2284 *Journal of Mechanical Science and Technology (KSME Int. J.), Vol. 20, No. 12, pp. 2284~2291, 2006*

Effect of Swirling Flow by Normal Injection of Secondary Air on the Gas Residence Time and Mixing Characteristics in a Lab-Scale Cold Model Combustor

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The present study investigates gas residence time and mixing characteristics for various swirl numbers generated by injection of secondary air into a lab-scale cylindrical combustor. Fine dust particles and butane gas were injected into the test chamber to study the gas residence time and mixing characteristics, respectively. The mixing characteristics were evaluated by standard deviation value of trace gas concentration at different measurement points. The measurement points were located 25 mm above the secondary air injection position. The trace gas concentration was detected by a gas analyzer. The gas residence time was estimated by measuring the temporal pressure difference across a filter media where the particles were captured. The swirl number of 20 for secondary air injection angle of 5° gave the best condition : long gas residence time and good mixing performance. Numerical calculations were also carried out to study the physical meanings of the experimental results, which showed good agreement with numerical results.

Key Words : Swirl Combustor, Residence Time, Recirculation Flow, Mixing Characteristics, Incinerator

Nomenclature

C : Gas concentration, kmol/m^3
C_{avg} : Average gas concentration, kmol/m^3
C_C : Cunningham correction factor, ~1
D_1 : Diameter of the chamber, m
D_2 : Diameter of the secondary air nozzle, m
d_p : Particle diameter, m
L : Characteristic length of the volume flow, m
N : Number of measurement positions
n : Number of secondary air nozzles

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S : Swirl number
t : Residence time, sec
U : Velocity, m/s
U_1 : Primary chamber gas velocity, m/s
U_2 : Secondary air nozzle velocity, m/s
V : Output voltage of manometer, V

Greek Letters

θ : Injection angle of the secondary air nozzle, degree
α : Mixing performance parameter
μ : Fluid viscosity, kg/m s
ρ_p : Particle density, kg/m^3

1. Introduction

Recently, incineration treatment of wastes has become a popular method because it decreases volume and mass of wastes, effectively. The performance of a combustion chamber in an incinerator has been enhanced to reduce pollutants generated by incomplete combustion (Shin et al., 1998 ; Nasserzaheh et al., 1991). As an important technology to enhance combustion performance, staged combustion has been suggested, where the first combustion zone is under the oxygen-starved condition by insufficient air injection, and the following secondary combustion zone is operated with sufficient air injection to complete the combustion (Turns, 1996). In general, secondary air is injected into the combustion chamber by jet nozzles to induce turbulence and control the flow pattern to maximize the residence time and complete mixing. Swirling flow pattern is usually generated by tangential injection of the secondary air by tilting the nozzle directions from the radial direction.

Figure 1 shows schematic flow patterns of two cases of swirling flow according to swirling strength. When no or low swirl is introduced, the up-flow velocity pattern is a parabolic shape. However, a further swirl distributes the flow to a side-concentrated, up-flow pattern, and a strong swirl can make the center flow to be directed downward, which causes a recirculating zone. The recirculation zone is a kind of dead zone occupying the furnace volume and reducing gas residence time.

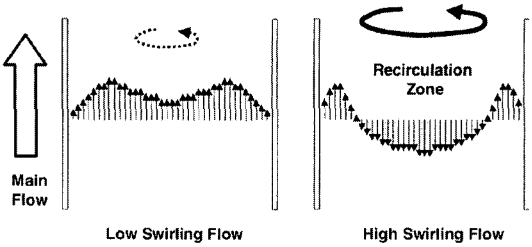


Fig. 1 Recirculation zone by swirl effect

Residence time and mixing of combustion gas are important factors which determine combustion performance. The probability of residence time distribution in a swirling flow was measured by helium gas and hot wire measurements (Lans et al., 1997). The measurements were performed by injecting helium gas in a swirling furnace and by suddenly closing the injection, and then, measuring the helium gas concentration by hot-wire system at a point of the furnace. Mixing performance was measured by the tracing tracer method. CO_2 gas and its analyzer were utilized to observe the mixing performance of a swirling flow (Huang and Tsai, 2004). A swirl generator generated the swirling flow, and the distribution of CO_2 that was injected to on the centerline of the swirl generator was measured to estimate the mixing performance.

