for axial type fuel nozzle 1 is presented in Figure 7. For the consideration of calorific value effect on the flame stability limit, fuel bulk velocity is changed during the experiment. The flame stability limit is gradually decreased with increasing fuel bulk velocity. Flame stability region with fuel bulk velocity of 13.3 m/sec is not affected by variation of swirl number and excess air. The flame stability with fuel bulk velocity of 40.4 m/sec has relatively narrowed region comparing with lower fuel bulk velocity conditions. The flame stability limits for axial type fuel nozzle 2 and nozzle 3 are presented in Figure 8 and 9. As shown by Figure 9, the axial type 3 nozzle can only stabilized with swirling air (S'>0.8) at 30% excess air. Whereas the axial type 1 and 2 fuel nozzles on experimental conditions have a much wider swirl stability range, i.e., 0.1≤S'≤1.0 at entire excess air range. The axial type 3 nozzle that operates over 71.8 m/sec experimental conditions can not be stabilized under any swirl or excess air conditions. The effect of fuel gas composition on flame stability region can not

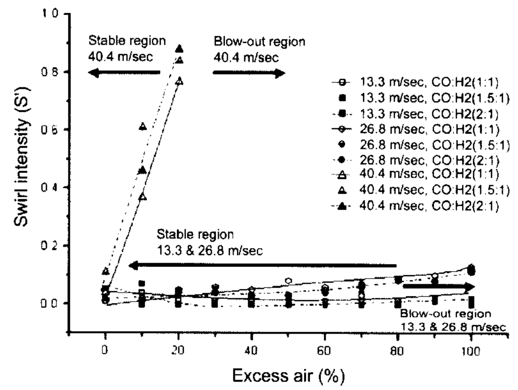

Figure 7. Flame stability limit for axial type 1 fuel nozzle.

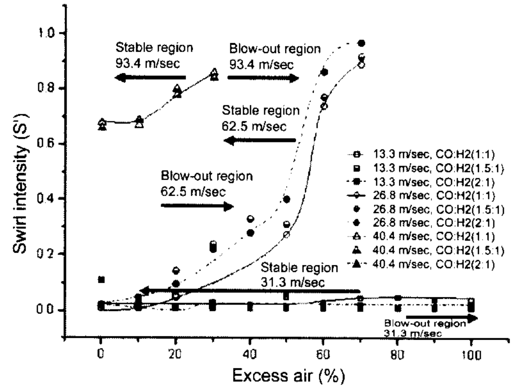

Figure 8. Flame stability limit for axial type 2 fuel nozzle.

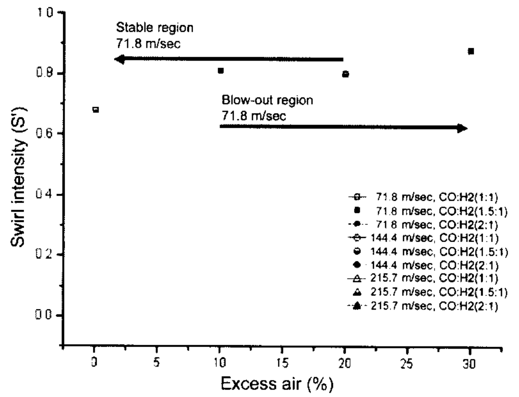

Figure 9. Flame stability limit for axial type 3 fuel nozzle.

found within axial type 1 and 2 experimental conditions. However for the axial type 3 fuel nozzle in CO:H_2 (2:1) flame only showed stable flame region.

The general shapes of flame on axial type nozzles exhibit cone shape. As the excess air is increased, the flame length decreases for all experimental conditions. The axial type 1 and 2 fuel nozzle has a wider swirl stability range than the axial type 3 fuel nozzle for whole excess air range on 71.8 m/sec. Axial jet nozzles exhibit a type I flame structure due to the fuel jet penetration into the recirculation zone. For the smallest axial nozzles, the fuel jet fully penetrates the recirculation zone, resulting in a small blue, bulbous, off-axis recirculation zone at the base of the flame with a long yellow flamelet tail. As the amount of excess air is increased for high swirl cases, the tail length and luminosity decrease as the recirculation zone size increases. At the lower swirl cases, the recirculation zone is less easily identified. For the largest axial nozzle, the fuel jet flamelet does not extend as far downstream of the recirculation zone boundary. Due to its lower fuel injection velocity, similar to the experimental of other axial nozzle, the flame becomes wider, more compact and bluish as excess air is increased.

