EVAPORATION CHARACTERISTICS OF SPRAY IN A LEAN PREMIXED-PREVAPORIZATION COMBUSTOR FOR A 100 KW AUTOMOTIVE CERAMIC GAS TURBINE

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ABSTRACT
Spray characteristics of liquid fuel air-assisted atomizers developed for a lean premixed-prevaporization combustor were evaluated under two kinds of conditions: in still air under non-evaporation conditions at atmospheric pressure and in a prevaporization-premixing tube under evaporation conditions with a running gas turbine. The non-evaporated mass fraction of fuel spray was measured using a phase Doppler particle analyzer in the prevaporization-premixing tube, in which the inlet temperature ranged from 873K to 1173K. The evaporation of the fuel spray in the tube is mainly controlled by its atomization and distribution. The NOx emission characteristics measured with a combustor test rig were evaluated with three-dimensional numerical simulations. A low non-evaporated mass fraction of less than 10% was effective in reducing the exhausted NOx from lean premixed-prevaporization combustion to about 1/6 times smaller than that from lean diffusion (spray) combustion. The flow patterns in the combustor are established by a swirl chamber in fuel-air preparation tube, and affect the flame stabilization of lean combustion.

NOMENCLATURE
- \( D_{90} \): spray diameter of 90% by volume <\( \mu \)m>
- \( E_{\text{NOx}} \): NOx emission index <NO\(_x\)/kg-fuel>
- \( G \): mass flow rate <g/s>
- \( \text{NMF} \): non-evaporated mass fraction of fuel spray <wt.%>
- \( P \): pressure <MPa>
- \( R \): radial position <mm>
- \( \text{RMS} \): root mean square of velocity <m/s>
- \( \text{SA} \): spray cone angle <degree>
- \( \text{SMD} \): Sauter mean diameter <\( \mu \)m>
- \( T \): temperature <K>
- \( V \): velocity <m/s>
- \( V_{\text{D}} \): validation of data measured by PDPA <\%>
- \( V_{\text{F}} \): volume flux <cc/s/cm\(^2\)>
- \( Z \): stream axis <mm>
- \( \theta \): circular angle <degree>
- \( \lambda \): excess-air-ratio
- \( \rho \): specific gravity <g/cc>

SUBSCRIPTS
- \( a \): air
- \( d \): droplet
- \( f \): fuel
- \( i \): initial or inlet condition
- \( p \): primary
- \( z \): Z axis

INTRODUCTION
The ceramic gas turbine is expected to be one of the promising automotive engines for various applications in the next generation because of its potential for achieving high thermal efficiency and low pollutant emissions. A 100 kW automotive ceramic gas turbine was equipped with a high-efficiency regenerator to reduce fuel consumption at partial load conditions. It was designed so that the air temperature at the combustor inlet rises to be the range of 973K to 1373K, and the gas temperature at the combustor outlet reaches 1623K. A thermal efficiency of more than 40% is aimed for in the Japanese 100 kW automotive ceramic gas turbine (CGT) project. As a part of this project, a lean premixed-prevaporization combustor (LPP combustor) [1] has also been developed, because it enables substantial reduction of NOx without exceeding the CO emission level. The target emission...
performance set for the engine is to meet the Japanese 10-15 mode emission standards (NOx $\leq 0.25$ g/km, CO $\leq 2.1$ g/km, HC $\leq 0.25$ g/km) for gasoline engine passenger cars without using an aftertreatment system. The Petroleum Energy Center (PEC), with the support of the Ministry of International Trade and Industry, has been working on this project since the 1990 fiscal year. Japan Automobile Research Institute, Inc. has been participating in the project along with members of the petroleum industry. This study is a part of the automotive ceramic gas turbine development program of the PEC.

