Proceedings of the International Gas Turbine Congress 2003 Tokyo
November 2-7, 2003

**IGTC2003Tokyo TS-152**

# Study on Pre-vaporized and Premixed Gas Turbine Combustion Technology for High Carbon Ratio Fuel (HCRF)

Youichi MARUTANI[1] , Toshiro FUJIMORI[1], Dirk RIECHELMANN[1], Taku MIZUTANI[1] and Masato MIKAMI[2]

[1]Thermal & Fluid Technology Department, Research Laboratory, Ishikawajima-Harima Heavy Industries Co, Ltd.
1, Shin-Nakahara-cho, Isogo-ku, Yokohama 235-8501, JAPAN
Phone: +81-45-759-2867, FAX: +81-45-759-2210, E-mail: youichi_marutani@ihi.co.jp
[2]Department of Mechanical Engineering, Faculty of Engineering, Yamaguchi University

## ABSTRACT

Lean Pre-vaporized Premixed (LPP) combustion characteristics such as combustion efficiency, NOx, smoke emission and flash back of a High Carbon Ratio Fuel (HCRF) are investigated. Here, Light cycle oil (LCO) is used as a kind of HCRF.

Measurements reveal almost same combustion efficiency levels for LCO and kerosene under air supply condition of 0.5 to 3 MPa, 623-823 K. It is found that NOx emission level of LCO is the same as that of kerosene at low pressure conditions, and that it becomes larger at higher pressure. Smoke emission of the conventional air-blast burner increases rapidly as pressure increase, while that of the LPP burner is almost zero for all conditions. It is further found that flash back occurs at almost same condition for both fuels. This investigation shows that LPP combustion technology is effective for low NOx and low smoke emission combustion of gas turbines for HCRFs.

## INTRODUCTION

Current efforts in efficient use of energy focus on the consumption of fuels derived as byproducts in chemical plants, residual fuels or blended fuels in gas turbine power generation or cogeneration business.

As carbon number of distillate fuel components increases, atomization of spray deteriorates due to higher viscosity. That tends to increase emissions of smoke and unburnt hydrocarbons (UHC) and cause carbon deposit in combustion chamber and nozzles. Also, aromatics, especially multi-ring components, increase the emissions. Among the HCRFs Light Cycle Oil (LCO), which is obtained by Fluid Catalytic Cracking, is one of the fuels expected to be used in gas turbines. It contains only small amounts of heavy metals and other impurities. It is used to adjust the viscosity of heavy oils. However, it contains large amounts of aromatics. Because the Cetane number is below 30, it cannot be used in diesel engines. If it could be used in gas turbines with high efficiency, this would contribute to cleaner exhaust gas and lower $CO_2$ emissions.

Bowden (1983) performed experiments with HCRF in gas turbine combustors. The results show an increase in smoke for fuels with high carbon ratio. It is further known that smoke generation depends rather on C/H ratio than aromatics content. Measures against smoke generation through the use of mono-aromatic distillate fuel in gas turbines are considered by Gadiou etal. (2001). They proved by experiment that water injection or additional use of catalysts are effective. However, no technology for dry combustion of high hydrocarbon ratio C/H without any addition to the fuel is established so far.

Lean pre-vaporized premixed combustion has been developed as a technology for low NOx emissions and commercialized for kerosene. In this method fuel and air are mixed to yield a lean mixture before combustion. Therefore it can be anticipated that beside NOx decreasing effects it may also lead to less smoke. Furthermore, less smoke should lead to lower liner heat-up by radiation; hence, dry burning of fuels with high hydrocarbon ratio should be possible. This research is aimed at the use of LPP combustion of HCRF in gas turbines.

A fuel injection nozzle has been developed which yields homogeneous composition at the exit of the LPP tube for LCO. The nozzle enhances atomization and control distribution of fuel spray in LPP tube. Combustion tests to investigate NOx, smoke emissions of the LPP have been performed at various airflow conditions from aero-derivative high pressure ratio gas turbines to micro-gas turbines. Combustion characteristics of LCO were evaluated by comparison with those of kerosene. Finally, combustion stability has been evaluated from results regarding flash back.

## EXPERIMENTAL APPARATUS

Experiments have been performed with a facility of blow-down type, which can be used to simulate a variety of combustion conditions ranging from high temperature high pressure conditions in derivative gas turbines to conditions in micro-combustors. Highly compressed air is stored in a tank. For the experiment, this air is driven through bricks of a storage heater. Air temperature is controlled by mixing with air of ambient temperature. Even under pressure of 3MPa and temperature of 1000K, experiments can be performed with air flow rates of 10 kg/s for 2 minutes.

The combustor is modeled by 2D-box type combustor mounted in a pressure chamber (Fig.1). Main burners are LPP type. Between the two main burners one pilot burner of conventional air-blast type is set. Figure 2 shows a sketch of the main burner. The nozzle is a pre-filmer air-blast nozzle. Fuel is injected from the ring-shaped slit and mixed with air through the shear flow generated by inner and outer swirled air streams. Swirl strength and flow rate distribution are optimized with respect to fuel concentration at the LPP exit and flame stability. Fuel concentration at the LPP exit has been measured by traversing a sampling probe in radial direction for non-reacting flow. The connecting tube between sampling probe and gas analyzer is heated in order to prevent condensation. The sampled gas is completely oxidized by a catalyst; then, fuel concentration is estimated from the $CO_2$ concentration.