The flame stability limits for tangential type fuel nozzles are presented in Figure 10-12. The flame of tangential type fuel nozzles are only stabilized in the 90.6 m/sec experimental condition. Different nozzle version i.e., radial, clockwise, counter-clockwise doesn't show much effect on the flame stability. However, counter-clockwise version of tangential type nozzle represents widest flame stability region because of its superb mixing phenomena. The radial type fuel nozzle held flame stability region in the non swirling air and up to excess air of 50% and the flame stability region is exponentially decreased over if the excess air exceeded over 50%. The clockwise and counter-clockwise type fuel nozzles also have similar trend of flame stability limit with the radial type fuel nozzle.

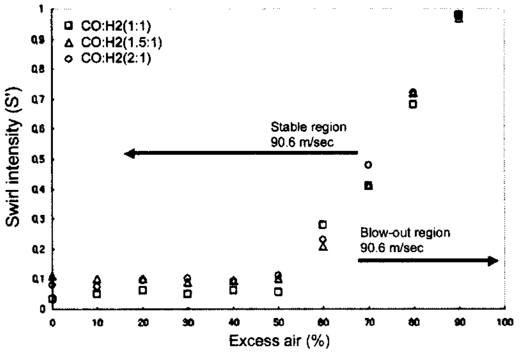

Figure 10. Flame stability limit for radial version of tangential type nozzle.

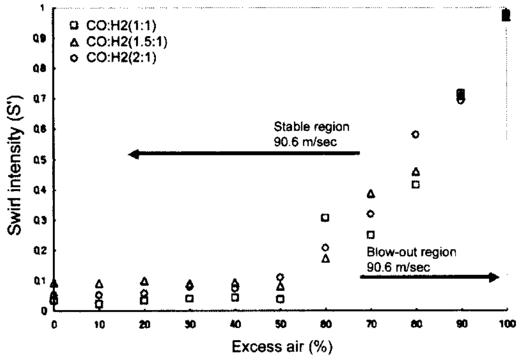

Figure 11. Flame stability limit for clockwise version of tangential type nozzle.

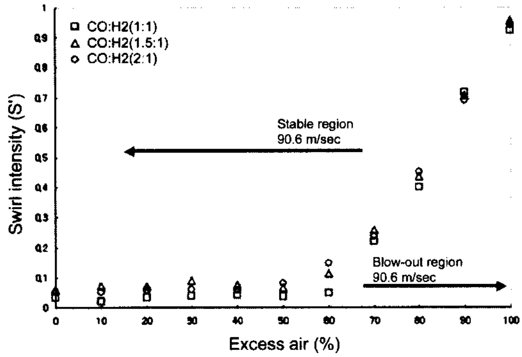

Figure 12. Flame stability limit for counter-clockwise version of tangential type nozzle.

Relatively, for the tangential type fuel nozzles, the counter-clockwise fuel nozzle has the widest swirl stability range, e.g., $0.9 \leq S' \leq 1.0$ at 100% excess air. The tangential type fuel nozzles exhibit short, blue "petal-like" flames from each jet exit with a non-luminous inner core. At high swirl, the shear layer caused by the swirling air and entrained air forces the fuel jets outward to form thin petals. At lower swirl, the petals are closer to the centerline, due to the decreased expansion, and held together forming less discrete jets. These flames are type II flames. Type II flames are shorter and more intense with higher swirl such that the recirculation zone prevents fuel jet penetration. These flames have, again due to the off-axis, annular fuel injection and low fuel penetration in the recirculation zone. Considering the flame stability, increasing the calorific value of fuel accordance with the fuel bulk velocity on the same nozzle, flame stability region gradually decreased. Figure 13 represents the U_F/U_A ratio on the excess air variation of the fuel nozzle types. Considering the tendency of U_F/U_A ratio in axial type nozzles in excluded effects of swirl, high U_F/U_A ratio caused the flame stability to reduce its region around the excess air variation. U_F/U_A ratio of tangential type nozzles has less value than axial type nozzles, the flame stability region of tangential type nozzles are larger than the axial type nozzles within experimental conditions. These results proposed high U_F/U_A ratio caused fuel jet to penetrate combustion region. Although each injection fuel velocity of 6 hole tangential type nozzles are higher than axial type nozzles, increasing of fuel jet tangential momentum enhanced the mixing effect between fuel and air.