In the last two decades, LPP combustors have been studied mainly for the application to aircraft engine gas turbines. However, they have severe limitations to be overcome, that is, autoignition, flashback, and narrow range flame stabilization conditions in lean premixed combustion. In order to maintain reduced NOx emission and flame stabilization, strict control of the fuel-air-ratio in the combustion zone is needed. Therefore, combustors with variable geometry have been studied [2-9]. Many papers have also been published on the subjects of LPP combustors. They include studies on spray characteristics of the fuel injectors and evaporation characteristics of fuel spray in the preparation tube[10,11], the mechanisms of autoignition and flashback in the prevaporization-premixing tube [12-15], exhaust emission characteristics of lean premixed combustion [16,17], and the effect of fuel-air unmixedness on the NOx formation [18-20].

An automobile engine is generally operated at light load, and rapid response of the output power to frequent acceleration and deceleration is required. In order to satisfy this requirement, rapid response of the fuel supply system and wide turn-down-ratio of more than 45 of fuel atomization must be realized. This means that the design of a fuel injector and a prevaporization-premixing tube (PP-tube) is one of the key subjects for the promotion of evaporation of fuel droplets, the mixing of fuel vapor with air in a limited space, and the prevention of flashback/autoignition in a high temperature flow field.

The aim of this study is to clarify the knowledge of evaporation characteristics for design improvement of a fuel atomizer and a preparation tube which consists of a PP-tube and a swirl chamber. In this paper, the following topics are presented: (1) Fuel injectors which obtain a fine spray of less than 30μm in SMD are discussed. Spray characteristics and local structure within the spray were measured with a phase Doppler particle analyzer (PDPA). (2) Evaporation characteristics of the fuel spray were evaluated in the PP-tube at high velocity and high temperature. The degree of evaporation measured in the experiments was higher than that calculated by numerical simulations. (3) The influence of the non-evaporized fuel content in the combustion chamber on the NOx formation was compared for calculations and experiments. In the calculations, the non-evaporized fuel content was varied by the method of forming the fuel-air premixture before it entered into the combustion chamber. It was confirmed that the reduced NOx can meet the emission standards when the non-evaporated mass fraction, which is defined as the rate of total non-evaporated droplets divided by fuel flow rate, is less than 10% with excess-air-ratio of 2 to 3.

**RUNNING CONDITIONS OF 100 KW AUTOMOTIVE CGT**

In automotive ceramic gas turbine, the running conditions simulated the Japanese 10-15 modes are maximum fuel flow rate of 2 g/s, maximum air flow rate of 200 g/s and combustor inlet temperature of 973-1373K. The range of the required fuel flow rate is from 0.2 g/s to 6 g/s as the result of the cycle simulation. Figure 1 shows the fuel supply system of the 100 kW automotive CGT. As listed in Table 1, maximum fuel supply pressure is specified to be 6 MPa because pressure endurance of the fuel metering unit is limited. The fuel supply system has two lines of fuel supply, that is, a primary injector and a secondary injector, to obtain the turn-down-ratio of more than 45. The primary injector is used in the lean premixed-prevaporization combustion under light part load conditions. The secondary injector, which forms a diffusion flame, is used in starting, accelerations and heavy load conditions. In the mode operation, the primary injector is used solely so that the exhaust can meet the Japanese emission standards.

**LEAN PREMIXED-PREVAPORIZATION COMBUSTOR**

Figure 2 shows the schematic construction of a LPP combustor. The minimum fuel flow rate required for the primary injector is as small as 0.2 g/s. A single-hole-type injector was adopted instead of a multi-hole-type injector to prevent the clogging of the injection hole with solid particle contamination of fuel and to stabilize the fuel supply. The mixture of prevaporized fuel vapor and air is formed in the PP-tube and introduced into the swirl chamber in the tangential direction. The premixture of fuel vapor and air with swirl velocity is introduced into the combustion chamber through a flameholder. The amount of the air flow through the PP-tube is controlled to produce an excess-air-ratio of 2 to 3 by a mechanism which varies the flow area at the outlet of the flameholder. The flame in the lean combustion zone is held in a recirculation field formed by the flameholder wake and the swirled flow of the premixture. The burning gas in the dilution zone is mixed with fresh air to reduce the gas temperature and make the temperature distribution uniform at the inlet of the turbine rotor.