In the present study, the residence time and mixing performance of a swirling flow in a cylindrical chamber were analyzed by numerical analysis and a series of experiments. Secondary air was injected in the direction normal to the axial primary flow. The ratio of the secondary to primary air was varied as the total flow rate was kept constant. The secondary airflow rate and the nozzle injection angle from the radial direction were selected as the major parameters affecting the residence time and mixing performance. The residence time was measured by injecting fine dust particles (2 micron of mean diameter) and measuring the temporal pressure difference across the filter media where the particles were captured. The mixing performance was estimated by using butane gas as a trace gas and a hydrocarbon analyzer to measure the concentration distribution of butane gas in the chamber. Computational

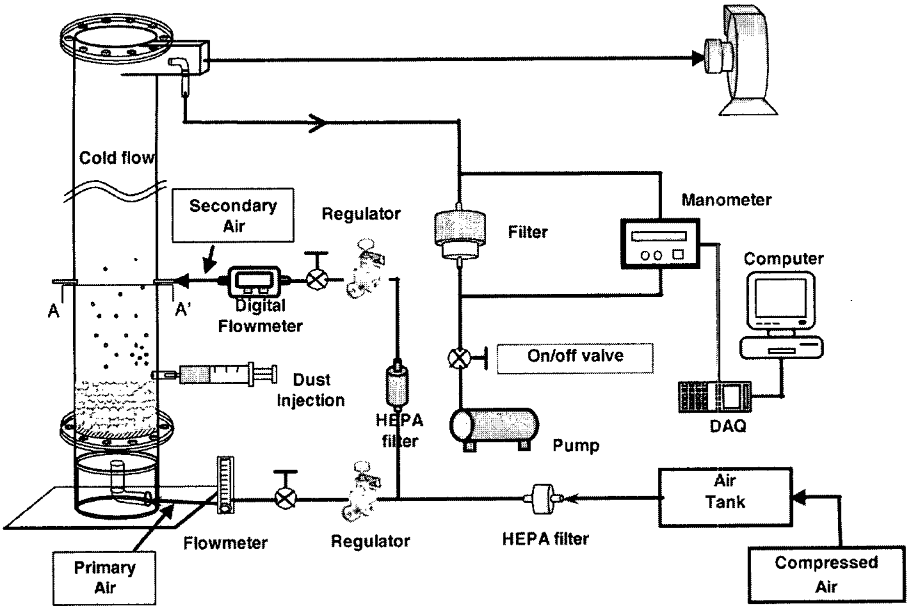


Fig. 2 Schematic diagram of experimental setup

fluid dynamics was also utilized to generate the numerical results, and the results were compared with the experimental data.

2. Experiment

Figure 2 shows the conceptual diagram of the experimental apparatus, which consists of three functional divisions : cylindrical chamber, air and dust injection systems, and measurement systems of gas residence time and mixing performance.

The chamber is a transparent plastic cylinder of 0.12 m inner diameter and 1.5 m height. The primary air is distributed through a steel bead layer of 40 mm height at the bottom of the furnace to obtain uniform up-flow. Dust injection point is just above the bead layer. The secondary air is injected at the 0.38 m height from the dust injection point via four nozzles. The butane gas is injected at the 50 mm under the secondary air nozzles. The primary and secondary airs from compressor are pre-cleaned through a HEPA filter and their flow rates are measured by a ball type flow-meter and a digital flow-meter (TSI 4043), respectively.

The experimental parameters in the measure of residence time and mixing performance are the flow rate of secondary air and its injection angle.