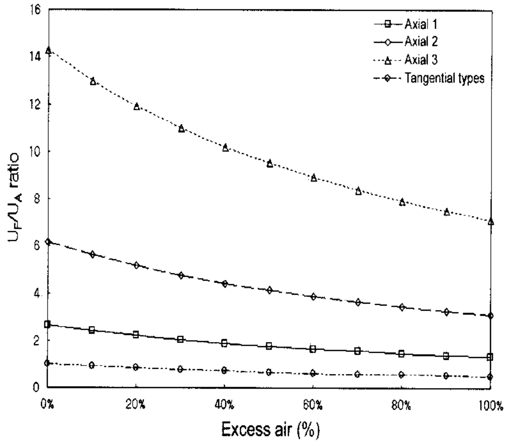

Figure 13. UF/UA ratio on the excess air variation of the fuel nozzles.

CONCLUSIONS

On the investigation of the determination of flame stability region with varying CO/H_2 ratio for each condition with axial and tangential type fuel nozzles. The flame stability region of $CO:H_2$ mixture with axial type nozzles was narrower than that of tangential type nozzles. Shapes of flame of axial type nozzles were not different in the range of equivalence ratio between $\Phi=1$ and $\Phi=0.67$. However, by changing equivalence ratio up to $\Phi=0.5$, shape of flame rapidly became unstable. Considering effect in the direction of tangential type fuel injection on flame stability region, stability limit of counter-clockwise type nozzle was relatively broaden the other type of nozzles. The flame stability region of $d_F=1.93$mm has about four times the fuel bulk velocity of a nonswirling flame. Yuasa [7] reports a fourfold improvement in the maximum fuel velocity due to swirl, and Douglas et al [8] reports a fivefold improvement compare with non-swirling flame. The stability limit on axial type fuel nozzle mainly depends on calorific value of fuel condition that related with fuel and air input velocity. The behavior of different CO/H_2 ratio on axial and tangential type fuel nozzles showed similar flame stability limit on same experimental conditions. As the swirl number was increased within $S \leq 1$, flame stability limit was increased. These experiment results on swirl stability effect are well matched with study of Douglas et al [8] and Yuasa, S [7].

NOMENCLATURE

A_t : total area of the four tangential air inlets [m]
d_F : fuel nozzle inner diameter [m]
d_A : annulus air diameter [m]
L : visible flame length [m]
m_A : mass flow rates of the axial air [kg/sec]
m_θ : mass flow rates of tangential air [kg/sec]
$\dot{m}_0$: input mass flow rate [kg/sec]
M_∞ : molecular weight of ambient gas [g/mole]
M_1 : mean molecular weight of combustion products of a stoichiometric air/fuel mixture at

the adiabatic flame temperature [g/mole]

Q_{swirl} : swirl air flow rate [kg/sec]
Q_{axial} : axial air flow rate [kg/sec]
r_0 : radius of the tangential air tube [m]
Re_L : flame tip Reynolds number
Ri_L : Richardson number
S : swirl number
S_g : geometric swirl number
S' : swirl intensity
T_l : adiabatic flame temperature of a stoichiometric air/fuel mixture [k]
T_∞ : surrounding gas temperature [k]
U_F : fuel bulk velocity [m/sec]
W_l : mass fraction of source stream material in a stoichiometric mixture with the ambient gas
β : $(M_\infty T_l / M_l T_\infty)^{1/2}$
μ_∞ : surrounding gas viscosity [micropoises]
ξ_L : dimensionless flame length
ρ_∞ : ambient gas density [kg/m^3]

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