Effect of Combustion Air Temperature on Combustion Characteristics of New Type Combustor with Upward Swirl

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Abstract

Our research group has proposed a low-NOx spray combustor for kerosene-fueled micro gas turbine based on an upward swirl concept. This combustor consists of primary and secondary combustion zones, and they are connected by a throat. A swirler is set between the primary and secondary combustion zones. In order to enhance the recirculation of burned gas in the primary combustion zone, the combustion air is introduced through the swirler and forced to flow upward to the combustor bottom, from which fuel is injected through a nozzle. In this study, effect of combustion air temperature on combustion characteristics of an experimental combustor with the upward swirl concept was investigated experimentally. The experimental combustor was installed in a casing. The combustion air introduced into the casing flows between the secondary combustion tube and the casing (heat exchange zone), and the air is ejected into the primary combustion zone through the swirler. Since the heat of combustion gas in the secondary combustion zone is transferred to the combustion air in the heat exchange zone, the preheated temperature of combustion air can be raised by increasing lengths of the secondary combustion tube and the casing simultaneously. Kerosene was used as a liquid fuel. Characteristics of exhaust gas and distributions of combustion gas velocity, temperature and species concentrations (CO and NOx) in the primary combustion zone were measured in order to discuss combustion characteristics of the combustor.

Preheated temperatures of combustion air were measured at the inlet of swirler in the casing. It was clear that the preheated temperatures increased with increasing the lengths of the secondary combustion tube and the casing.

Relations between excess air ratio in the primary combustion zone λ_p and characteristics of exhaust gas were investigated. It was clear that emission index of NOx in the case of higher preheated temperature greatly increased in λ_p = 1.05 and 1.26. The increases of NOx were mainly caused by the rise of combustion air temperature.

Introduction

Recently, dispersed generations such as fuel cell, diesel engine generator and micro gas turbine have received much attention from the viewpoint of highly efficiency power generation by an effective use of the generation facilities. Especially, the micro gas turbine system can generate electric power and heat simultaneously, and it has been introduced into hospital, hotel, and factory which have the demand of electricity and heat [1]. Moreover, the micro gas turbine system is very promising as a generator for emergency. In particular, a liquid-fueled micro gas turbine has an advantage in the supply of fuel in disasters such as earthquake. If gaseous fuel line is broken, a gas fueled gas turbine cannot work, but there are various ways to transport liquid fuel in quantity. Therefore, we have carried out the development of high performance combustors for liquid-fueled gas turbines [2, 3]. Generally, regenerative cycle is applied to small size gas turbine such as micro gas turbine in order to increase thermal efficiency. In regenerative cycle, combustion air was preheated by exhaust gas of high temperature.

In this study, therefore, effect of combustion air temperature on combustion characteristics of new type combustor with upward swirl was investigated.

Experimental Methods

Schematic diagram of the experimental apparatus is shown in Fig. 1. This apparatus consisted of the combustor, air and fuel lines, temperature measurement system and combustion gas sampling system. The temperature distributions at the outlet of the combustor were measured by a Pt-PtRh 13% thermocouple of 0.3 mm diameter. The exhaust gas was sampled by a water cooled sampling probe at the outlet of the combustor and collected in a sampling bag. The composition of the sampled gas was analyzed by an exhaust gas analyzer (MEXA-4000FT, HORIBA Ltd.) and NOx, CO and HC (Hydrocarbon) concentrations in the gas were measured. When the distributions of tem-

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perature and concentrations of combustion gas components in the primary combustion zone were measured, a thermocouple and a gas sampling probe were inserted into the chamber through holes made on the chamber wall. Moreover, combustion gas velocities in the primary combustion zone were measured by LDA (Laser Doppler Anemometer). In the measurement of gas velocity, the primary combustion tube with a quartz window was used.