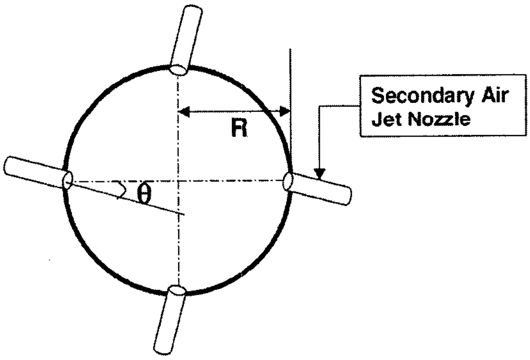


Fig. 3 Cross section of A-A′

The swirl number related to the parameters is derived as follows from its definition (Coghe et al., 2004 ; Zhengqi et al., 2002);

$$S = n \times \left(\frac{U_2 D_2}{U_1 D_1} \right)^2 \times \sin \theta \qquad (1)$$

θ is the injection angle from the radial direction as shown in Fig. 3. Radial and tangential velocity components disturb the axial main flow direction. In particular, the tangential velocity component generates angular momentum, so swirling flow is generated.

The experimental conditions shown in Table 1 are used to tabulate the primary air and second-

Table 1 Experimental conditions

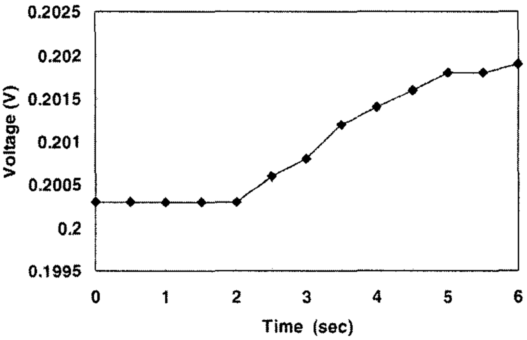
θ	Flow rate (l/min) Velocity (m/s)	Swirl number						
		0	5	10	20	30	50	100
5°	1st air flow rate	200	155	142	126	117	104	87
	1st air velocity	0.295	0.228	0.209	0.187	0.172	0.153	0.127
	2nd air flow rate	0	45	58	74	83	96	113
	2nd air velocity	0	11.16	14.46	18.29	20.64	23.68	27.86
25°	1st air flow rate	200	177	169	158	151	141	126
	1st air velocity	0.295	0.261	0.249	0.233	0.223	0.208	0.185
	2nd air flow rate	0	23	31	42	49	59	74
	2nd air velocity	0	5.79	7.82	10.33	12.10	14.58	18.35
45°	1st air flow rate	200	182	175	166	160	151	137
	1st air velocity	0.295	0.268	0.258	0.245	0.236	0.223	0.202
	2nd air flow rate	0	18	25	34	40	49	63
	2nd air velocity	0	4.60	6.26	8.39	9.91	12.07	15.49

ary airflow rates according to swirl number and nozzle injection angle. The total airflow rate is fixed to 200 liter per minute, and the swirl number ranges from 0 to 100.

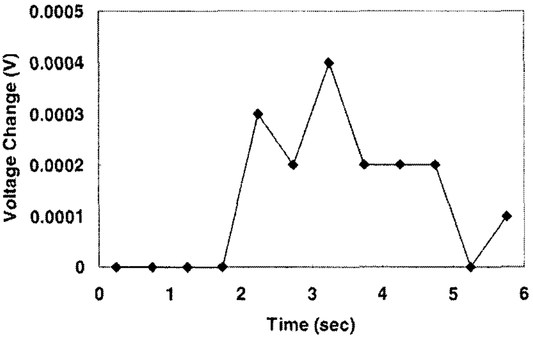
For measurements of residence time, a portion of the exit air was sampled, and the sampling flow rate was controlled by a vacuum pump (ULVAC, G-2DA). The residence time was estimated by measuring the temporal pressure difference across a filter media (Whatman Inc's glass fiber micro filter of 1 micron pore size), where the particles were captured. The digital data from a micro-manometer (OKANO, POP202) were recorded at the data acquisition board (DAQ-100) and by using a personal computer system. The dust particles injected instantly at the dust nozzles were dispersed in the chamber along with the primary air, and collected at the filter after exiting from the chamber. Therefore, the collecting rate of the dust particles at the filter is related to the gas residence time. In the estimation of the gas residence time, it was assumed that the dust particles followed concurrently the air. Thus the Stoke's number, which is interpreted as the particle-flow stabilization time over average flow residence, should be much lower than 1. The definition of Stoke's number is as follows ;

$$Stoke's\ number = \frac{C_c \rho_p d_p^2 / 18\mu}{L/U} \tag{2}$$

The calculated Stoke's number was about 2.7×10^{-5} for the test particles of 2 μm in mean diameter.



