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Development of Low NOx Diffusive Burner Applying Spiral Flame Combustion

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ABSTRACT

A spiral flame burner is tested for application in gas turbines. In spite of being diffusion type, it is distinguished by low NOx performance and high combustion stability in ultra lean condition. For application in industrial gas turbines, the new burner has been extended to high intensity combustion and the design been improved to realize lower NOx combustion as compared to conventional diffusive burners. The burner shows excellent characteristics such as prevention of flashback, self-ignition and oscillatory combustion. In addition, this burner has wider stable combustion limits, even compared to conventional diffusive burners. Low NOx performance is confirmed by combustion tests. Comparison of the results with conventional non-premixed combustors reveals that the NOx emissions from the spiral flame burner are by 50% lower. Furthermore it is found that the low NOx performance is related to intensity of local strain rate in strong swirl flow.

INTRODUCTION

In response to the demand of high cycle efficiency for gas turbines, combustor inlet pressure and temperature are increased. With increasing pressure and temperature, more amount of NO_X is produced. In contrast, regulations for NOx emission from gas turbines are restricted more strictly to lower values. To overcome this problem, various combustors have been developed to reduce NOx emission under condition of high temperature and pressure. Among these, lean premixed combustion is commonly regarded as the most established and effective technology to reduce thermal NOx in practical combustors. However, lean premixed combustion has many problems, for example, self-ignition, flash-back and combustion stability. Therefore, application of lean premixed combustion to actual gas turbine combustors is limited even at present temperature and pressure levels. It can be expected that inlet temperature and pressure will be further raised in future. On the other hand, restrictions on emissions are likely to become even stricter than today. Therefore, it seems be difficult to apply premixed combustion to combustors for future gas turbines. For this reason, researches related to NO_X reduction in the field of non-premixed combustion are being performed (Gabler, 1998) (Alkabie, 1991).

In the present work new burner is designed, which adopts spiral flame combustion as a measure to achieve higher combustion stability and, at the same time, prevent troubles such as self-ignition and flash-back. The spiral flame combustion essentially belongs to the category of diffusive combustion methods; a quenching region produced by flame strain coexists with a stable combustion region realized by strong swirl flow. In the spiral flame, since fuel is injected into an intense shear flow produced by a strong swirling flow, a partial flame quenching brings about by a flame stretch phenomena, which gives rise to a temperature decrease. And, since the fuel rapidly mixes with air in a short duration to form a near-uniform mixture, heat spots frequently produced in the case of diffusion combustion are not easily generated, and then the formation of thermal NOx is depressed. Talking about flame stability, the spiral flame can be stabilized at the upstream central region of the swirling flow where is suitable to maintain a flame stable because of weak shear and low velocity. The reaction region is formed around this region and spiral flames appear at several fuel ports. The concept of the burner is to reduce NOx and sustain stable combustion simultaneously. The characteristics of low NOx and stable combustion has been proved under atmospheric condition (Yajima, 2002).

By applying spiral flame combustion to gas turbine combustors, the following merits are anticipated:

(1) Low NOx and stable combustion in a wide range of operating conditions
(2) Shortening liner length by short flame due to rapid mixing
(3) High reliability regarding safety (no self-ignition, no flash back)
(4) Simple structure of the burner, low manufacturing cost

On the other hand, it is necessary to evaluate the performance of spiral flame combustion in the wide range of operating conditions in order to adopt it as technology for gas turbine combustors. In addition, it must be possible to deal with the high combustion load as it is required in actual gas turbines. In fundamental studies reported earlier, a single port burner has been used (Yajima, 2002). The experimental conditions had been set to atmospheric temperature and pressure, and combustion load has been much lower than for an actual burner. The performance at high temperature and pressure has not been investigated yet. Furthermore, the new multi-air port design of the burner is needed to correspond to high combustion load for actual applications.

The purpose of this research is to investigate the combustion performance of the newly designed multi-port type burner using spiral flame combustion, with special interest in NOx reduction characteristics. In detail, the following points are investigated:

(1) Effect of inlet temperature, pressure, velocity at the air port on NOx reduction
(2) Effect of the following design parameters for high combustion load on NOx reduction
  a) number of air ports
  b) number of fuel ports and location
  c) air port shape（air port height）

The burner investigated here is designed for gaseous fuel, and so

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targets are low NOx combustors for applications on land or sea. Since this burner has been proved be very safe, i.e. good performance without self-ignition, flash-back and oscillatory combustion, it is thought that the burner can be further developed to burn liquid fuels and, hence, can also be applied in future aero-engines at further elevated temperatures and pressures.