R-type thermocouples are used to measure liner and exhaust gas temperature. A water-cooled sampling probe is used to measure

Manuscript Received on April 16, 2003

NOx, $O_2$, CO, $CO_2$ and UHC in the exhaust gas. Again, the connection between sampling probe and analyzer is heated to prevent water condensation. Smoke is sampled by driving 3LN (liter at standard condition, i.e. 273.16K, 10132Pa) of exhaust gas through a filter. Behind the filter, the sample gas is released to the ambient air. In order to prevent carbon from settling down in the sampling line, preheated air has been blown through the line after each sampling. The surface area of the filter is $8 \pm 0.24\text{cm}^2$. A Bosch smoke meter has been used to measure the deposits optically and estimate the particulate concentration. Regarding the flash back experiments, the air flow rate has been fixed and fuel supply to the LPP burner increased. Then, the fuel flow rate where flash back occurs has been measured. The LPP tube is made of glass to allow recording by high speed camera. Here, we define flash back as the situation where a hot flame is stable localized in the LPP tube.

## FUEL PROPERTIES

The properties of LCO and JIS No.1 kerosene as used in the experiments are compared in Table 1. The sample fuel used is LCO with larger density, viscosity and C/H ratio than kerosene. The 50% BP of the fuels is almost the same. However, the distillation temperatures for LCO extend over a wider range than kerosene (10% BP is 16 degree lower, 90% BP is 48 degree higher). Also, for LCO the concentration of aromatics is higher, resulting in a lower Cetane number and a lower smoke point. Therefore, it is difficult to use LCO for diesel engines. Gas turbine combustor of diffusion type may cause problems of higher smoke emission and higher liner temperature.

The effect of experimental conditions on the evaporation properties is examined by model calculations. For this purpose the fuels are analyzed and the species with high boiling points are identified. Here, n-tridecane (BP=243℃) for kerosene and n-nonylbenzene (BP=282℃) for LCO are chosen, which boiling point is close to the 90% BP. For the evaporation analysis the initial droplet diameter is defined as follows. From El-Shanawany etal (1980) SMD for an air-blast atomizer can be approximated by the following equation.

$$\frac{SMD}{D_h} = \left(1 + \frac{1}{ALR}\right)\left[0.33\left(\frac{\sigma}{\rho_A U_A{}^2 D_p}\right)^{0.6}\left(\frac{\rho_L}{\rho_A}\right)^{0.1} + 0.068\left(\frac{\mu_L{}^2}{\rho_L \sigma D_p}\right)^{0.5}\right]$$

Here, $ALR$ denotes air-to-liquid mass ratio, $\mu_L$ fuel viscosity, $\rho_L$ fuel density, $\sigma$ surface tension, $\rho_A$ air density, $U_A$ air velocity, $D_P$ prefilmer diameter and $D_h$ hydraulic mean. From $SMD$, the initial diameter of the 90% BP species, i.e. n-tridecane or n-nonylbenzene, is obtained by assuming that the droplet volume is reduced to 10%, namely,

$$d_0 = \left(0.1 SMD^3\right)^{1/3}$$

Evaporation time is estimated following the method of A.H.Lefebvre (1989) by considering heat up and evaporation as follows:

$$t_e = \frac{d_0^2 - d_1^2}{\lambda_{hu}} + \frac{d_1^2}{\lambda_{st}}$$

Here, $d_1$ denotes droplet diameter at end of the heat-up period, $\lambda_{hu}$ the evaporation constant during heat-up period and $\lambda_{st}$ the evaporation constant during steady-state. Figure 3 shows the effect of flow velocity, temperature and pressure on evaporation time. It is seen that an increase of flow velocity, temperature and/or pressure yields shorter evaporation times. Furthermore, the evaporation time for LCO is approximately 30% longer than for kerosene at all conditions.

## FUEL INJECTION NOZZLE FOR HCRF

LCO has higher viscosity than kerosene and contains more compounds with high boiling point. Therefore, the evaporation distance is longer than for kerosene. In a LPP tube with strong swirl, a larger droplet diameter and a longer evaporation distance leads to an increased drift of fuel towards the outer walls by centrifugal force, which then causes higher local fuel concentrations and higher NOx emissions. Furthermore, delayed evaporation causes impact of spray to the LPP tube walls and the liner; then, complete combustion becomes difficult to achieve, combustion efficiency decreases, flash back and carbon deposit occur. In order to solve these problems, a burner is needed which prevents fuel accumulation in the outer regions and promotes homogeneous fuel distribution. To achieve this, a good mixing must prevail and profile of fuel distribution must be well controlled in the LPP tube.

The center flow of the LPP air-blast nozzle is straight so that less spray is carried to the outer regions as would happen due to centrifugal forces in swirled flow. Fast mixing is achieved by taking advantage of vortex breakdown in the downstream part of the LPP tube. The velocity fluctuations within the LPP tube are measured by LDV. The model for the LDV measurements is 2 times larger than the burner model; measurements are done at ambient conditions. Figure 4(a) shows rms of flow velocity in the LPP tube. It is much larger for a swirl angle of 1. Two peaks in axial velocity (Fig.4(b)) can be explained with the existence of vortices, which then break down and lead to good mixing.