The schematics of the prototype upward swirl combustor based on our new concept are shown in Fig. 2. This combustor has two combustion zones connected by the throat which diameter is smaller than those of primary and secondary combustion zones. The cross section A-A shows the bottom of primary combustion zone. The scroll-type guide vane is placed on the bottom and the combustion air with hot burned gas from the swirler was effectively guide to the nozzle by this vane. At the outlet of swirler, the swirler plate is placed as shown in the cross section B-B so that the upward swirl combustion air flows along the inner wall of primary combustion chamber. In this experiment, the swirler vane angle α was set at 45°, the height of guide vane H_g was 22mm and the length of primary combustion zone Z_p was 109mm. The combustion air introduced into the casing flows between the secondary combustion tube and the casing (heat exchange zone), and the air is ejected into the primary combustion zone through the swirler. Since the heat of combustion gas in the secondary combustion zone is transferred to the combustion air in the heat exchange zone, the preheated temperature of combustion air can be raised by increasing lengths of the secondary combustion tube and the casing simultaneously. In Fig. 2, Z_t represents the length of casing. The larger Z_t means the larger heat exchange zone. Kerosene was used as a liquid fuel and fuel feed rate M_f was set at 4.3g/s. Combustion air flow rate M_a was changed from 0.067kg/s to 0.095kg/s. Consequently, excess air ratio in the primary zone λ_p changed from 1.05 to 1.50.

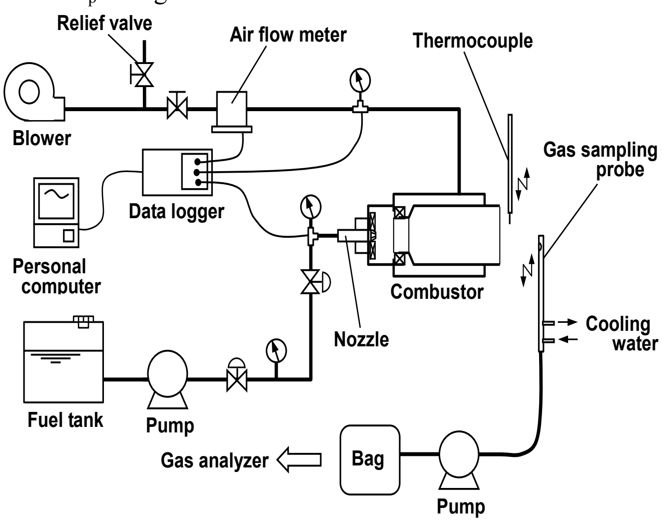

Figure 1. Experimental apparatus

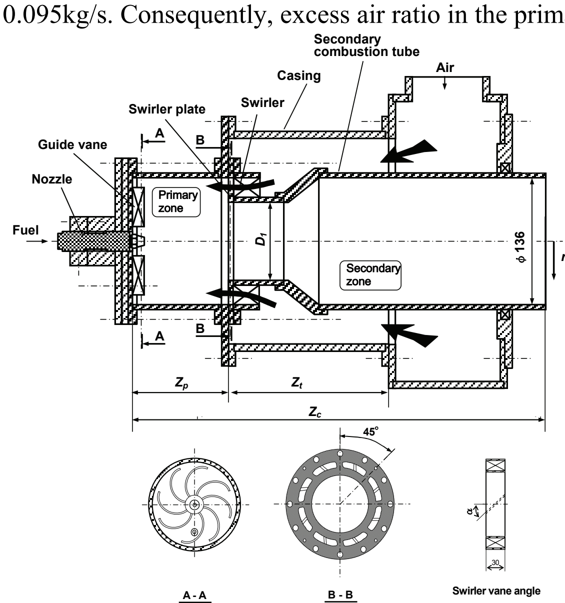

Figure 2. Schematics of prototype upward swirl combustor

Results and Discussion

Relations between the length of casing Z_t and preheated temperatures of combustion air

Relations between the length of casing Z_t and preheated temperatures of combustion air measured at the inlet of swirler in the casing were investigated. The length of casing Z_t was changed to 170mm, 325mm and 495mm. The measured results are shown in Fig. 3. The larger Z_t means the larger heat exchange zone. It was clear that the preheated temperatures in Z_t = 495mm was around 110K - 160K higher than those in Z_t = 170mm. From Fig. 3, the conditions of Z_t = 170mm, 325mm and 495mm were called LTCA (Low Temperature Combustion Air), MTCA (Middle Temperature Combustion Air) and HTCA (High Temperature Combustion Air), respectively.

Lean combustion limit

The lean combustion limits were measured in LTCA (Z_t = 170mm) and HTCA (Z_t = 495mm). The measured results are shown in Fig. 4. The fuel flow rate M_f and the excess air ratio in the primary combustion zone λ_p are indicated in horizontal and vertical axes, respectively, and λ_p when flame blew off are plotted in this graph. Therefore, a stable combustion was realized under the condition in the lower area of the lines. From this figure, it was shown that the excess air ratio of blow-off in LTCA was higher than in HTCA. The volume of combustion air in HTCA was larger than that in LTCA owing to preheat, and the combustion gas velocity in the combustor seemed to be higher in HTCA. It was considered that, therefore, the flame in the combustor was easy to blow off in HTCA.