TEST BURNER AND EXPERIMENTS

Fig 1 shows the outline of the multi-port type burner and the combustion test rig. Air is tangentially supplied through equidistant ports. Fuel is supplied through small holes in the upstream injection plate. The burner consists of cylindrical liner, tangential swirler and fuel injection plate. Multiple jet ports for combustion air supply are uniformly fitted to the liner wall in the swirler. Gaseous fuel is injected through a number of ports (holes) into the strong swirl flow. Proper air flow for cooling of burner liner and dilution of exhaust gas is ensured by another air supply. A small gas burner torch is installed on the side wall of the exhaust casing downstream of the burner liner for ignition. The torch is only used for ignition and, hence, is cut off when stable combustion is achieved.

The design of the test burner can easily be changed by replacement of tangential swirler and fuel injection plate. Design parameters are number of air ports *Na*, air port height *h*, number of fuel ports *Nf* and position of fuel ports *r* (see Fig.1). For each design, NOx emission characteristics are investigated for various inlet air conditions (temperature *T3*, pressure *P3*, mean flow velocity *Vp*) and air-to-fuel mass ratios (AFR). Reference burner design and reference test conditions are given in Tables 1 and 2, respectively.

Table 1 Reference conditions

Na_{ref}	Nf_{ref}	r/R
8	8	0.67

Table 2 Test conditions

T3(K)	*P3*(MPa)	*Vp*(m/s)
300～673	0.3～0.7	45～

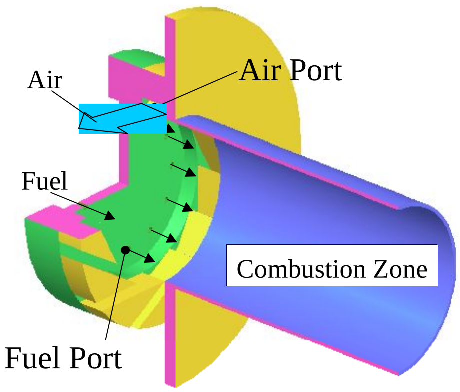
RESULTS AND DISCUSSION

The conformity of the spiral flame burner for actual combustor was discussed from the evaluation of the result of combustion tests examined on the conditions of raised pressure and temperature.

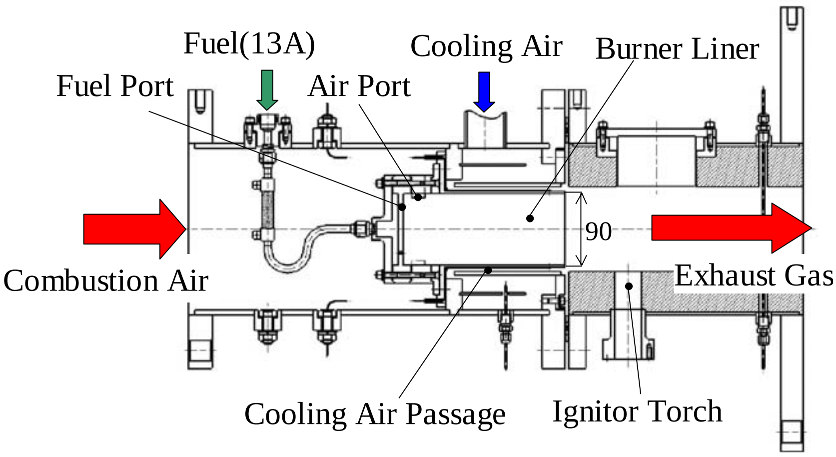
Effect of inlet pressure

First of all, combustion tests have been performed with the single air port version to reconfirm the experimental results under atmospheric condition as reported by Yajima et al (2002) and confirm the effect of inlet pressure *P3* on NOx emission. The inlet air temperature *T3* is set to 300K in this test. The relation between *P3* and NOx emission is shown in Fig 2. From the results it is seen that NOx emission hardly changes with *P3*.