**FUEL INJECTOR**

Figure 3 shows a construction of the fuel injector developed for the combustor of the 100 kW automotive CGT. The fuel injectors, INJECTOR TYPE 1 and TYPE 2, are combined with a swirled airstream which assists atomization and distribution of the fuel. INJECTOR TYPE 1 is a pressure-swirl atomizer surrounded by a rapid airstream swirled by a vane set in the air path. This injector requires atomization air at a rate of more than 2 g/s. The injection...
velocity of the atomization air is more than 75m/s at atmospheric pressure.

A fine spray is formed by a large amount of atomization air. However, the target spray characteristics need to be achieved by as small amount of air as possible to reduce the power consumption for compressing air. In still air at atmospheric pressure, fuel supply pressure, spray cone angle and spray diameter were measured for fuel sprays of the primary injector as shown in Figures 4. The spray diameter is represented by 90% of the droplets by volume that can be measured with a laser diffraction drop size analyzer. As shown in the figure, INJECTOR TYPE 1 produces the target spray characteristics with less air supply and power consumption than INJECTOR TYPE 2. The properties of the test fuel are listed in Table 2.

**FIG. 4 SPRAY CHARACTERISTICS OF PRIMARY INJECTORS**
TABLE 2 PROPERTIES OF TEST FUELS

<table>
<thead>
<tr>
<th></th>
<th>Kerosene (JISNo.1)</th>
<th>Gas Oil (JISNo.2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>0.782</td>
<td>0.825</td>
</tr>
<tr>
<td>(at 25°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viscosity</td>
<td>1.37</td>
<td>3.68</td>
</tr>
<tr>
<td>(at 23°C) cSt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface tension</td>
<td>25.0</td>
<td>27.6</td>
</tr>
<tr>
<td>mN/m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latent heat of</td>
<td>62</td>
<td>55</td>
</tr>
<tr>
<td>vaporization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>kcal/kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat of</td>
<td>10,300</td>
<td>10,240</td>
</tr>
<tr>
<td>combustion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>kcal/kg</td>
<td></td>
<td></td>
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<tr>
<td>Flash point</td>
<td>316</td>
<td>346</td>
</tr>
<tr>
<td>K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distillation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IBP</td>
<td>428</td>
<td>449</td>
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<td>10</td>
<td>442</td>
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<td>90</td>
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<td>605</td>
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<tr>
<td>FBP</td>
<td>538</td>
<td>628</td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paraffins</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vol%</td>
<td>81.4</td>
<td>69.8</td>
</tr>
<tr>
<td>Olephenes</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Aromatics</td>
<td>18.3</td>
<td>30.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refractive index</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(at 589.3nm)</td>
<td>1.439</td>
<td>1.464</td>
</tr>
</tbody>
</table>

Doppler particle analyzer (PDPA) made by Aerometrics, Inc. Measurements were made at 2.5mm intervals in the radial direction (R) inside the spray at the section 50mm from a injector tip in the stream direction (Z). The probe area determined by PDPA is approximately 1.4x10⁻⁵ cm². Figures 5 and 6 show spray velocity (V), Sauter mean diameter (SMD) and volume flux (VF) against the abscissa of a non-dimensional radial position (R/Z). The cumulative number of droplets with the size distribution at each measuring points was merged to give the overall SMD in the cross section at a certain fuel flow rate.

Effect of Fuel Flow Rate

Figure 5 shows the values of V, SMD and VF at various fuel flow rates from 0.2g/s to 3g/s at an atomization air rate of 2g/s. The spray structure is affected by fuel flow rates. The mean diameters of the spray in the outer region are twice as large as that in the center region. The spray velocity is highest in the center region. Although the spray cone angle on the outer surface measured by the observation of spray is about 60 degrees (R/Z=0.58), the maximum value of volume flux is about 33 degrees (R/Z=0.3).