Figure 5(a) shows profiles of fuel concentration at the exit of the LPP tube. An almost flat profile of local equivalence ratios is achieved by adjusting the swirl strength of the outer air flow. The profiles show local peaks around shear layer between the inner and outer flow for non-dimensional swirl angles of 0.33 and 0.67, while the peak locates at the center for an angle of 1. Figure 5(b), (c) show the effects of flow velocity and temperature on fuel concentration at the LPP tube exit. It is readily seen that increase of temperature leads to higher concentrations in the center and lower concentrations in the outer region. Higher flow velocity enhances fuel atomization and, hence, decreases the initial diameter of spray droplets. So, less spray is driven to the outer region by centrifugal forces and, by this, lower fuel concentration is achieved there. Higher temperature enhances evaporation. Then, for the same reasoning as in the case of velocity increase, lower fuel concentrations are obtained. LCO tends to show higher fuel concentrations in the outer regions than kerosene due to poor atomization and lower evaporation rate. The burner used here is especially designed for yielding favorite concentration profiles.

## NOX EMISSION AND COMBUSTION EFFICIENCY

Figure 6 shows the effect of flow velocity on NOx emission and combustion efficiency. Here, LPP equivalence ratio denotes the average equivalence ratio at LPP tube exit. Combustion tests have been performed with swirl angle 1. It is seen from Fig. 6(a) that lower NOx emissions are obtained for higher flow velocity. For LPP equivalence ratio of 0.6, NOx is reduced by 70%. As the flow velocity increases, atomization of the spray is enhanced and fuel concentrations in the outer region at the exit of the LPP tube become lower. The characteristics result in lower NOx emission levels. From Fig. 6(b) it is seen that an increase in flow velocity does not affect combustion efficiency largely. Investigation of the relation between combustion efficiency and NOx emission reveals that best results are obtained for a flow velocity of 1.9 (see Fig.6(c)). Reduction of NOx emission by 70% is larger than can be ascribed to the decrease of residence time which may be estimated as (1/1 – 1/1.9)*100=47%. This larger reduction is believed due to improved fuel atomization and then fuel concentration profile. The fact that combustion efficiency could be sustained at the same level is caused by enhanced fuel atomization and evaporation (Fig. 3(a)). As a result, less of the fuel spray moves to the walls and possibly attaches to them.

At a flow velocity of 1.9, the pressure drop is about 5%, which is reasonable for actual applications. In conclusion of the above mentioned results, with the nozzle designed here good results can be expected for LCO combustion. Therefore, in the following experiments have been performed with flow velocity 1.9.

In the following, characteristics of LCO combustion are compared with those of kerosene. Figure 7(a) shows the change of NOx emission with LPP equivalence ratio for different gas temperatures at 0.5MPa and a mean non-dimensional flow velocity of 1.9. It is readily seen that the NOx emissions from LCO are the same as those from burning kerosene. At lower combustion pressure, formation rate of NOx is slow compared to mixing rate of the combustion gas. Therefore, difference in EINOx between LCO and kerosene is small.

Combustion efficiency shows the same dependency on Tout regardless of T (Fig. 7(b)). Here, Tout is the average temperature measured at the exit of the combustor that includes the pilot combustion and cooling gas. The curves of combustion efficiency vs. Tout coincide for both fuels. Burning velocity of the premixed gas primarily affects combustion efficiency. The result indicates that the burning velocity of LCO is almost the same as that of kerosene at the same flame temperature.

Figure 7(c) shows the trade-off between combustion efficiency and NOx emission. Note that the combustion efficiency considered here is everywhere above 99%. For higher equivalence ratio, and thus higher NOx emissions, combustion efficiency levels off, but does not reach 100%. Calculations show that evaporation takes more time for LCO than for kerosene and that there is a tendency to longer times for lower temperatures (Fig. 3(b)). Therefore one can conclude that the lower combustion efficiencies for lower temperature are due to less fuel evaporation and, hence, fuel attachment to the LPP tube wall.

The change of NOx emission and combustion efficiency with pressure at fixed temperature of 550℃is shown in Fig. 8(a), (b). Combustion efficiency (Fig. 8(b)) is the same for both fuels. The higher NOx levels of LCO for the higher pressures (Fig. 8(a)) are ascribed to inhomogeneous fuel concentrations. As shown by Fujimori etal. (2001) NOx generation is strongly affected by non-uniformity in fuel concentration at higher pressures. Production rate of NOx increases as pressure rises, and it becomes comparable to mixing rate of the combustion gas. Therefore, at higher pressures only small variations in fuel concentration can easily lead to higher NOx emission. Also, the flame is established closer to the exit of the LPP nozzle as pressure increases. At low pressure no difference in NOx emission can be observed for LCO and kerosene. For high pressure, on the other hand, LCO tends to show higher NOx emissions than kerosene, especially for higher equivalence ratios. Under low pressure, production rate of thermal NOx is low, and, hence, NOx emissions can be expected to be comparable even for different fuel concentrations. Under higher pressure, there are almost no differences in the evaporation properties between the fuels; however, for the LPP tube considered here one can suppose that, although differences in evaporation properties are quite small, the fuel concentration at the location of the flame is affected, and this may cause differences in NOx emissions. In this context, more investigations are needed regarding fuel evaporation and the relation between fuel concentration at the LPP tube exit and NOx emission.

For LCO the evaporation time is longer than for kerosene, so higher non-uniformity in fuel concentration can be expected; this dose finally cause higher NOx levels.