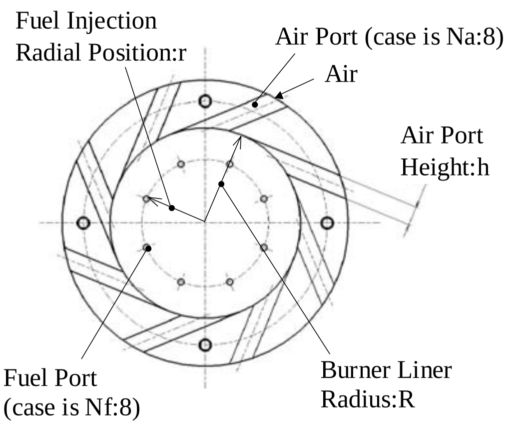
The relation between *P3* and NOx emission for the multi-port version with same air port height and fuel injection position is shown in Fig 3, namely h/h_{ref}=1 and r/R=0.67. Inlet air temperature is set to actual gas turbine operating temperature of 673K and to 300K for comparison with the single port version. For the higher temperature, AFR is varied in order to investigate the trend of NOx emission with combustion load. The AFR data are representative and show typical trends observed. The results obtained here prove that NOx emission is not influenced by *P3*, irrespective whether single or multi port burner is used. For lower temperature the NOx level decreases, while it is almost the same for double AFR. From these results, one can state that there is little influence of inlet pressure on NOx emission for the spiral flame burner presented here.



(a) Test Burner Image



(b)Burner test rig



(c)Section drawing of tangential swirler

Fig 1 Multi-port version of burner for spiral flame combustion test

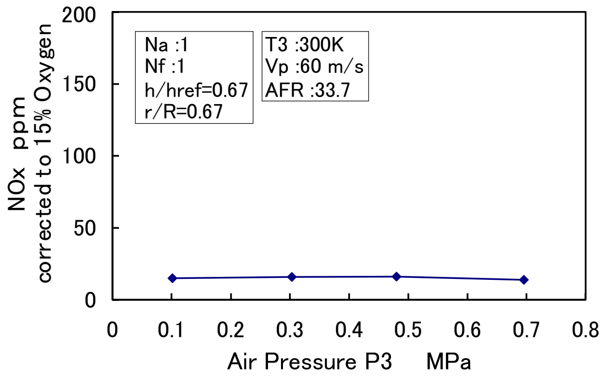


Fig 2 Relation between inlet air pressure and NOx emission (Single-port version)

Effect of inlet temperature

Typical results for the effect of inlet air temperature on NOx emission is shown in Fig 4. It is seen that NOx emission increases with temperature as commonly expected. For temperatures above 623K, NOx emission increases remarkably. Although differences are noticed for the NOx emission with increase of number of air ports and velocity in the air port, which results are not shown here, this tendency of sudden raise for high inlet air temperature appears for all types. From observation of the flame it is believed that there is some possibility that the combustion in the burner changes remarkably when the temperature exceeds 623K, although the cause is not understood at present.

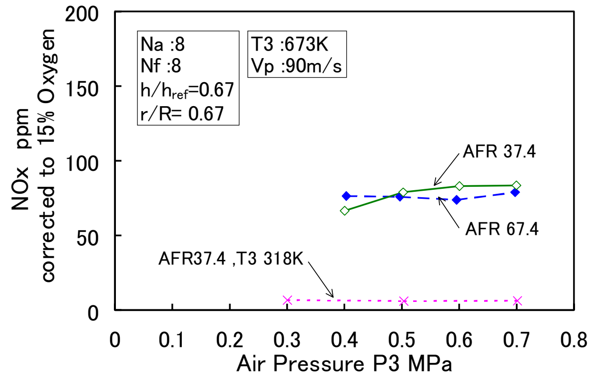


Fig 3 Relation between inlet air pressure and NOx emission (Multi-port version)