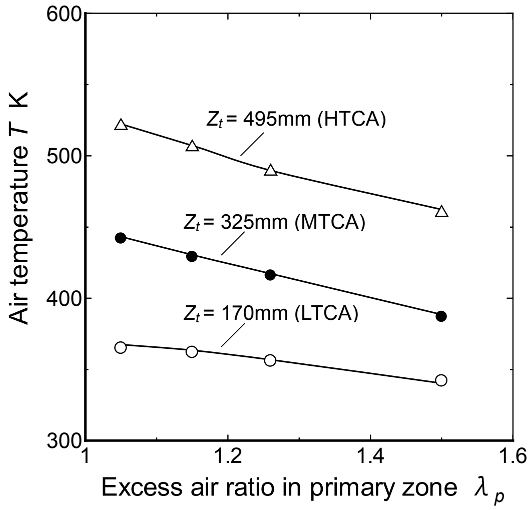

Figure 3. Preheat temperature of combustion air

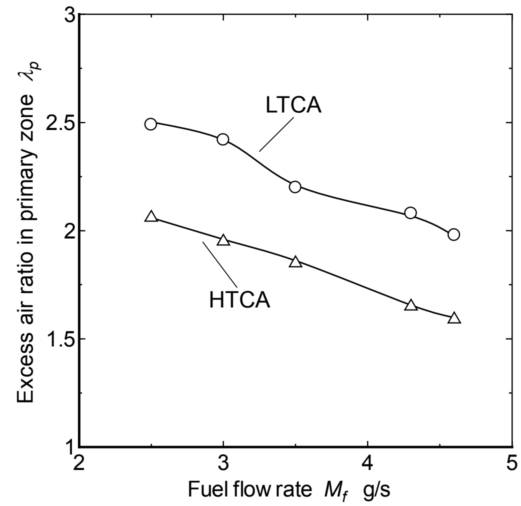

Figure 4. Lean combustion limit

Characteristics of exhaust gas

In order to clarify the emission characteristics of the upward swirl combustor in detail, the relations between excess air ratio in the primary combustion zone λ_p and gas temperature, the emission indexes of CO, HC and NOx were investigated when the length of casing Z_t was 170mm(LTCA) and 495mm(HTCA). The emission indexes were calculated from the averaged concentrations of them at the combustor exit and the fuel flow rate. The measured results are shown in Fig. 5. The averaged combustion gas temperatures at the combustor exit are also shown in this figure. The gas temperature at the exit in HTCA was about 50K higher than in LTCA though the temperature of combustion air was 110K-160K higher as shown in Fig. 3. This result showed that the heat of combustion gas was effectively transferred to the combustion air in HTCA. *EI*(CO) in HTCA was larger than in LTCA. This probably caused by the increase of combustion gas velocity owing to preheat. It seemed that the residence time of combustion gas in combustion zone was shorter in HTCA than in LTCA. On the other hand, there was little difference in *EI*(HC) between them. It was considered that evaporation of fuel droplets was promoted by preheated combustion air in HTCA. It was clear that *EI*(NOx) in HTCA greatly increased in λ_p = 1.05 and 1.26. The increase of NOx was mainly caused by the rise of combustion air temperature.