Effect of Atomization Air

Figures 6 and 7 show the spray characteristics for atomization air flow rates between 2g/s and 0g/s. The INJECTOR TYPE 1 can atomize a minimum fuel flow rate of
kerosene spray. The SMD of gas oil spray is larger by about 10μm compared with that for kerosene spray at the fuel flow rate of less than 0.6g/s. This suggests that the atomization process is influenced by the viscosity of gas oil, which is three times as high as that of kerosene.

**EVAPORATION CHARACTERISTICS OF PRIMARY SPRAY IN PREVAPORIZATION-PREMIXING TUBE**

Figure 9 shows the test rig with a fuel injector joined to the PP-tube. The incoming air is supplied to the test section after it is heated to the inlet temperature of 873-1273K by an electric heater. The airstreams in the tube are adjusted to the average velocity range of 80-110m/s. Fuel is atomized into the airstreams with a primary injector. The fuel spray was measured at a Z=85mm section from the injector tip. Figure 10 shows a result of the measurements. The main airstream velocity is typically about 80 m/s. The velocity at the center of the PP-tube is a little smaller than that in its surrounding region because of the swirler vane set at the inlet of the PP-tube. The velocity of the air (assumed to be that of the 3μm droplets) is about 10-15 m/s higher than the velocity of the 30 μm droplets, as shown in Figure 11. The RMS velocity is relatively high in the center and near the wall. The temperature distribution in the measuring section shows a maximum of 823K at an inlet air temperature of 873K. The maximum temperature is 50K lower when both the atomization air and fuel are injected into the tube. The temperature on the wall is 723K at an inlet air temperature of 873K, and 1000K at 1173K.

1g/s at a fuel pressure of 0.5MPa when there is no air for atomization for which the SMD of the spray is smaller than 60μm. However, the desired atomization is impossible at fuel pressures less than 0.5MPa. An atomization airstream with velocity of more than 75m/s is needed to disintegrate liquid fuel in the lower pressure range. As a result, INJECTOR TYPE I shows the characteristics of both a simplex and a twin-fluid atomizer. The maximum Sauter mean diameter was measured as 32±3μm at a fuel flow rate of about 0.6g/s, which shows the change in the spray characteristics.

**Effect of Fuel**

Figure 8 compares the SMD for gas oil spray with that for
In the measuring theory of PDPA [21], the droplets passing through the intersection of the two beams scatter the laser light which produces a far field interference fringe pattern. The scattered light is measured by three detectors (PMT) located at the selected spacings. The spacing between these projected fringes is directly proportional to the droplet diameter, and depends on droplet refractive index. The refractive index on fuel is listed in Table 2. This value was measured using the D line light of Sodium at room temperature and atmospheric pressure. The changes in the refractive index ranged from 1.464 to 1.171 indicated the decrease in SMD on gas oil spray from 17μm to 13μm in the PP-tube. The effect of refractive index on the spray diameter measurement under the evaporation conditions is considered to be small.

The mass fraction of non-evaporated spray (NMF) is defined as shown in equation <1>. It is calculated by multiplying the flux (VF) measured by PDPA per local semicircular area, with the assumption of symmetrical spray. Considering non-spherical droplets as fuel droplets, the value is then divided by the measured validation (VD). The main factor of errors on PDPA measurement is supply voltage of PMT used in PDPA. The supply voltage of PMT was set at 400 volts. Because the measurement under non-evaporation condition shows that the mass of injected fuel is nearly equal to the mass of the droplets merged on the measuring section of the spray. The measured volume flux reappears under the same set conditions. The maximum error of NMF was evaluated to be ±40% if the error was considered to be the same order of validation (VD) which varied between 0.5 to 0.8.

\[
NMF = \frac{100 \rho a \sum_{R=17.5}^{R=17.5} \left( \frac{VF(R)}{VD(R)} \right)^{-1} \Delta R^2 (\pi R^2)}{Gr} \%
\]

(1)

**Effect of Air Temperature**

Figure 12 shows the SMD and NMF at various inlet air temperatures (Tai). The average velocity of the air at the cross section in the PP-tube increases and the evaporation time decreases with air temperature rise. However, only a few fuel droplets were observed at the outlet of the PP-tube at Tai=1173K. The SMD shows the same tendency with air temperature rise. The spray diameters in the tube were smaller by about 5μm than those under atmospheric pressure in still air. This means the fuel spray is disintegrated in the main airstream.

