Development of Advanced Combustion Technology for Intermediate Fraction and Heavy Oil

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1. Purpose of Research and Development

Building relationships with the Middle East and other oil-producing countries, as well as the various countries in Southeast Asia, is a vital issue for Japan especially because of our need to secure stable supplies of petroleum fuel, which accounts for the bulk of Japan's energy consumption. For this reason, it is crucial to lend support for energy conservation and preservation of the atmosphere and environment in these countries, since oil continues to rank as a vital form of primary energy. In order to build cooperative relationships, including joint research, with research institutions in these countries, support will be given to R&D covering advanced combustion technology for petroleum fuels in Japan.

In addition, a system will be established to make R&D more practical by establishing research laboratories not only at the Advanced Technology and Research Institute but also at equipment makers. R&D on advanced combustion technology will proceed as follows.

Methods and techniques will be established for assessing the performance characteristics of burners, oil combustion, etc.; techniques for measuring various combustion phenomena will be established, together with simulation methods for estimating or forecasting such phenomena; and basic, oil-combustion technology will be developed, including methods for clarifying the relationships between oil fraction properties, combustion characteristics and NOX generation. In addition to these basic technologies, advanced combustion technologies will be developed which can burn oil fuel, primarily intermediates, purely and at good efficiency. Examples include burner combustion and high-temperature air combustion that will satisfy long-term regulation values in the future.
2. Contents of R&D

(1) Studies were done on low NOx burner of the oil vaporization format and on exhaust gas recycling burner. Concerning relationships to exhaust gas properties, test combustion furnaces were used to examine intermediates.

(2) In simulations of combustion values, the temperature distribution and flow of combustion exhausts inside the furnace and adjacent to burners were examined by making comparisons between simulations and combustion tests.

(3) Respecting fuel properties, the combustibility of heavy oil and of intermediates was examined using thermal analysis techniques.

(4) As for the combustibility of kerosene, a technical survey was conducted and themes were abstracted, then a kerosene accelerated deterioration unit was introduced together with an initial deterioration analyzer.

(5) For the development of a system for evaluating combustion units in the home, a survey was conducted on trends in R&D in Europe, etc., and various other surveys were completed, while steps were also taken to introduce evaluation units.

(6) In order to examine the mechanism of low NOx combustion in high-temperature air combustion, measurements were taken at combustion sites, and the impact of combustion properties on high-temperature air combustion was investigated.

(7) For R&D on systems in the home, all types of combustion formats were examined and screened.

(8) In taking measurements at combustion sites, an investigation was made of the strength of radicals, for instance, through the self-luminescence spectrum, and measurements were taken of secondary flame temperature.

(9) For turndown ratio expansion technology, a study was done on a format in which a low-combustion-volume pilot burner for ratio expansion is added to an existing burner.

(10) In an examination of burner firing mechanism, flame formations were photographed by high-speed camera and firing conditions were observed.

(11) The second Asian Combustion Technology Seminar was held in Malaysia as an international cooperation project.

3. R&D Results and Future Issues
3.1 Development of Low NOx Burner for Commercial Use

(1) Development of low NOx burner

The purpose of the research is to develop a small, low NOx oil burner for commercial use that could satisfy long-term regulations; this theme will be continued until 2004. The final objective for NOx exhaust level is 50 ppm or less with combustion of fuel oil A (nitrogen component 200 ppm). The intermediate goal for the year 2000 was set at 50 ppm or less for kerosene and 70 ppm or less for fuel oil A, but with an exhaust gas self-recycling burner at the base of a trial-produced burner, this fiscal year’s goal was reached.
From research findings last fiscal year, it was discovered that by dividing the air supply for combustion into primary air for the inside and secondary air for the outside, it is possible to achieve exhaust gas self-recycling, and thus target low NOx combustion. This fiscal year, by adjusting the percentages of primary air and secondary air, an investigation was made of the behavior exhibited by recycling exhaust gas and of the impact such behavior has on achieving low NOx. No.1 long pipe, No.1 short pipe, and No.2 renovated pipe were trial produced, but in each case, a recycling port was installed at the base of the burner in order to return recycled exhaust gas to the nozzle upstream component. A typical trial-produced nozzle is shown in Figure 3.1.1.

The results of kerosene combustion and A heavy oil combustion are presented in Figures 3.1.2 and 3.1.3, respectively. Using the type of burner with recycling port at the base, it was found that in both combustion modes, low NOx could be achieved by lowering the percentage of primary air in the total air volume (hereinafter, primary air percentage). In kerosene combustion, the intermediate goal of 50 ppm or less could be reached by reducing the primary air percentage to 20 to 35 % or lower. In A heavy oil combustion, the intermediate goal of 70 ppm or less could be attained by reducing the primary air percentage to 15 to 30 % or lower.