(a) Voltage Measurement



(b) Voltage Difference

Fig. 4 Output voltage of the micro-manometer detecting the pressure difference of the filter

Figure 4(a) shows typical temporal output voltages measured at the micro-manometer. As the dust particles injected into the chamber were collected at the filter, the relative pressure increased due to the reduction of porous area of the filter surface, and thus, the output voltage increased. The voltage is proportional to the amount of collected dust, which is also related to the residence time of the gas. The voltage change at each time, shown in Fig. 4(b), represents the collection rate of the dust in the time interval. Hence, the average residence time of the dust particles in the chamber can be calculated by the following equation ;

$$\text{Average residence time} = \frac{\sum t_i \Delta V_i}{\sum \Delta V_i} \tag{3}$$

In the mixing performance measurements, butane gas was injected at the flow rate of 3 lpm, and the concentration was measured by a gas analyzer (Greenline MK II) along the horizontal positions located 25 mm above the secondary air injection nozzles, where there was active mixing due to the secondary air jet injection. The mixing characteristics were calculated according to the definition of the following parameter α ;

$$\alpha = \sqrt{\frac{\sum (C - C_{avg})^2}{N-1}} \tag{4}$$

where α is the standard deviation of the tracing gas (butane) concentration. It is 0 when the mixing is complete, so that the concentrations over the measurement points equal to C_{avg}, which is the average concentration of the tracing gas at the chamber exit.

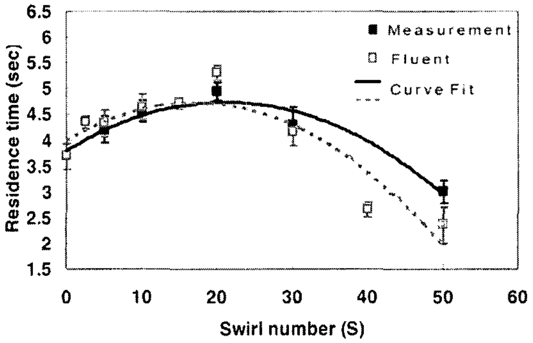
3. Numerical Calculation

Numerical calculation based on computational fluid dynamics was carried out to study the swirling flow characteristics. The results of this calculation were compared with the experimental data. A commercial CFD code (FLUENT 6.1.22) was used with a 3-dimensional grid system of 31,000 nodes. Continuity equation, momentum equations, species equations, and RNG k-ε equations were solved by utilizing a segregated solver including SIMPLE for velocity-pressure correlation, multigrid for rapid convergence, and 1st order up-wind scheme for the equations' discretization. The residence time of dust particles was calculated by the Lagrangian method, which calculates the drag force, gravity force, and dispersion by turbulent gas movement. A stochastic model utilizing random eddy lifetime technique was applied to investigate the effect of turbulence.