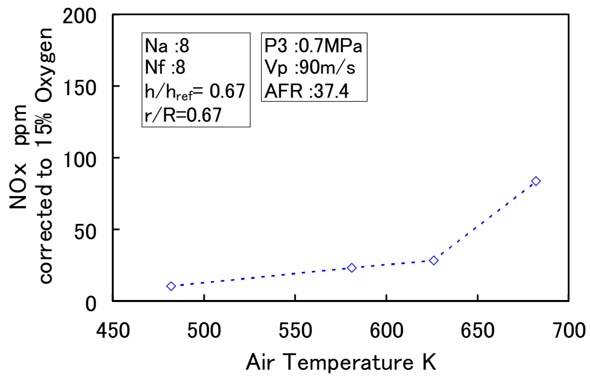


Fig 4 Relation between inlet air temperature and NOx emission (Multi-port version)

Effect of air inlet velocity

The change of NOx emission with mean inlet air velocity *Vp* is shown in Fig 5. When *Vp* is increased, NOx emission are seen to decrease. It is believed that flame strain rate (FSR) as generated by the velocity shear layer between fuel and air supply becomes large; this decreases flame temperature and leads to flame quenching.

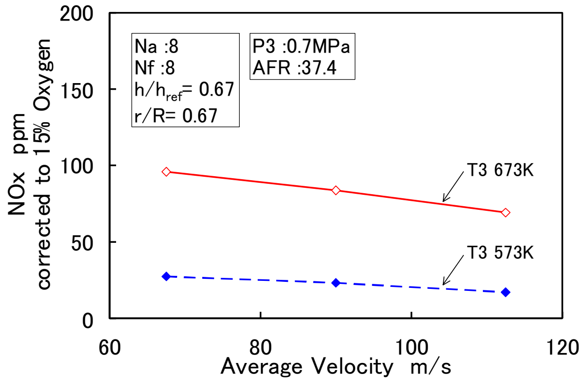


Fig 5 Relation between air inlet velocity and NOx emission

RELATION BETWEEN HIGH COMBUSTION LOAD AND NOx EMISSION

Influence of number of air ports on NOx emission

The characteristics of NOx emission regarding number of air ports *Na* is shown in Fig 6. The NOx emission for the single-port version with same velocity is also plotted for comparison. According to an increase in *Na*, NOx emission increases only a little. The air flow rate from each air port and also the overall equivalence ratio are fixed at constant values in the experiments to examine the effects of inlet air-port number on the NOx emission. According to the establishment of experimental condition, the increase of air-port number brings about the increase of combustion load and results in the rise of combustion temperature, which is caused by the heat balance of heat generation and heat loss. This is the reason why the emission of thermally generated NOx increases with the increase of *Na*. Also, it appears there is only little influence of AFR on NOx emission.

Fig 7 shows the relation between NOx and *Na* for higher inlet temperature *T3*. It is seen that NOx emission increases with number of ports, although the change can be regarded as small.

Another positive effect of introducing multiple air ports should be mentioned. For the single port version it has sometimes been observed that local high temperature regions occur, where the liner wall temperature rises and leads to glowing in a few cases. In the case of the multi port version, more uniform flow and temperature fields are obtained. The temperature distribution along the liner wall is evaluated by the pattern factor in Fig 8. The pattern factor is defined as (*T*max – *T*mean) / *T*mean, where *T*max and *T*mean denote maximal and mean temperature along the liner wall at a given axial position, respectively. Comparison of the pattern factors for single and multi port versions reveals that a strong non-uniformity is observed for the single port burner, while a uniform wall temperature is achieved with the multi port version.

In spiral flame combustion, non-reacting zones are observed between flame and liner wall, especially for the multi port burner. The wall temperature has been lower than that for conventional burners. The maximal wall temperature of the multi port burner has been below 1000K, while the mean flame temperature has been above 1700K. Hence, no cooling air has been necessary for the liner wall (measured condition is indicated in Fig 8).