Flame formation also varies greatly with primary air percentage. When the primary air percentage is high, a long luminous flame can be held at the atomizer; at a primary air percentage of 40 % or more, the length of this flame measures about 1.2 m. On the other hand, when the primary air percentage is reduced to 20 % or lower, there is no firing at the atomizer and a lifted flame appears detached from the nozzle. Flame length also shortens, and at a primary air percentage of 20 % or less, the length is about 1 m. In kerosene combustion, when the primary air ratio is reduced, the flame becomes light in color and at 12 % or less, a blue flame appears. In A heavy oil combustion, it was observed that the flame tends to become more or less light in color as the primary air percentage is lowered, but a luminous flame still remains. A photo of the flame when burning kerosene is shown in Figure 3.1.4.

When the primary air percentage has been reduced, primary air becomes mixed with recycled exhaust gas at the fuel atomizer, the concentration of oxygen declines, and a lifted flame is quickly formed without firing. At the atomizer, a relatively uniform flame is formed because pre-vaporization and pre-mixing are promoted so that fuel can be easily vaporized through recycling of high-temperature exhaust gas. As a result, a blue flame of low flame temperature is formed and low NOx is achieved. On the other hand, when the primary air percentage is high, exhaust gas is also recycled, but flame temperature and NOx become high, and this is ascribed to the fact that the oxygen concentration is high at the atomizer, due to differences in dilution rate, and to the fact that an explosive air-fuel mixture is formed which is immediately fired.
Figure 3.1.1 Exhaust Gas Recycling Burner at Base of Burner (No.2 Renovated Burner)

Figure 3.1.2 Primary Air Percentage vs. NOx and Flame Length (Kerosene Combustion)

Figure 3.1.3 Primary Air Percentage vs. NOx and Flame Length (A Heavy Oil Combustion)
Impact of fuel properties on exhaust gas properties

The impact of fuel properties on exhaust gas properties was evaluated by implementing actual burner combustion. The following three types of burner were used for evaluation: 1) single-stage combustion burner as standard burner, 2) low NOx burner on the market, and 3) low NOx burner trial produced at our laboratory. Presented in Figure 3.1.5 are the NOx values obtained when each type of burner was used to burn kerosene, straight distillation light oil (LGO-1, LGO-2), direct desulfurized light oil (DDS), cracked light oil (LCO) and fuel in which nitrogen content was adjusted with quinoline as necessary. The NOx exhaust levels when burning kerosene with each burner were roughly 75 ppm, 50 ppm and 30 ppm.

1) Impact of distillation properties

Three types of burner were used to burn kerosene, straight distillation light oil (LGO-1, LGO-2) and fraction in which the nitrogen content was adjusted with quinoline; NOx exhaust volumes were measured, and the impact of distillation properties on NOx exhaust volumes was investigated. Presented in Figure 3.1.6 are the data from Figure 3.1.5 summarized for an air ratio of 1.3. The straight lines in the figures are proximate lines drawn from the data on kerosene and LGO-1, 2. With the standard burner, the NOx value is higher for kerosene than for LGO, but with both of the low NOx burners, the NOx value is higher for LGO. With the standard burner, because atomized fuel is burnt quickly and the flame is preserved, combustibility is better with light kerosene that can be easily vaporized, and the NOx value becomes high. On the other hand, the low NOx burner has been designed to cause self-recycling of exhaust gas from combustion inside the furnace and to lower the concentration of oxygen at the fuel atomizer, so the flame lifts. Because of the lifted flame, fuel pre-vaporization and pre-mixing takes place until atomized fuel fires, and the impact of the vaporization process on flame formation is weak in comparison to that with the standard burner. For this reason, it is suspected that the combustion temperature becomes high for light oil fraction in which calorification per unit volume is high, and NOx value becomes high.
2) Impact of aromatics

After adjusting nitrogen content with quinoline, straight distillation light oil fraction with little aromatic content and cracked light oil fraction of high aromatic content were burnt; NOx exhaust volumes were measured, and the impact of aromatic content on NOx exhaust volume was investigated. The results are shown in Figure 3.1.7. When the aromatic content was increased, using all three types of burner, it was observed that the NOx exhaust volume tends to decline. This can be ascribed to the fact that, because combustion speed of the aromatic content is slow, flame temperature drops and NOx generation is curtailed.

![Figure 3.1.5 Air Ratio and NOx Value with Each Burner](image)

![Figure 3.1.6 Fuel Nitrogen Content and NOx Value in Each Burner (Air Ratio 1.3)](image)
Figure 3.1.7  Fuel Aromatic Content and NOx Value in Each Burner

(3) Future Issues

Efforts to develop low NOx burners will continue in the future. Differences in the burners themselves, of course, have a large impact on burner performance, but compatibility with the main unit is also an important factor. At present, the only type of test furnace available at our laboratory is the lateral forward flow type, but introduction and evaluation of a vertical test furnace is scheduled for the next fiscal year. Further advances are also expected in internal furnace measurements and in simulation analysis, and the types of phenomena that occur inside the furnace will be verified.
3.2 Numerical Simulation of Furnace Internal Spray Combustion

Research on numerical simulation of furnace internal spray combustion was conducted with the aim of providing support for the creation of a numerical simulation model that represents furnace internal spray combustion, for search of the optimum technology for achieving low NOx using this model, and for design of low NOx burners. The items of implementation this fiscal year are as follows.