**Effect of Atomization air**

Figure 13 shows the SMD and NMF at atomization air flow rates (Gap) of 1.5g/s, 2g/s to 4g/s at Tai=873K. The SMD and NMF is a maximum at fuel flow rates of about 0.6g/s. The spray characteristics changed when the atomization air was 1.5g/s. The NMF was less than 10% at atomization air of more than 2g/s. This indicates that the atomization and distribution of fuel are improved.

**Effect of Fuel**

Figure 14 compares the SMD and NMF for kerosene spray with those for gas oil spray. The evaporation for kerosene spray is faster than that for gas oil spray. As shown in Figure 17, the gas oil spray requires an evaporation length twice as long as kerosene.

**SIMULATION OF SPRAY EVAPORATION**

**Description of Numerical Simulation**

The spray evaporation and the NOx formation were simulated by a multi-dimensional numerical code "FIRE3D-
The calculation was performed with the following assumptions: (1) The fuel was cetane, which has properties that are clearly defined. (2) The spray diameter measured by PDPA was used as the initial diameter, and the distribution function of droplet size was given by the Nukiyama-Tanasawa equation. Each droplet was injected at random at a direction of 40° - 70° with an injection velocity of 100 m/s.

(3) A physical model of the atomization process is not considered. The droplets do not coalesce nor break up in the airstream. (4) The motion of a droplet is determined by the conservation equation, and the trajectories of the droplets are traced. (5) The temperature distribution within a droplet is held constant. (6) The temperature of the droplet is fixed when it reaches the boiling point of 560 K. The heat conducted from air to a droplet is dissipated as the latent heat of vaporization. (7) The thermal conduction from the wall to the droplets is not considered.

Figure 15 shows the computational grid for a PP-tube. The number of cells is 5620 when 1/16 of the tube diameter is calculated. Figure 16 shows the computational grid for an LPP combustor which consists of a PP-tube, a swirl chamber, a combustion chamber and a dilution chamber. The number of cells is 13000.

Comparison between Measurements and Calculations of Spray Evaporation

The velocity distribution of the airstream, the spray mean diameter and the non-evaporated mass fraction were calculated as shown in Figures 11 and 17. The airstream in the PP-tube has a uniform flow pattern at the end of the tube. The
flow velocity in the tangential direction is about 1/3 times as small as that in the axial direction. The RMS velocity is larger in the central region and near the wall. When the initial diameter has an SMD value of 30µm, the fuel vapor concentration in the central region of the PP-tube is higher, and many non-evaporated droplets of the spray are flowing along the wall. In this calculation, the spray evaporation is mainly controlled by turbulent intensity in the main airstream. The measured SMD agrees with the calculated one when the initial diameter is 30 µm SMD for gas oil spray, and 20 µm for kerosene. The NMF for the droplets of initial diameter of 20 µm SMD was calculated to be about 30% at the measuring section of Z=85 mm. In the measurement by PDPA, more than 99% of the non-evaporated spray droplets are flowing in the region from R=10 mm to R= 17.5mm (the wall) as shown in Figure 10. The measurement result indicates the amount of the non-evaporated droplets flowing along the wall agree qualitatively with the calculation results. However, the measurements of NMF were quantitatively smaller than the calculation results. These differences in the calculation are thought to result from the omission of thermal conduction from the wall and the atomization process at high airstream velocity.

