Development of Dry Two-Stage Low-NOx Combustor for a Gas Turbine

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ABSTRACT

A dry two-stage low NOx combustor for a 73 MW gas turbine has been developed to meet stringent NOx limitations in Japan. This combustion system has a fuel-air control mechanism to ensure stable switching from one-stage combustion to two-stage combustion. NOx emission is very low not only at full load but also in the entire gas turbine operating range.

The NOx characteristics have proved to be within the goal in full scale, full pressure combustion tests.

This paper outlines the development plan and describes the structure and combustion characteristics of the low NOx combustor.

INTRODUCTION

In the future, the steam and gas turbine combined plant will be predominant for its high efficiency.

One important problem to be solved in constructing the plant in Japan is the reduction of NOx. Though it depends on the area, there is very stringent regulation of NOx. For development of this combustor, the target gas turbine exhaust NOx value is 75 ppm at 15% O2, about a half that of existing plants.

The many methods of reducing NOx are roughly divided into wet methods and dry methods.

Dry methods are better because there is no decrease in performance, which occurs with wet methods. Dry methods are the most desirable for combined cycle NOx reduction, but they usually pose very difficult technical problems concerning the control of combustion phenomena which must be solved.

We have been developing a dry low NOx combustor for a 73 MW (MS7001E) gas turbine for several years. Much effort has been made for NOx abatement in the field of dry low NOx combustor for heavy duty gas turbines (Ref. 1, 2). The important feature of our combustor is that above-mentioned very large NOx reduction is required not only at full load, but also in throughout the full operating range.

This paper outlines the development plan for the low-NOx combustor and describes its structure and combustion characteristics.

LOW-NOX COMBUSTOR DEVELOPMENT PLAN

The low NOx combustor development plan for Hitachi's 73 MW heavy duty gas turbine (MS7001-E) consists of three phases according to the NOx concentration target. (Fig. 1)

The Phase I NOx emission target is 75 ppm or less at 15% O2 over the entire operating range. The Phase II target is 50 ppm or less at 15% O2. The value for Phase III is 10 ppm or less, which will be achieved by using catalytic combustion. The black arrows in Fig. 1 show past achievements. The single-stage combustion type combustor is the primary model for Phase I. It is based on a lean combustion system in which fuel is fed by a single nozzle and the combustion air is fed in multiple stages in the axial direction. A series of tests showed that the lowest possible NOx concentration achievable by this type of combustion system would be 120 ppm. The combustion system screening test was carried out over several years to select the best combustion method to meet the NOx target.

Based on the test results, the two-stage combustion system in which diffusion combustion is combined with premixed combustion was selected for the Phase I combustor. In full-scale testing under actual machine conditions, this combustor met the NOx concentration and...
This structure of the low NOx combustor is shown in Fig. 3. The overall length and the diameter of the main chamber remained unchanged so that the newly developed combustor can easily replace the conventional one. The combustor is constructed of separate first and second stage chambers to ensure reliability and to make assembly easy.

COMBUSTION TEST EQUIPMENT

The equipment for testing combustion under actual machine conditions is schematically shown in Fig. 4. A complete view of the test equipment is shown in Fig. 5.

Table 1 Specifications of the test equipment

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air flow rate</td>
<td>36.3 kg/s</td>
</tr>
<tr>
<td>Air pressure</td>
<td>1.46 MPa</td>
</tr>
<tr>
<td>Volume of methane gas</td>
<td>3900 Nm³</td>
</tr>
</tbody>
</table>
COMBUSTION TEST RESULTS

Flame structure in the first stage

The first stage flame structure is sketched in Fig. 6. In the first stage, the fuel is injected into the head of the chamber through multiple nozzles, reducing the NOx concentration in partial load operation by more uniform dispersion of fuel.

The flame in the first stage chamber is stabilized by a pair of vortex flows formed by air jets, one through the combustion air holes of the first stage chamber and the other through the opening around the fuel nozzles.