### SMOKE GENERATION AND LINER TEMPERATURE

Figure 9 shows smoke emission versus pressure. Compared are emissions caused by firing kerosene (indicated by Main KR) with those caused by firing LCO (indicated by Main HCRF). Here, the smoke emission is found by subtracting the smoke emission from the pilot (where kerosene is burnt) from the total smoke emission. In Fig. 9, Pilot KR and Pilot HCRF indicate smoke emission for conventional non-premixed combustion. Over all equivalence ratio of the LPP burner and the pilot burner are set to 0.22 and 0.040 respectively for all smoke measurements. Then LPP equivalence ratio becomes 0.45. For pressures below 1MPa no smoke emission has been detected. At 2MPa, smoke emission is below 1/10 of the pilot emission. The reason for this good result is a consequence of good mixing before combustion sets in.

The liner temperature (Fig.10) increases by less than 10℃ when firing LCO, proving the successful nozzle design. LPP combustion of LCO yields flames with less luminescence and, hence, less heat transfer to the liner walls by radiation.

### COMBUSTION STABILITY (FLASH BACK)

Flash back has been investigated by observation with a high speed camera (Fig.11). The pictures show that the flame enters the LPP tube in the center, propagating in upstream direction. Since no self-ignition is observed, locally higher fuel concentrations leading to higher flame propagation speeds are considered to cause the flash back.

Figure 12 shows the change of equivalence ratio at which flash back occurs as functions of temperature, flow velocity and pressure, respectively. Reference point is the equivalence ratio at 550℃, 2MPa and non-dimensional flow velocity of 1.9. It is readily seen that flash back behavior is the same for both fuels. The critical equivalence ratio decreases with temperature. The increase in flame propagation speed is considered to cause this trend. For larger flow velocities flash back occurs at higher fuel concentrations, showing that the increase in turbulent propagation speed is not enough to compete with the flow velocity. Flash back under higher pressures occurs at lower fuel concentrations. Since the effect of pressure on turbulent flame propagation speed is not sufficiently understood, the trends shown in Fig. 12(c) cannot be explained by now.

### CONCLUSIONS

With the purpose of developing a combustor for the dry combustion of High Carbon Ratio Fuels, combustion experiments have been performed with Light Cycle Oil as one representative of HCRF. The results are summarized as follows.

- A nozzle which realizes rapid mixing by vortex break down and favorable profile of fuel concentration for LCO has been developed.
- A large NOx reduction could be achieved by increased flow velocity, which enhances atomization and evaporation. As pressure increases, NOx emissions become sensitive to non-uniformity in fuel concentration. NOx emission for LCO is higher than for kerosene at high pressure conditions over 1 MPa.
- By increase of flow velocity same levels of combustion efficiency are achieved for LCO as for kerosene at pressures in the range 0.5 to 3 MPa.
- The generation of smoke is reduced to less than 1/10 of that for common air blast nozzles.
- The combustion stability for LCO is almost the same as for kerosene.

From the above it is concluded that LCO can be economically burnt at same levels of NOx emission, combustion efficiency, smoke generation and flame stability as kerosene, when dry combustion with LPP tube is applied.

## ACKNOWLEDGEMENT

This work has been performed under the management of Japan Space Utilization Promotion Center as the NEDO R&D project “Fuel Diversification Combustion Technology”.

## REFERENCES

Bowden, T. T. and Pearson, J. H. (1983), “The influence of fuel composition upon soot emissions and flame radiation in a model gas turbine combustor,” International Conference on Combustion in Engineering, Vol. 2, C70/83, pp. 105-112.

Naegeli, D. W., and Moses, C. A. (1978), “Effect of fuel properties on soot formation in turbine combustion,” SAE 781026., Aerospace Meeting Town & Country, San Diego November 27-30.

Blazowaki, W. S. (1979), “Dependence of soot production on fuel blend characteristics and combustion conditions," ASME 79-GT-155.

Bowden, T. T., Pearson, J. H., and Wetton, R.J. (1984), "The influence of fuel hydrogen content upon soot formation in a model gas turbine combustor", ASME 84-GT-6.

Gadiou, R. (2001), "Combustion of Aromatic distillates fuels in gas turbines: impact on gaseous emissions," CIMAC congress, Hamburg, pp. 401-412.

Ikezaki, T., Hosoi, J., Fujimori, T. and Saito, T. (2001), "The performance of the low NOx aero gas turbine combustor under high pressure," ASME 2001-GT-0084.

Fujimori, T., Saito, T., Mizutani, T. and Marutani, T. (2001), "Experimental investigation of a lean premixed and pre-vaporized combustor in high temperature and high pressure conditions," CIMAC congress 2001, Hamburg, pp. 414-421.

El-Shanawany, M. S. M. R., and Lefebvre, A. H. (1980), "Airblast atomization: The effect of linear scale on mean drop size," J. Energy, Vol. 4, pp.184-189.

Lefebvre, A.H. (1989) "Atomization and Sprays", Taylor & Francis, pp. 311-339.

Table 1 Properties of test fuels

| | | | | | | | | | Distillation temperature ℃ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Higher Heat Value MJ／kg | Density @15℃ g/cc | Cetane Number (CNO) | Kinetic viscosity mm2/s @30℃ | C/H (mol/mol) | Carbon wt% | Hydrogen wt% | Smoke Point, mm | IBP | 10% | 50% | 90% | FBP 97.5% |
| HCRF(Light cycle oil) | 44.5 | 0.874 | 28 | 1.77 | 0.64 | 88.3 | 11.5 | 8 | 94 | 163 | 205 | 288 | 322 |
| Kerosene | 46.3 | 0.795 | | 1.35 | 0.52 | 86.0 | 13.9 | 23 | 160 | 179 | 201 | 240 | |