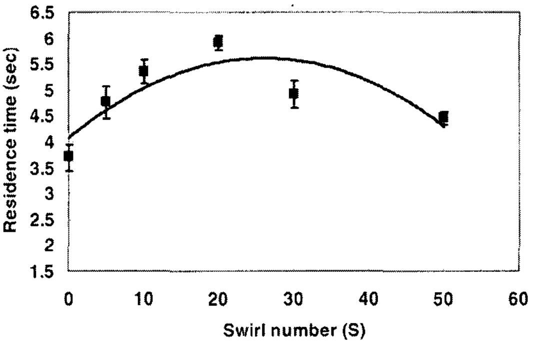
4. Results and Discussion

4.1 Residence time

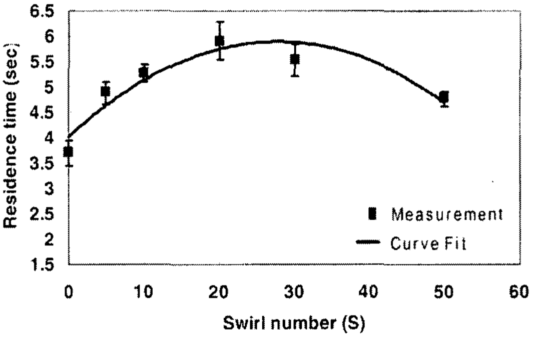
The effect of swirl number on the residence time for various injection angles (θ) of secondary



(a) $\theta=5°$



(b) $\theta=25°$



(c) $\theta=45°$

Fig. 5 Residence time

air nozzle was investigated. At every experimental condition shown in Table 1, experiments were performed at five times and then the average residence time was calculated by Eq. (3). Figure 5 shows the results in the form of error bar. The variances of the data at each condition are within 10% of the mean values. The average residence time of gas increased until the swirl number increased up to 20. However, when the swirl number became higher than 20, the residence time reduced due to unexpected reverse flow in the center of the chamber as the swirl number increased. Computational results by FLUENT also simulated the trend of swirl number effect as shown in Fig. 5(a). The swirl numbers at the larger injection angles shown in Figs. 5(b) and 5(c) had similar effect on the residence time. As the injection angle increased from 5° to 25° and 45°, the residence time slightly increased accordingly.

Figure 6 shows axial velocity distributions at 200 mm above the secondary air injection, obtained by computational fluid dynamics for various swirl numbers at the injection angle of 5 degrees. When there was no swirl, the flow velocity was almost uniform. As the swirl number increased, reverse flow area near the centerline of the chamber increased when the swirl number became higher than 5. As the reverse flow generated recirculating flow, which makes a dead zone where most of the gas skips in the chamber, the gas residence time inevitably decreased. Once a gas element entered in the dead zone, it escaped from the recirculating zone after a long time.

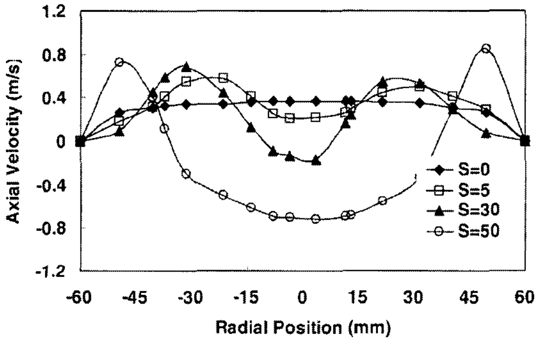
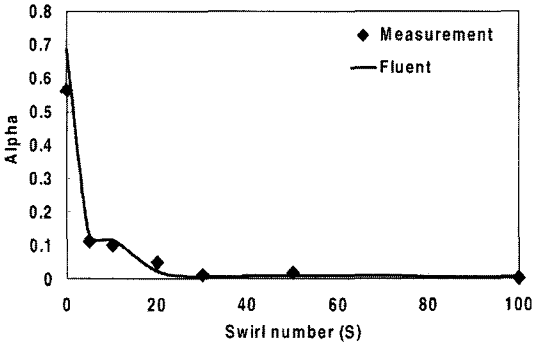


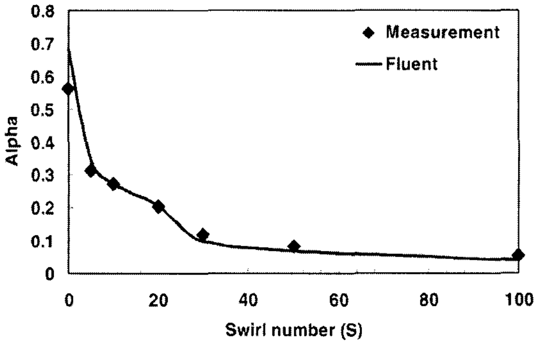
Fig. 6 Axial velocity distribution for various swirl numbers at the height of 605 mm ($\theta=5°$)