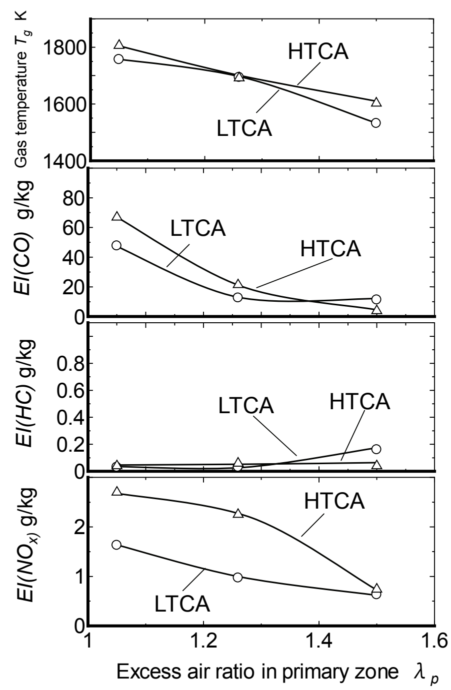

Figure 5. Characteristics of exhaust gas

Combustion gas velocity in the primary combustion zone

Distributions of combustion gas velocity in the primary combustion zone were measured and behavior of the recirculation of burned gas was investigated. The combustion experiments were carried out in LTCA and HTCA. In these measurements, the excess air ratio in the primary combustion zone λ_p was set in 1.50, and the fuel flow rate kept constant (M_f= 4.3g/s). The measured distributions of axial velocity of combustion gas are shown in Fig. 5. Positive values in these figures indicated that gas flowed toward the combustor exit (from left to right). From these figures, it was clear that the combustion air ejected through the swirler flowed toward the combustor bottom along the wall, and then flowed toward the combustor exit near the center line of the combustor with acceleration in both cases. It was also clear that gas velocity near the center line of the combustor in HTCA was faster than in LTCA. This probably caused by the increase of combustion air volume with preheating.

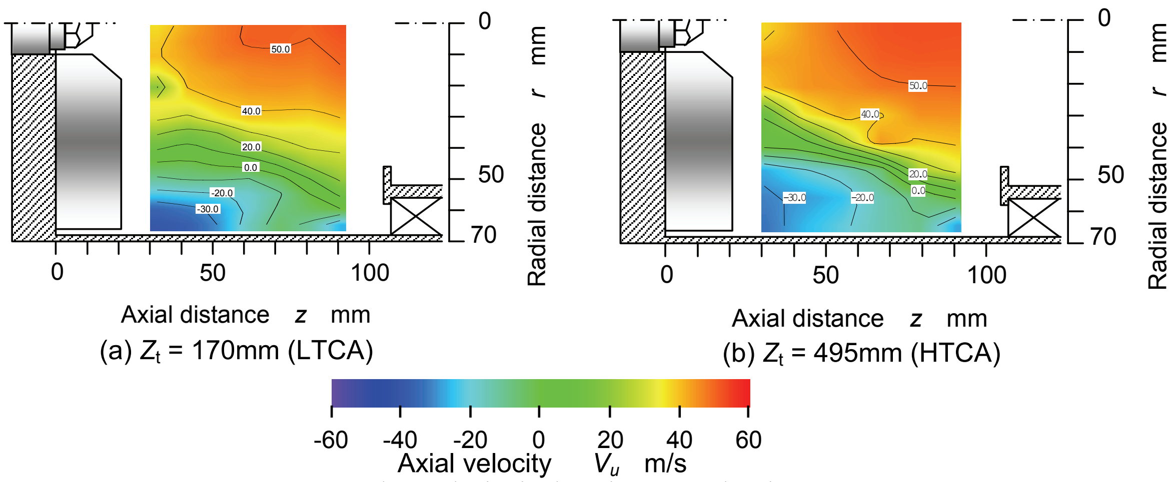

Figure 6. Flow velocity in the primary combustion zone

Distributions of temperature and species concentrations (CO and NOx) in the primary combustion zone

In order to investigate the combustion condition in the primary combustion zone, the distributions of temperature, CO and NOx concentrations were measured in detail. Measurements were carried out in LTCA and HTCA. The measured temperature distributions are shown in Fig. 6. The temperatures were measured by the thermocouple, but the radiation error did not collect in the measurements. Moreover, the fuel droplets probably collided with the thermocouples in the fuel spray. It seems that, therefore, the temperatures shown in this figure are lower than the actual temperatures of combustion gas, because the inner wall of the primary zone was cooled by the combustion air and the temperature of droplets was probably lower than that of combustion gas. In these measurements, the excess air ratio in the primary combustion zone λ_p was set in 1.50, and the fuel flow rate kept constant (M_f=4.3g/s). When *Zt* was 170mm (LTCA), there were high temperature regions (over 1100K) between the swirler plate and the combustor axis. Moreover, the middle temperature regions (over 900K) expanded toward the bottom of the primary combustion zone. From this distribution, it seemed that the flame was held near the swirler plate. When *Zt* was 495mm (HTCA), on the other hand, the high temperature regions disappeared and the region of over 900K became small compared with in LTCA. This result showed that the combustion zone moved to the throat and the secondary combustion zone owing to the increase of combustion velocity mentioned before. The measured distributions of CO and NOx concentrations in the primary combustion zone in HTCA when λ_p = 1.50 and M_f = 4.3g/s are shown in Fig. 8. In the distribution of CO concentration, there were the high concentration regions in z = 40mm and r = 40mm. In the distribution of NOx concentration, it was clear that NOx hardly formed. From this distribution, it was found that NOx was mainly formed in the downstream of the combustor, namely in the throat and the secondary combustion zone.