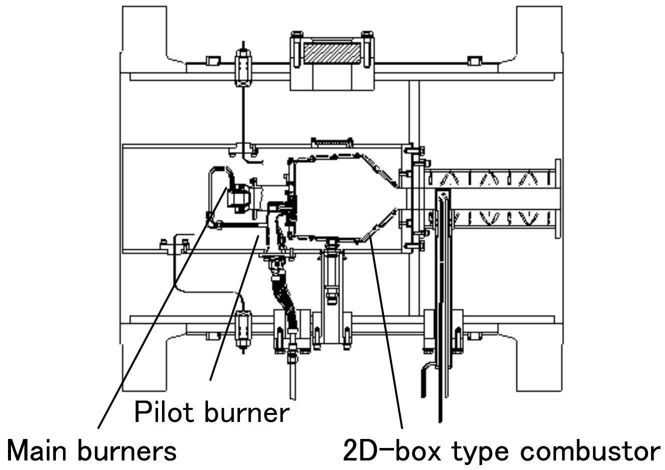

Fig. 1 High pressure, high temperature two-dimensional model combustor test rig

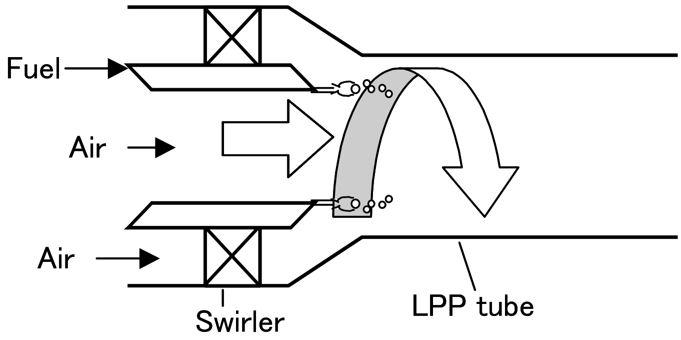

Fig. 2 Injection nozzle and lean pre-vaporized premixing tube

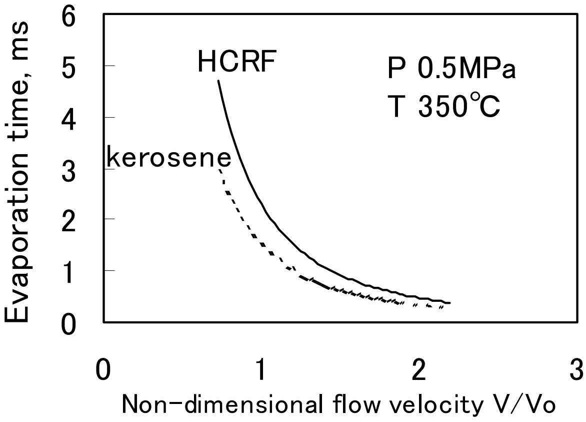

Fig. 3(a) Effect of flow velocity on evaporation time (calculation)

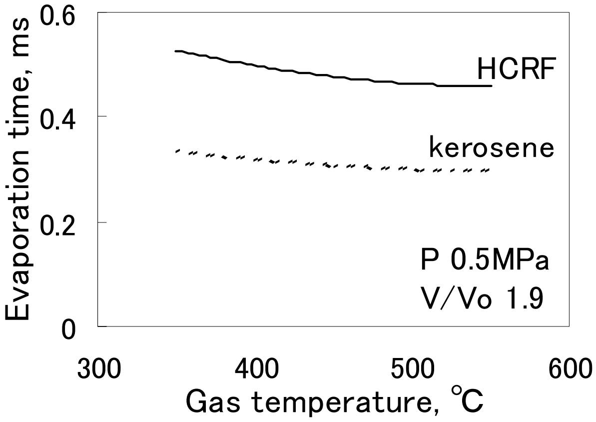

Fig. 3(b) Effect of gas temperature on evaporation time (calculation)

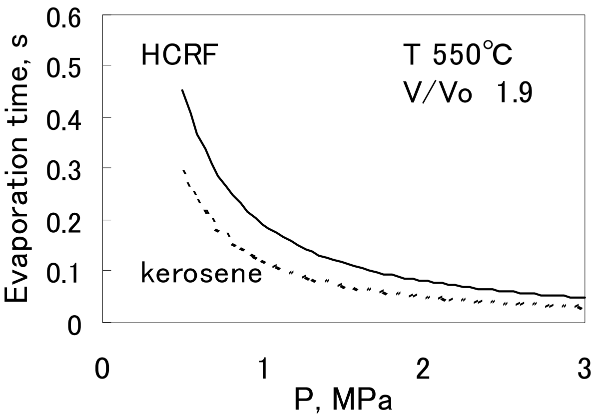

Fig. 3(c) Effect of gas pressure on evaporation time (calculation)