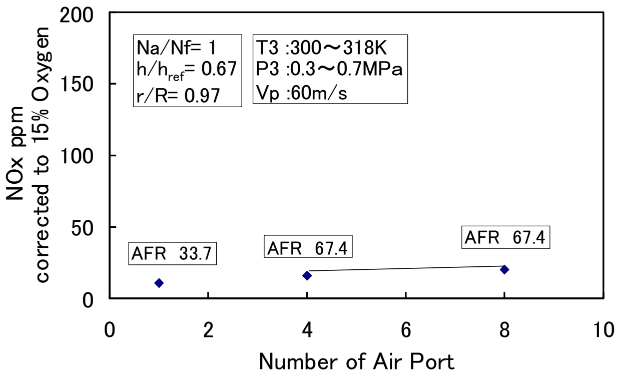


Fig.6 Relation between number of inlet-air ports and NOx emission

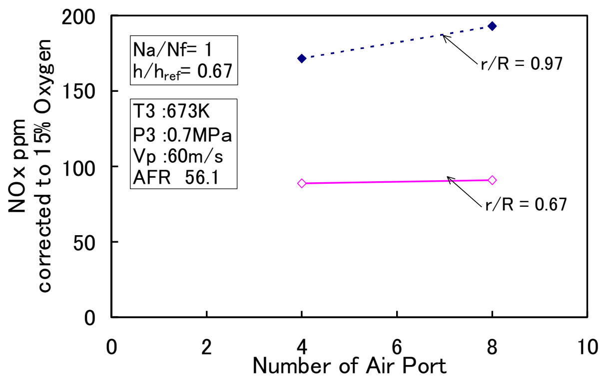


Fig.7 Relation between Number of Inlet-Air Ports and NOx emission

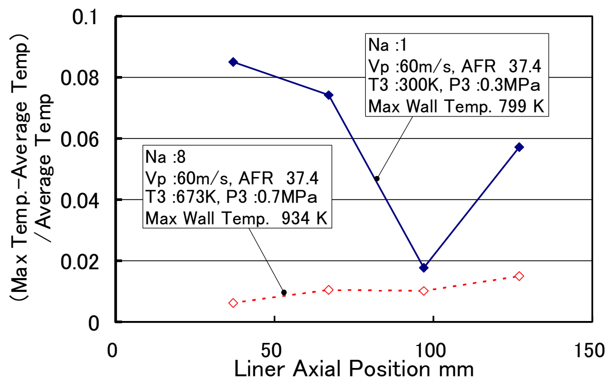


Fig 8 Comparison of wall temperature uniformity for single and multi port burner

Influence of number of fuel ports on NOx emission

The effect of fuel injection velocity on NOx emission has been investigated for fixed air flow conditions, i.e. number of air ports, cross-sectional area, air supply velocity and air-to-fuel ratio are fixed. Fuel jet momentum has been varied by the number of fuel ports *Nf* for fixed flow rate and cross-sectional area of the nozzles. *Nf* was changed to twice the reference condition and one half of the reference condition. The experimental results are shown in Fig 9. It is readily seen that there exists an optimal design point, since NOx increases for lower as well as for higher fuel injection velocities (number of ports). When the number of fuel ports is decreased, i.e. fuel injection velocity increased, mixing of fuel with air is advanced. Furthermore, increase of velocity implies an increase of flame strain rate (FSR). Advanced mixing and higher FSR are believed to yield less NOx emissions. When the number of fuel supply ports is reduced too much, however, regions with high fuel concentration occur, which then lead to higher flame temperatures and, finally, to higher NOx emission. On the contrary, when the fuel injection velocity is decreased by using more fuel supply ports, there is a possibility that fuel does not reach the predetermined place to maintain the characteristics of spiral flame combustion. This reasoning is supported by visual observation of the flame behaviour for different number of fuel ports.

The results presented so far suggest that NOx reduction and combustion behaviour are controlled by *Nf* and that there exists an optimal condition where fuel jet momentum, FSR and fuel concentration are balanced.