Effect of preheat of combustion air on fuel spray evaporation

In order to investigate effect of combustion air preheating on fuel spray evaporation, the combustion experiment was carried out using an fuel nozzle which has poor atomization performance. Specifically, the fuel nozzle which has larger rated flow rate (6.0gallon/h) was used, while the nozzle of which rated flow rate was 3.0gallon/h was used in previous sections. The SMD of fuel spray formed with the 6.0gallon/h nozzle was 31.9μm, and that of

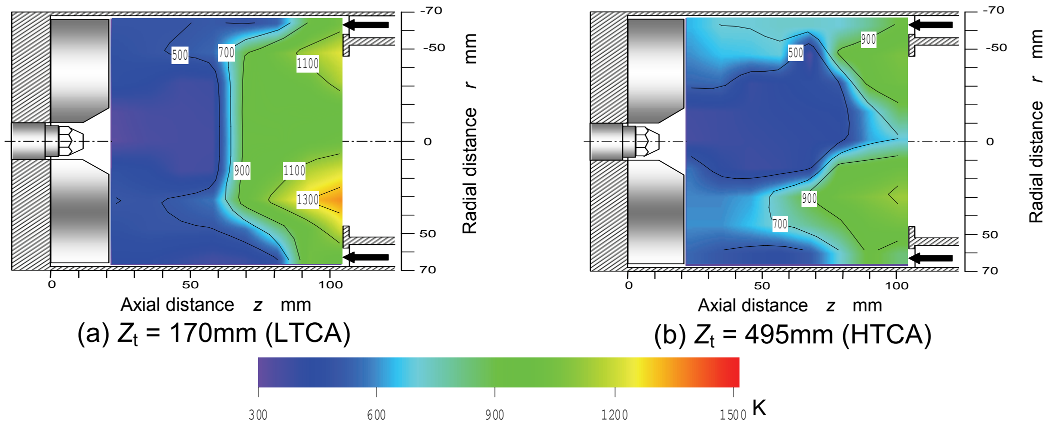

Figure 7. Gas temperature in the primary combustion zone

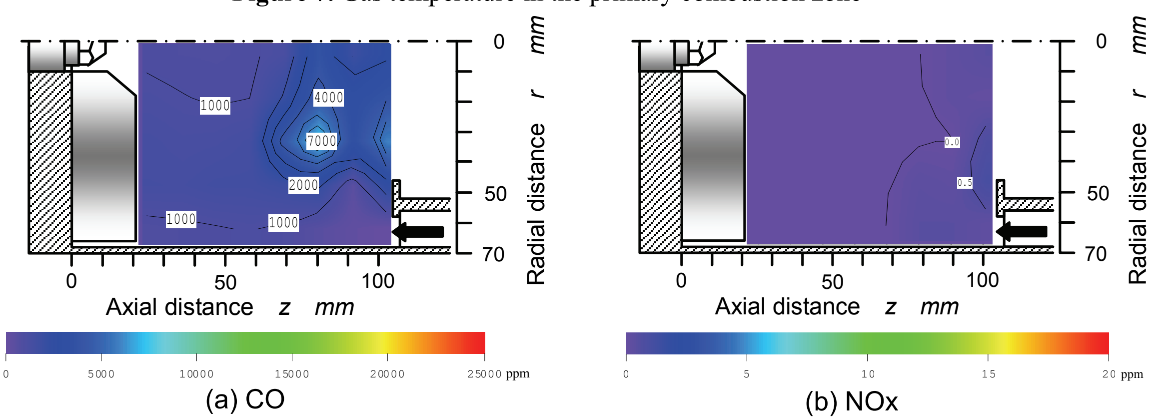

Figure 8. CO and NOx distributions in the primary combustion zone in HTCA (Z_t = 495mm)