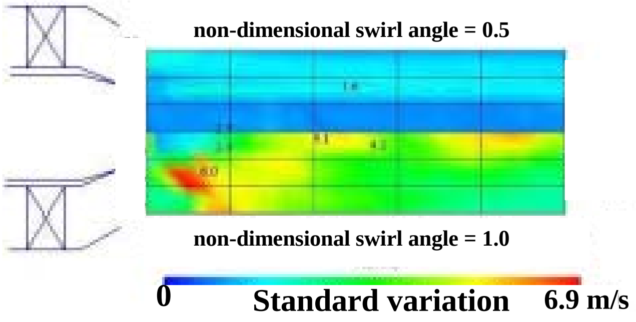

Fig. 4(a) Standard variation of flow velocity in a LPP tube

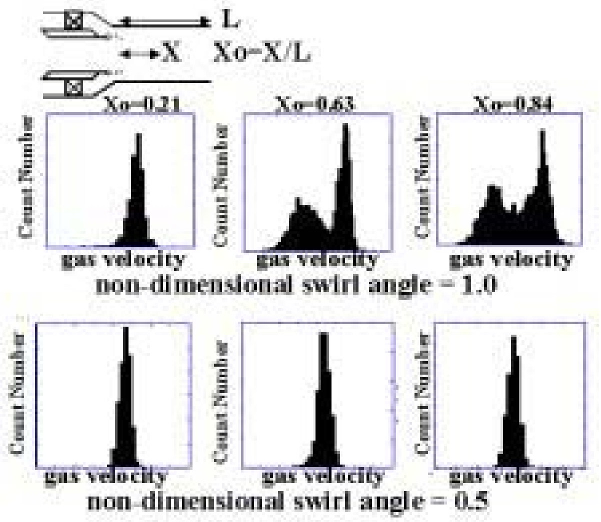

Fig. 4(b) Variance of axial velocity component

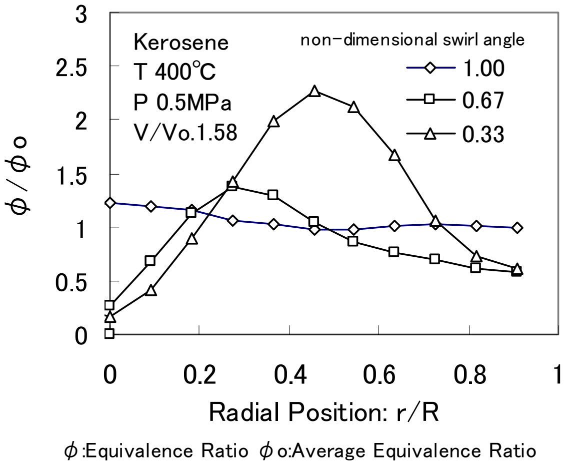

Fig. 5 (a) Effect of swirl angle on fuel concentration at LPP burner exit

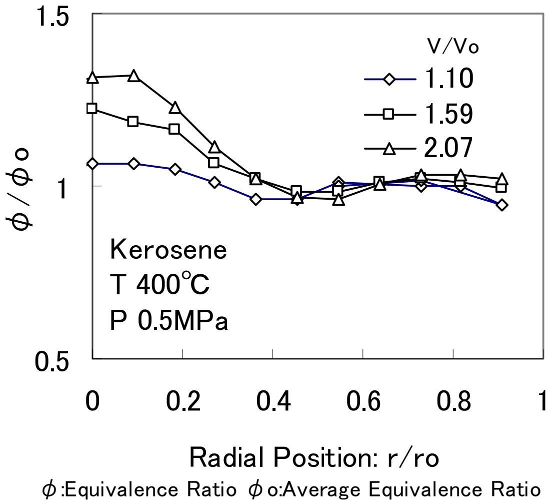

Fig. 5(b) Effect of LPP gas velocity on fuel concentration at LPP burner exit

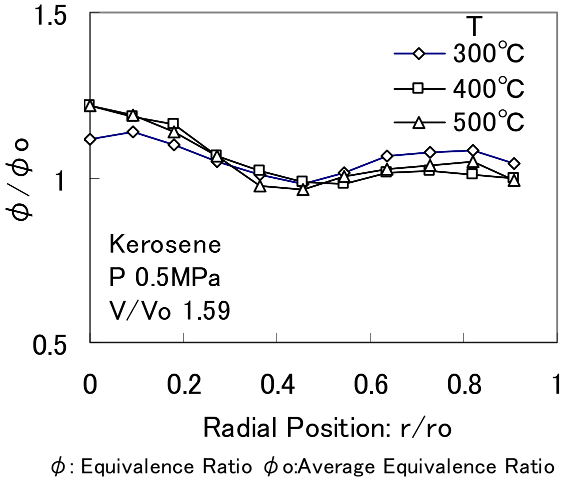

Fig. 5 (c) Effect of LPP gas temperature on fuel concentration at LPP burner exit