SIMULATION OF CHARACTERISTICS OF LEAN PREMIXED-PREVAPORIZATION COMBUSTOR

Effect of Swirl Chamber
The developed LPP combustor has a 52 mm long PP-tube, a swirl chamber existing under the tube and a flameholder in the outlet of the swirl chamber. The PP-tube and the swirl chamber provides a space in order to evaporate fuel spray. Table 3 lists the conditions of the calculations. The
calculation results shown in Figure 18 indicate the concentration of fuel vapor in the space is higher on the wall of the swirl chamber and the flameholder because of the droplets moving along the wall. The mixture of fuel vapor and air is highly promoted such that the fuel vapor concentration is almost uniform at the inlet of the combustion chamber. The NMF of fuel spray was calculated to be about 70% at the outlet of the PP-tube, and less than 10% at the inlet of combustion chamber. The velocity distributions of the airstream, which depends on the shape of the swirl chamber as shown in Figure 19, are compared in 20. This calculation result suggests that the minimum velocity and higher concentration of fuel vapor on the wall cause flashback in the LPP combustor. In particular, the flashback in the circular type swirl chamber was easily observed at the required operating conditions of the CGT. A uniform velocity distribution at the inlet of the combustion chamber is required to stabilize the flame in the lean combustion.

### Table 3 Calculation Conditions

<table>
<thead>
<tr>
<th></th>
<th>Air</th>
<th>Fuel (Cetene)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (K)</td>
<td>1173</td>
<td>300</td>
</tr>
<tr>
<td>Flow rate (g/s)</td>
<td>21</td>
<td>1.5, 2.0, 2.5</td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Excess air ratio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel injection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMDi (μm)</td>
<td>Primary</td>
<td>Secondary</td>
</tr>
<tr>
<td>Injection angle (deg.)</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>Injection velocity (m/s)</td>
<td>45-70</td>
<td>60-100</td>
</tr>
<tr>
<td>Boundary conditions on wall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>Adiabatic</td>
<td></td>
</tr>
<tr>
<td>Velocity</td>
<td>Law-of-the-wall</td>
<td></td>
</tr>
</tbody>
</table>

### FIG. 18 Concentrations of Fuel Vapor at the Center of the Tube and Outlet of the Flameholder

**NOx Emission Characteristics**

Figure 21 shows the comparison between calculated and measured NOx emission indexes of the LPP combustor. The calculated NOx emission indexes shown in the vertical axis is given by a relative value divided by the one at an excess-air-ratio of 2. The tendency of relative NOx indexes depends on
the excess-air-ratio, and the calculation and measurement agree well when the excess-air-ratio is less than 2. However, the tendency of relative NOx indexes differs between calculation and measurement when the excess-air-ratio is higher than 2. This means the calculation in the lean combustion of fuel-air premixture must be investigated because the actual atomization process was not considered. Therefore, the following calculation is compared under the same condition with excess-air-ratio of 2.