4.2 Mixing performance

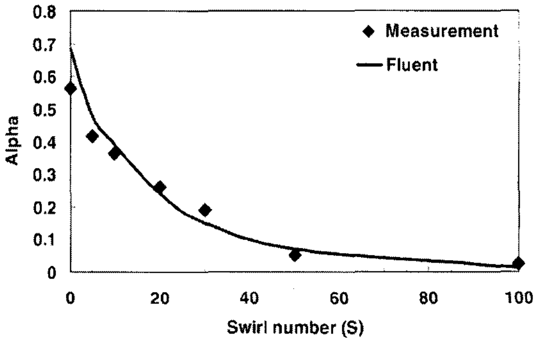
The effect of secondary air injection angle and swirl number on the mixing performance was studied. At every experimental condition, steady state concentrations of butane were measured at five radial positions and then the mixing characteristic parameter α was calculated by Eq. (4). The results include numerical simulations as well as measurements. The numerical results in Fig. 7 show good agreement with the measurement data.



(a) $\theta=5°$



(b) $\theta=25°$



(c) $\theta=45°$

Fig. 7 Standard deviation of butane concentration at the height of 605 mm

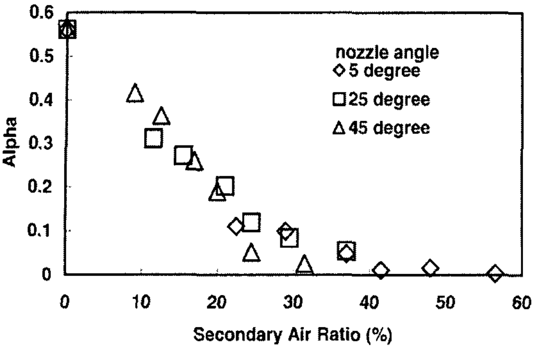


Fig. 8 Effect of secondary air ratio on mixing performance

For any injection angle, α decreased as the swirl number increased, which was due to increased secondary air rate or velocity as shown in Table 1. From the definition of α, decreased α means better mixing.

Meanwhile, the case of Fig. 7(a) shows the strongest effect of swirl number on α. As shown in Table 1, the secondary air ratio decreased as the secondary air injection angle increased for the same swirl number, and the secondary air injection rate was more effective than the swirl number or the secondary air injection angle. Figure 8 shows the rearranged data of all the measurement results according to the secondary air ratio and the apparent relationship between the secondary air ratio and the mixing performance.

5. Conclusions

A series of cold flow experiments and numerical simulations were performed to analyze the effect of secondary air injection and swirl number on gas residence time and mixing performance. The methods applied in the present study showed reasonably how the swirling flow and recirculation zone affected furnace performance.

(1) Until the swirl number increased up to 20, the average residence time of gas increased accordingly. Meanwhile, when the swirl number reached over 20, the residence time reduced as the swirl number increased due to unexpected reverse flow in the center of the chamber. As the reverse flow generated recirculating flow, which makes a dead zone where most of the gas skips in the chamber, the gas residence time inevitably decreased.

(2) The mixing parameter α decreased as the swirl number increased for constant injection angle, but increased as the secondary air injection angle increased for constant secondary air ratio. Meanwhile, the secondary air ratio appears to be more important parameter on the mixing performance than the swirl number or the injection angle.

(3) The best conditions with respect to mixing and residence time were obtained for the nozzle injection angle of 5 degrees and the swirl number of 20 in the cold flow tests with 4 nozzles.

(4) The numerical results, which could be applied to various parametric studies for different furnace shapes and different scales, showed good agreement with the measurement data and are expected to generate reasonable simulations.

Acknowledgments

This work was supported by the new faculty research program 2005 of Kookmin University in Korea.

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