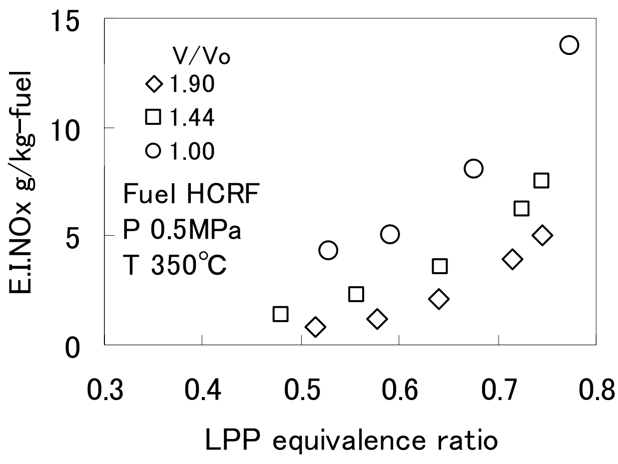

Fig. 6(a) Effects of gas velocity on NOx emission

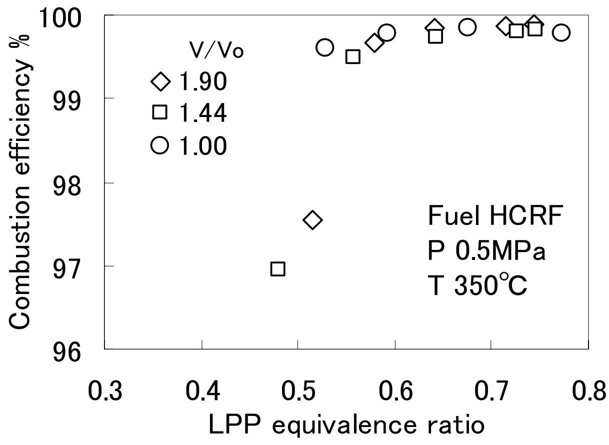

Fig. 6(b) Effect of gas velocity on combustion efficiency

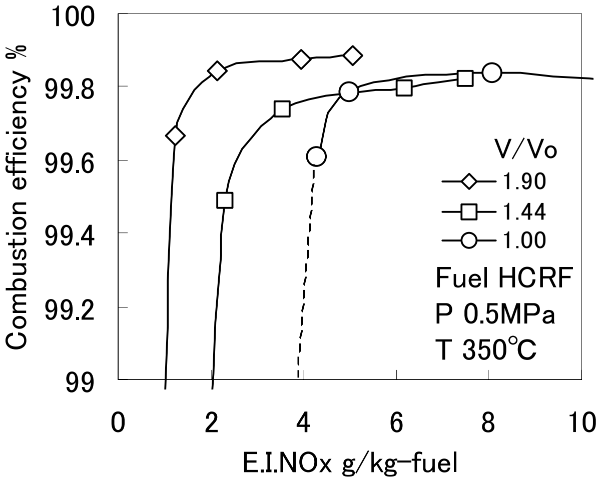

Fig. 6(c) Trade-off between NOx emission and combustion efficiency for various flow velocities

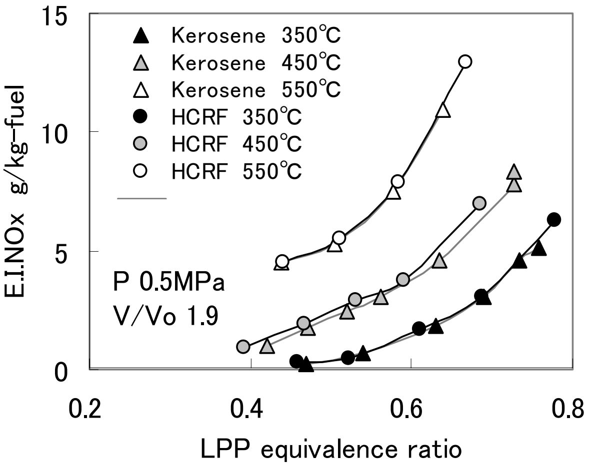

Fig. 7 (a) Effect of gas temperature on NOx emission

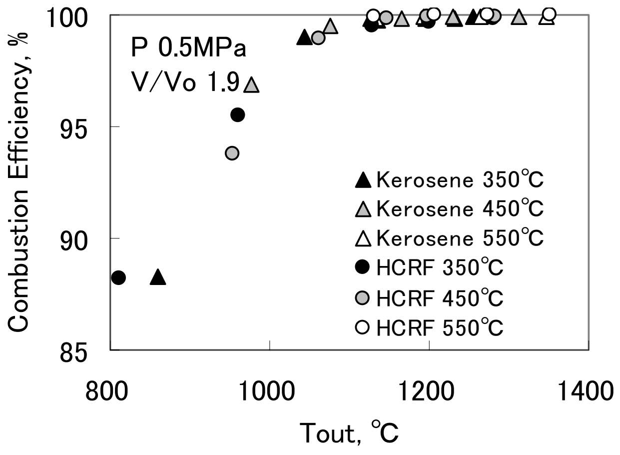

Fig. 7 (b) Relation between exhaust gas temperature and combustion efficiency

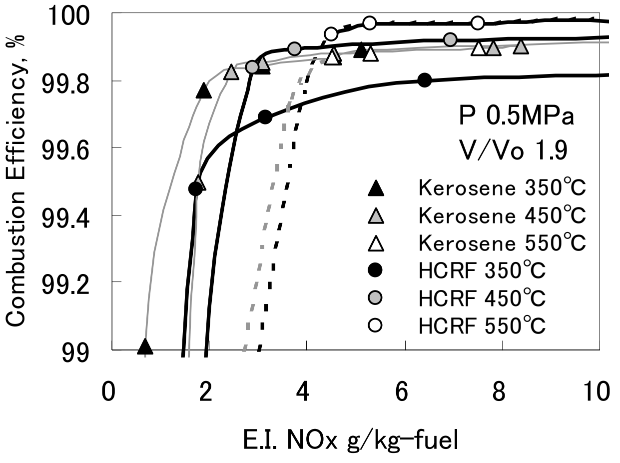

Fig. 7 (c) Trade-off between NOx emission and combustion efficiency for various temperature