Fig. 6 1st Stage Combustion Flame Holding Mechanism

The results of flow visualization by water flow and spark tracing tests is shown in Fig. 7 and the results of flame behavior observation by low pressure combustion tests indicate that the vortex flow forming above the root of the fuel nozzle is stable and effective for flame holding. The flame in the first stage is stabilized so that the fuel-air ratio leading to blow-off is less than about 0.004 at an air flow rate of 23.1 kg/s, the rated operating condition, confirming that there is no problem in flame stabilization.

The distribution of gas temperature and NOx concentration in the chamber measured under low pressure is shown in Fig. 8. High-temperature zones exist ahead of the nozzle and the swirler. The distributions are similar NOx concentration and gas temperature, and high-concentration zones exist ahead of the nozzle and the swirler corresponding to the temperature level. In general, the flame of this combustor has a more uniform temperature distribution and as a result, lower NOx emission, than the conventional swirl-stabilized flame.

Fig. 8 Gas Temperature and NOx Contours

(a) Temperature Contours (K)
(b) NOx Contours (ppm)

Characteristics of two-stage combustion

Investigation was carried out on switch over from first stage combustion only to first and second stage combustion and the NOx and CO characteristics during two-stage combustion. In each run of experiments, the air flow rate was fixed at 10.8 kg/s, about a half for an actual machine. The NOx and CO concentrations were measured as the fuel flow rate in the second stage was increased while that of the first stage was kept constant. The NOx and CO concentrations plotted against the fuel-air ratio are shown respectively in Fig. 9 and 10. Symbols “o” in the figures represent the data obtained with first stage combustion alone.

Fig. 9 NOx Emission Characteristics of 1st and 2nd Stage Burning Mode

<table>
<thead>
<tr>
<th>Conditions</th>
<th>NOx (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1 Only</td>
<td>0</td>
</tr>
<tr>
<td>F1 + F2; F1/F2 = 0.5</td>
<td>5.5</td>
</tr>
<tr>
<td>F1 + F2; F1/F2 = 0.2</td>
<td>8.6</td>
</tr>
</tbody>
</table>

The fuel flow of the first stage (F1) is expressed relative to fuel flow (F) at the fuel-air ratio of 0.02 (F/F=0.02). For example, if the relative value of the fuel flow ratio in the first stage is 0.5, the fuel feed to the second stage starts at the fuel-air ratio, F/A=0.01.

The NOx concentration increases very little as long as the fuel flow rate in the second stage is small, and it gradually increases when the fuel flow rate in the
second stage exceeds a certain limit (Fig. 9). Also the CO concentration rapidly increases as the fuel rate of the second stage increases (Fig. 10). In the period of increase in CO concentration, the gas temperature rises very little. The F/A value at which the NOx concentration begins to increase gradually coincides with that at which the CO concentration stops increasing and begins to decline. And the temperature of the combustion gas also begins to rise as the fuel flow rate in the second stage increases. As the flow rate increases further, CO concentration rapidly declines and complete combustion is realized, whereas the NOx concentration increases rapidly.

The above-mentioned results suggest that the fuel in the second stage is ignited when the fuel flow rate reaches the point at which the NOx concentration begins to increase and the CO concentration begins to decline from its peak value.

Considering these results from the viewpoint of second stage ignition condition, the greater the first stage fuel flow rate, the smaller the fuel flow rate necessary for second stage ignition. In other words, the more intensive the flame in the first stage, the more easily the fuel in the second stage ignites.

The total fuel-air ratio (F/A) which permits ignition in the second stage becomes small as the flow rate in the first stage (F1/F) becomes small (Fig. 10).

The relationship between the fuel-air ratio in the first stage (F1/A1) and the fuel-air ratio in the second stage (F2/A2), concerning with the ignition condition of the second stage fuel is shown in Fig. 11. Lines representing equal CO concentration and the boundary zone for a NOx concentration of 50 ppm are also shown. The former lines are approximately parallel to the line representing the ignition condition of the second stage.