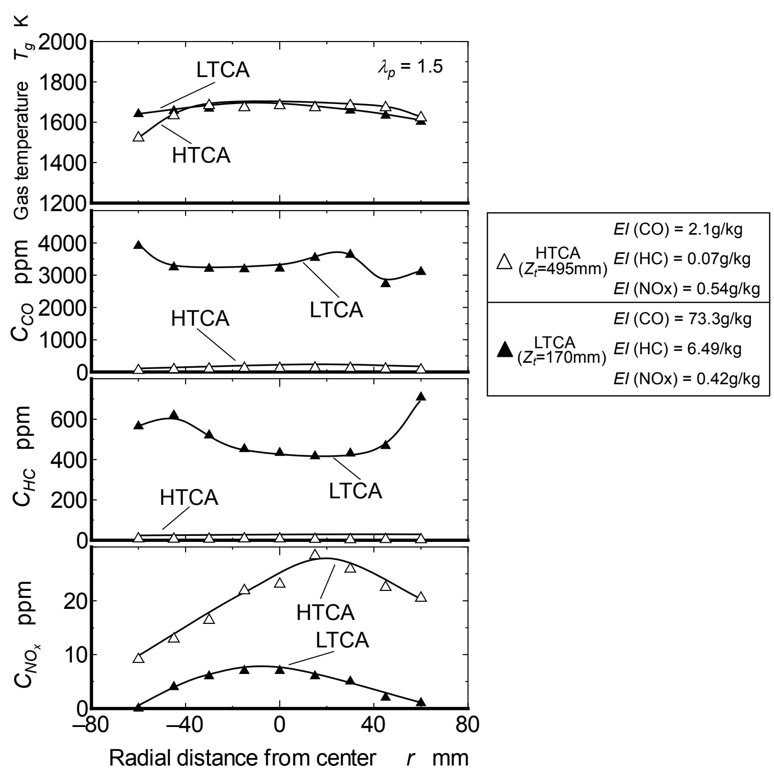

Figure 9. Radial distributions of CO, HC and NOx concentrations and gas temperature

the 3.0gallon/h nozzle was 19.8μm when fuel flow rate was 4.3g/s. The measured radial distributions of temperature, CO, HC and NOx concentrations at the combustor exit are shown in Fig. 9. In this experiment, the excess air rate in the primary combustion zone λ_p was set in 1.50, and the fuel flow rate M_f was 4.3g/s. From this figure, it was clear that the concentrations of CO and HC in HTCA were much lower than those in LTCA. It seemed that the evaporation of fuel spray was promoted by high temperature combustion air, and therefore higher combustion efficiency was achieved in HTCA in spite of poor atomization performance. In LTCA, on the other hand, the evaporation of fuel spray did not finish in the primary combustion zone, and fuel was mainly burned in the secondary combustion zone. Thus, higher concentrations of CO and HC were exhausted. However, NOx concentration in HTCA was much higher than that in LTCA. These results probably showed that the temperature of combustion zone in HTCA was higher owing to combustion air preheating. As for emission indexes of CO, HC and NOx, values of them in HTCA was similar to those using the nozzle of 3.0gallon/h shown in Fig. 5. It seemed that, therefore, combustion condition could be kept in good one by combustion air preheating even if atomization performance of fuel nozzle deteriorated.

Conclusions

In this study, the effect of combustion air preheating on combustion characteristics of the new type combustion with upward swirl for micro gas turbine was investigated experimentally. Characteristics of exhaust gas and distributions of combustion gas velocity, temperature and species concentrations (CO, HC and NOx) in the primary combustion zone were measured, and the relation between combustion air preheating and combustion characteristics of the combustor were discussed. The following results were obtained.

(1) The combustion air temperatures in Z_t = 495mm (HTCA) was around 110K - 160K higher than those in Z_t = 170mm (LTCA).
(2) In HTCA, *EI* (NOx) was high compared with that in LTCA. The increase of *EI* (NOx) was mainly caused by the rise of combustion air temperature.
(3) In HTCA, the axial velocity of combustion gas toward the combustor exit in the primary combustion zone was faster than that in LTCA. The combustion area seemed to move from the primary combustion zone to the secondary combustion zone by the increase of gas velocity.
(4) The evaporation of fuel spray seemed to be promoted by combustion air preheating.

Nomenclature

λ Total excess air ratio
λ_p Excess air ratio in the primary combustion zone
M_a Primary air flow rate
M_f Fuel flow rate
r Radial distance from center
$EI(CO)$ Emission index of CO
$EI(HC)$ Emission index of HC
$EI(NO_x)$ Emission index of NOx
HC Hydrocarbon
T_g Gas temperature
V_u Axial velocity in the primary combustion zone
z Direction of center axis
Z_t Length of casing
α Swirler vane angle
H_g Height of guide vane
Z_p Length of primary combustion zone

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