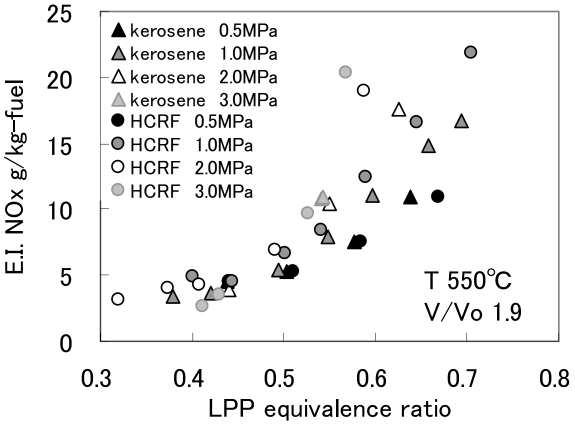

Fig 8(a) Effect of gas pressure on NOx emission

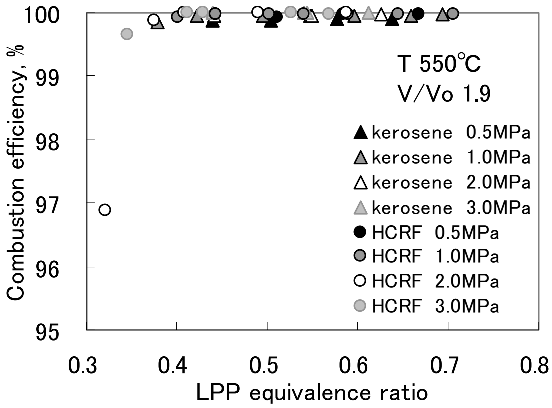

Fig. 8(b) Effect of gas pressure on combustion efficiency

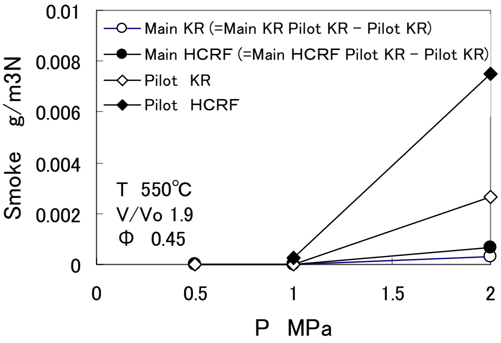

Fig. 9 Smoke emission

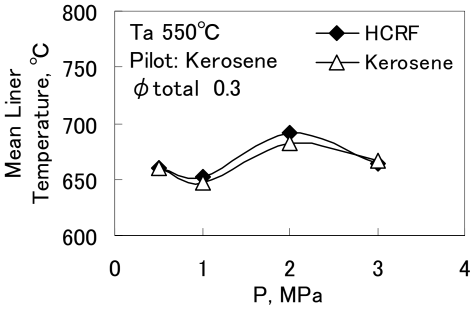

Fig. 10 Liner temperature

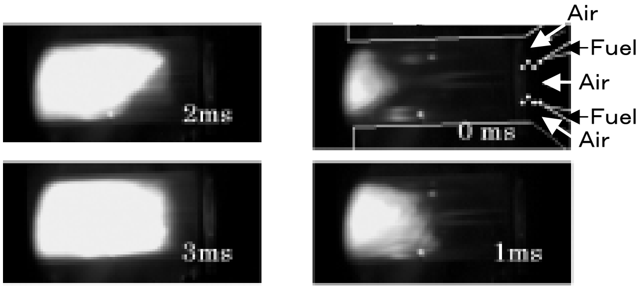

Fig. 11 Image of flash back. (P2.0MPa , Ta550℃)

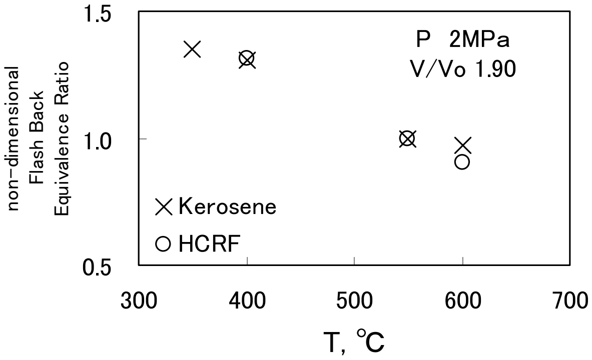

Fig. 12(a) Effect of gas temperature on flash back

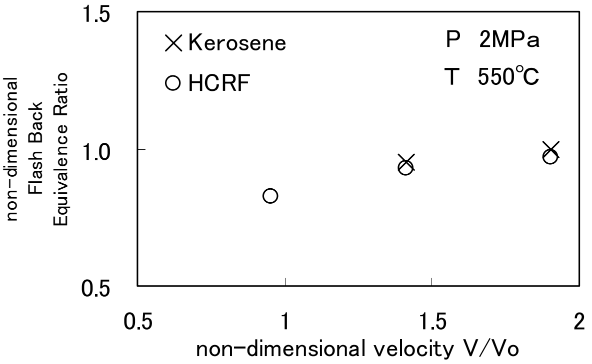

Fig. 12(b) Effect of LPP flow velocity on flash back

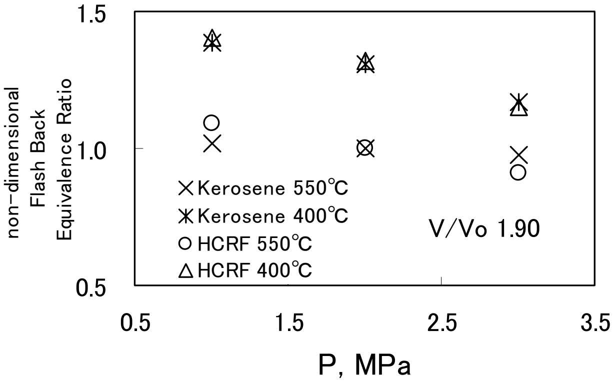

Fig. 12(c) Effect of gas pressure on flash back