When the fuel-air ratio in the first stage increases, the ratio of the NOx in the first stage to total combustor increases. So the effect of the second stage flame to the total NOx gradually diminishes. On the contrary, when fuel-air ratio in the second stage increases, the ratio of the NOx in the second stage to total combustor increases. So, when the fuel-air ratio in the second stage exceeds 0.04, the NOx produced in the second stage becomes predominant.

Considering the above-mentioned combustion characteristics in two-stage combustion, an operating fuel-air ratio of 0.01 to 0.02 was established for the first stage and 0.03 to 0.04 for the second stage. In order to ensure stable second stage combustion during low-load operation, including ignition in the transition to two-stage burning, control of the fuel-air ratio was employed for the second stage combustion. Control of the fuel-air ratio is accomplished by regulating the combustion air inlet window area for the second stage, by means of the internal flow rate controller (IFC).

The relation of IFC opening to the load of the gas turbine, and the ratio of the first and second stage fuel flow at different loads are shown in Fig. 12.

Combustion test results under actual machine conditions
The NOx concentrations at various loads measured in the combustion test under actual machine conditions. The NOx concentration is given in terms of the value corrected to 15% O2. The following formula was used for the correction of NOx concentration as a function of pressure (P), air temperature at the inlet (Tin), atmospheric specific humidity (H), and oxygen concentration (O2).

\[ \text{NOx} = 7 \cdot \text{NOx}^* \cdot \left( \frac{P}{P_{02}} \right)^{0.26} \cdot \exp \left( \frac{T_{\text{in}} - T_{\text{in}}^*}{250} \right) \cdot \exp \left( -19 \cdot (H - H^*) \right) \]  \tag{1} 

The asterisk (*) indicates the experimental value. The pressure ratio exponent is a value obtained by experiment. Other values for correction are taken from published literature (Ref. 5, 6).

Operation of the gas turbine from zero load to 25% load is achieved by first stage combustion only. At 25% load, two-stage combustion starts, and the gas turbine operates over the entire load range with low NOx concentrations. Just before 25% load, when the combustion is still in the first stage alone, the NOx concentration rate of increase drops. This is because the IFC is closing and the air entering the first stage increases. Under high-load, the CO concentration is on the order of ppm. The CO concentration is kept low by controlling the fuel-air ratio with the IFC, even during the period of high load operation, including the transition to two-stage combustion. Incidentally, in transition to the two-stage combustion, it is possible to lower the amount of unburnt matter by extracting some of the combustion air, thereby increasing the fuel-air ratio in the second stage combustion region.

The relation of combustion dynamic pressure to gas turbine load is shown in Fig. 14. The combustion dynamic pressure is lower than 0.02 kg/cm² over the entire load range including 25% load, at which the transition to two-stage combustion takes place. This level is as low as that of conventional type combustion.

The metal temperature of the combustor measured with thermocouples is shown in Fig. 15. The maximum temperature recorded was 600°C. The presence of local high temperature regions was checked with thermopaint also. No questionable spots were detected. Using the measured temperature data, thermal stress analysis was performed, and it was confirmed that the stress is within the acceptable range of values.

CONCLUSION

This paper outlines the development plan, and describes the structure and combustion characteristics of a low NOx combustor.

(1) A dry two stage low NOx combustor for the 73 MW gas turbine has been developed. Full-scale, full-pressure combustion tests confirmed that the goal of 75 ppm (corrected to 15% O2, at 273 K, 40% R.H.) NOx concentration has been achieved.

(2) The combustor is capable of stable switching from one stage combustion to two stage combustion, owing to the fuel-air ratio regulation achieved by controlling the amount of combustion air for the premixed combustion in the second stage.

(3) The low NOx combustor has the potential of reducing NOx concentration further by improving the premixed combustion zone.

REFERENCES