Temperature Distribution and NOx Concentration in the Combustion Chamber

In order to investigate the effect of the NMF, the distribution of temperature and NO concentration were calculated and compared for the three different fuel supply systems, as shown in Figure 22. The results are shown in Figure 23. The perfectly-fuel-air-premixed combustion, which means NMF of 0%, represents an ideal homogeneous combustion with uniform fuel-air-premixture concentration and no droplets. The lean diffusion (spray) combustion in the combustion chamber, which means NMF of nearly 100%, represents a heterogeneous combustion. The calculation of this spray combustion resulted in a temperature field of higher than 2200K and an extremely high NO concentration in the central region of combustion chamber. In the LPP combustor, which has a calculated NMF of 8% at the inlet of the combustion chamber, the temperature distribution in the central region is relatively uniform. However, the nonuniform temperature distribution appears near the wall because non-evaporated spray burns there. Figure 24 shows the tendency of NOx emission indexes in relation to NMF. NOx emission index of the LPP combustor shows 1/6 times smaller than that of the lean diffusion (spray) combustion, and 1.3 times larger than that of the perfectly-fuel-air premixed combustion.
In order to realize a LPP combustor, the prevention of flashback and the flame stabilization in the lean premixed-prevaporization combustion must be achieved. Therefore, a compact design of the prevaporization-premixing space is required. The airstream velocity and fuel vapor concentration at the inlet of the combustion chamber are important for stabilizing the lean flame and decreasing the NOx formation. The LPP combustor developed in this study has a prevaporization-premixing tube and a swirl chamber. For example, the flame stabilization in a circular type swirl chamber could not be satisfied under some light load conditions of CGT. The characteristics of flashback are complicated because of the 3-D flow characteristic established by the combustor of a swirl chamber, a PP-tube and a fuel injector. It is difficult to understand the design factor which controls the flame stabilization of lean combustion and the NOx formation from measurements. For analysis of this point, numerical simulations are very useful. Since the measured NMF differs from the calculated value, the development of a numerical simulation code which considers the wall effect and the atomization process is necessary. A more compact design on fuel preparation tube would enable not only an improvement in the degree of evaporation, but also the prevention of flashback/autoignition.

**SUMMARY**

For the sake of reducing exhaust pollution, a lean premixed-prevaporization combustor was developed for a 100 kW automotive ceramic gas turbine. In this type of combustor, it is very important to clarify the design specifications of a fuel atomizer and a prevaporization-premixing tube. The measurements of the local characteristics of the fuel spray structure were first conducted. Second, the evaporation characteristics of the fuel spray influenced by the distribution of spray droplet diameter, air temperature or fuel properties were evaluated and calculated. Finally, the measured exhaust NOx indexes were compared with the calculated NOx indexes using different non-evaporated mass fractions.
The following conclusions are obtained:

1. A fuel injector which combines a pressure-swirl atomizer with air atomization produces a fine spray with SMD of less than 30μm, with a turn-down-ratio of more than 15. The maximum diameter of the fuel spray appears at a fuel flow rate which changes the spray characteristics from pressure atomization to air atomization. The local mean diameter in the outside region of the fuel spray is almost twice as large as that in the center region of the fuel spray.

2. The degree of evaporation of the fuel spray was evaluated under the conditions of air temperature ranged from 873K to 1173K and air velocity of 80-110m/s. The non-evaporated mass fraction of fuel spray in the prevaporization-premixing tube is largely influenced by the atomization and distribution of fuel spray. Due to the swirled airstreams in the tube, almost all the non-evaporated droplets (more than 99%) are flowing collectively within the region of 7mm from the wall at a 85mm section from a tip of fuel injector. This indicates that the non-evaporated mass fraction in the prevaporization-premixing tube is mainly controlled by the evaporation rate of the spray near the wall. The measured non-evaporated mass fractions of the spray were relatively small compared with the calculations, even when the measurement errors by PDPA are considered. As a result, increasing factors such as the disintegration process in the airstream, the thermal conductivity to droplets moving along the wall and the turbulent intensity near the wall are necessary for improving the degree of evaporation.

3. The measurements and calculations clarify that the exhaust NOx emission indexes from the lean premixed-prevaporization combustor at an excess-air ratio of 2 and inlet air temperature of 1173K under atmospheric pressure. This value is 1.3 times as large as the one from a perfectly-premixed combustion. The reasons for this are deduced from the calculations: since the fuel-air nonuniformity in the non-evaporated mass fraction of less than 10% is estimated to be sufficiently low at the inlet of the combustion chamber, the relatively flat gas temperature in the combustion chamber results in the reduced NOx characteristics.

4. The flame stabilization in the lean premixed-prevaporization combustor is affected by three dimensional shape of the swirl chamber in the fuel-air preparation tube. It was found from the comparison between numerical calculation and measurement that the characteristics of flashback or autoignition were badly influenced particularly by the minimum air velocity and higher concentration of fuel vapor near the flameholder wall.

REFERENCES

[18] L. P. Cooper, AIAA 79-1320