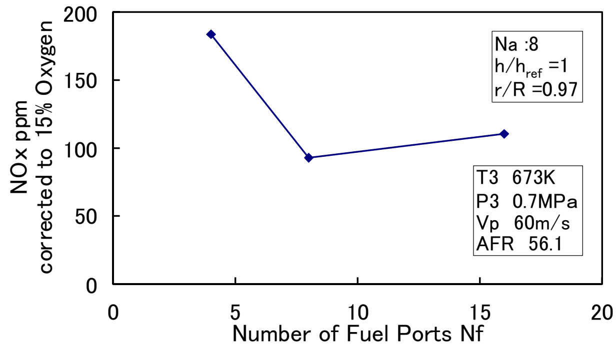


Fig 9 Relation between number of fuel ports and NOx emission

Influence of air port height on NOx emission

The principle idea of spiral flame combustion is to reduce NOx emission by realization of low flame temperature due to flame strain. When air port height *h* is changed, strength and position of flow velocity within the strong swirl flow changes, even if the mean velocity in the air ports is the same. Therefore, the air port height should have an effect on NOx emission characteristics because affecting flame strain rate and flame position. The flame stretch rate is equal to the increasing rate of mass flux of unburned mixture toward the flame propagating direction. In case of a large stretch rate, since the quantity of heat supplied by the reaction zone to heat the mixture increases, the flame temperature lowers, and at the rate over a critical value the flame blows off by the excess decrease of burning velocity, or the flame cannot propagate to an unburned mixture region. Figure 10 shows FSR and NOx emission as function of port height h. The flame strain rate is estimated by Eq. (1). The tangential velocity *Ut* is obtained from CFD computations. For FSR estimation the flame is assumed be established at the radial position of fuel supply.

$$FlameStrainRate = r\frac{d(Ut/r)}{dr} \qquad (1)$$

Experiments are performed for two fuel supply locations, namely the reference design, characterized by *r/R*=0.97, and a smaller radius of 67%, characterized by *r/R*=0.67. When *h* is decreased from 9mm(reference) to 6 mm, NOx emission is increased for fuel supply near the liner wall (*r/R*=0.97). In contrast, NOx emission is reduced, when fuel is supplied closer to the burner center (*r/R*=0.67). This trend is explained by evaluation of the flame strain rate as explained above. When the flame strain rate becomes high, NOx emission decreases due to quenching and the resulting low temperature combustion. In contrast, NOx emission increases for lower strain rates because of higher flame temperatures. When h is changed to 12mm, NOx emission increases compared to the reference condition for outer fuel supply (*r/R*=0.97), because the velocity gradient at the location of the flame becomes too weak.

The characteristics found here are in agreement with the principle concept of NOx reduction in spiral flame combustion.

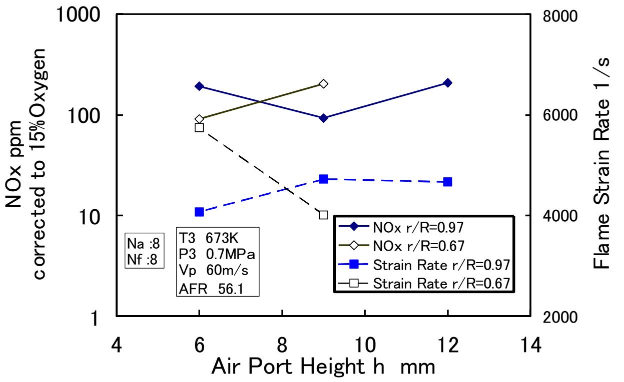


Fig 10 Effect of air port height on NOx emission for two different fuel injection positions and its relation to flame strain rate

Performance regarding ignition and blow off

In spite of the fact that the igniter has been mounted downstream of the burner outlet far from the fuel injection ports (Fig 1), no trouble has been experienced to ignite the fuel. Fig 11 shows AFR at ignition vs ignition parameter *I*, which is calculated by Eq. (2). It is readily seen that AFR at ignition is about 33.7 for almost all conditions, even though ignition parameter is varied over a wide range.

Blow off has not been observed for AFR below 168 . The blow off limit of this burner against air loading parameter *f* ¶is shown in Fig 12, where *f* ¶was calculated by Eq. (3). As shown in the figure, it is a feature of the spiral flame burner to have a very large stable range in the region of high AFR.

$$I = \frac{P3^{0.5} \cdot T3^{1.5}}{V_{ref}} \qquad (2)$$

P3: inlet pressure (psi)

$$\Omega = \frac{Wa \times 10^9}{P3 \cdot Vol \cdot \exp(T3/300)} \qquad (3)$$

Vol: volume of combustion liner (m^3)
Wa: air mass flow rate (kg/s)

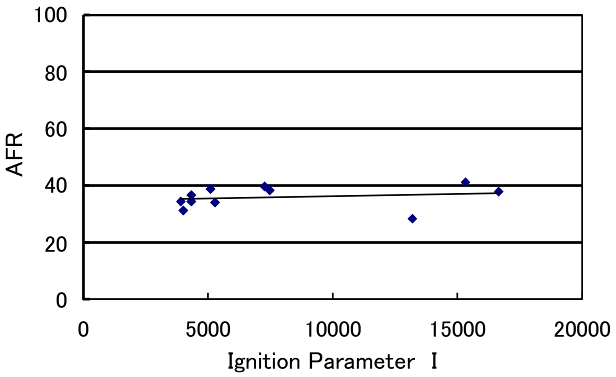


Fig 11 Ignition characteristics of spiral flame burner

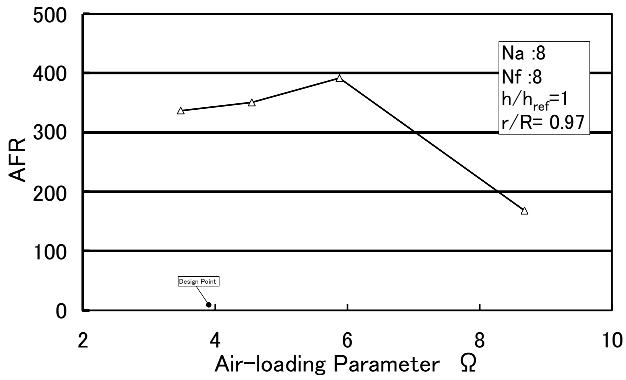


Fig 12 Blow off limit of spiral flame burner

COMPARISON OF THE MULTI AIR PORT VERSION OF SPIRAL FLAME BURNER AND TYPICAL DIFFUSIVE COMBUSTORS

A very good performance of NOx reduction is demonstrated here at air inlet temperatures below 623K under high combustion load. Also for temperatures above 623K, NOx emission is reduced by about 50% compared to a typical combustors, while combustion efficiency is maintained in the range from 92 to 99 % by choosing air port and fuel port conditions appropriately.

From these results it is thought that the burner investigated here is applicable in gas turbines as dry low NOx burner applying non-premixed combustion.

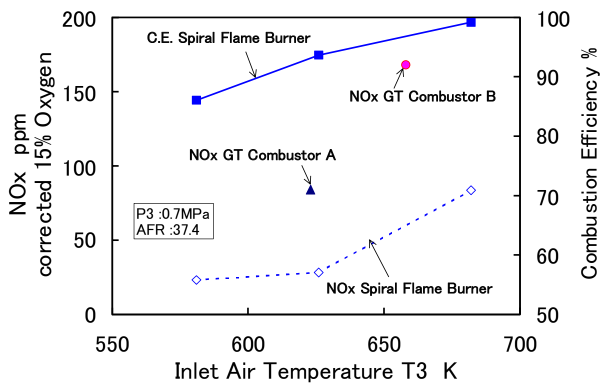


Fig 13 Comparison of NOx emission for spiral flame combustor and conventional non-premixed combustors

CONCLUSIONS

The burner using spiral flame combustion shows satisfactory characteristics regarding NOx reduction with high combustion load when the multi air port version is used. Good characteristics are even obtained for a symmetric flame. Main features of the burner are summarized as follows.

(1) A good performance of NOx reduction is demonstrated elevated inlet temperatures and pressures. About 50% of NOx reduction is achieved compared to conventional non-premixed burners.

(2) The flame is homogenously established along the liner wall in circumferential direction and, hence, prevents generation of local high temperature regions.

(3) NOx reduction characteristics of this burner are shown to be dominated by flame strain.

(4) The spiral flame burner has a very wide range of stable combustion.

Good performance for the multi air port version of spiral flame combustion has been confirmed by the combustion tests presented here. In future, much better performance regarding NOx emission will be demanded. This foreseeable circumstance has left the scope of many improvements such as optimization of port shape etc.

NOMENCLATURE

Na	number of air ports
Na_{ref}	number of air ports of reference burner
Nf	number of fuel ports
Nf_{ref}	number of fuel ports of reference burner
h	air port height (mm)
h_{ref}	air port height of reference burner
r	injection position (mm) (radial distance from center)
R	liner radius (mm)
$P3$	inlet air pressure (MPa)
$T3$	inlet air temperature (K)
Vp	mean velocity in air ports (m/s)
Ut	tangential velocity of liner flow (m/s)
Wa	air mass flow (kg/s)
Vol	liner volume (m^3)

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