(1) Construction of a simulation model

The simulation model of gas combustion developed last fiscal year was improved upon and a numerical simulation model of spray combustion was developed. In the newly developed model, target spaces were demarcated by computational lattice and changes in the physical amount of each control volume were formulated. Then, by solving equations that had been digitalized by difference calculus, an average model was produced for determining time average values at lattice points. Since the bulk of simulations were made in a lateral cylindrical furnace, the model was of two-dimensional axis symmetry. In the solver where digitalized linear equations are solved, the line-by-line method, which is an improvement upon the tri-diagonal matrix algorithm (TDMA), was used. For flow, the Navier-Stokes (NS) equations, which are dynamic equations of viscous fluids, were applied, and the k-e model, which is a type of turbulent viscosity model, was used as the turbulence model. Respecting spray combustion, atomized droplets were mobilized in air current while vaporizing, and a model of vaporized fuel vapor being burnt in a gaseous phase reaction was used. Droplets were represented by the Lagrange method, which treats them as individual particles. The correlation between droplets and gaseous phase was evaluated with a PSI-Cell model. For turbulent combustion in the gaseous phase, an overall reaction rate model was combined with a turbulent particle dispersion model. Presented in Figure 3.2.1 is a comparison of combustion experiments with the results of calculations using the newly-created numerical simulation model. As an example of simulation, furnace internal temperature distribution is shown. In combustion experiments with combustion test furnace, a good match is exhibited between temperature distribution measured inside the furnace and flame configuration in the vicinity of the burner.

(2) Numerical analysis by numerical simulation

A numerical analysis was conducted using the newly developed numerical simulation model. Through numerical analysis of the changes when combustion conditions and flame configuration are altered, an analysis was done on combustion in a combustion test furnace with a vaporization combustion type, low NOx burner under development (shown in Figure 3.1.1), and the low NOx mechanism was elucidated.
1) Changes in combustion by primary / secondary air percentage

For the vaporization combustion type, low NOx burner, a numerical simulation was performed of the case in which the percentages of primary combustion air and secondary combustion air are altered, and a comparative investigation was implemented. In experiments on the combustion test furnace, using this burner, it was found as shown in Figure 3.1.2 that when the primary air percentage is reduced, the NOx exhaust volume diminishes. In the simulation results, it was noted that when the primary air percentage is low, the temperature of the recycled gas passing through the burner's exhaust gas recycle component was high, and the oxygen concentration was low, but conversely, that the total recycled volume was slight. Nevertheless, when the flow of recycled gas was traced through simulation, it was discovered that recycled gas flowing to the outside of the flame when the primary air percentage is high, flows to the inside of the flame when the primary air percentage is low (Figure 3.2.2) From this it can be conjectured that NOx exhaust volume dropped because of a decline in the local oxygen concentration at the flame and a drop in flame temperature.

2) Changes in recycled gas flow due to differences in burner length

The case in which burner length is shortened in order to have a small-sized burner (short-pipe burner) was simulated and a comparison was made with the case of a long burner (long-pipe burner). In experiments with the combustion test furnace, the NOx exhaust volume increased with short pipe as shown in Figure 3.1.2. In an analysis of results by simulation, the volume of recycled gas flowing from the burner recycle port declined in the case of short pipe. Since there were no great differences in burner underside flow and in flame configuration, the slight increase in NOx exhaust volume can be ascribed to a drop in the volume of recycled gas.

3) Future issues

For the development of low NOx burner for even lower NOx in the future, it is not enough to focus on exhaust gas self-recycling technology alone. A search must be made for combustion technology, as never before seen, in which elemental technologies such as flame division or thick and thin combustion are effectively combined. In this case, numerical simulation with two dimensional axis symmetry for the conventional burner is problematic; a three-dimensional model must be introduced. It can also be expected that burner configuration will grow more complex, and in consideration of configuration reproducibility and computational convergence with numerical simulation, the introduction of a model in which the calculation lattice is a nonstructural lattice must also be considered.
Figure 3.2.1  Comparison of Test Results and Numerical Analysis

Figure 3.2.2  Trace of Burnt Gas Recycling Inside Furnace and of Flow to Burner Recycle Port
3.3 **Investigation of Fuel Properties and Combustibility**

Using thermal analysis methods (TG-DTA, DSC), the combustibility of heavy oil and of intermediate fractions was investigated, and the following results were obtained.

(1) **Evaluation by TG-DTA of the combustibility of heavy oil** (Figure 3.3.1)

- In order to investigate the combustibility of residual carbon in late-stage burning of heavy oil, combustion temperatures were measured using oil cokes of similar composition to residual carbon. It was found that combustion begins from around 500 °C, the same as the combustion temperature of residual carbon from heavy oil measured last year.

- For comparison, the combustion temperature of graphite powder obtained from amorphous carbon was measured, and it was found that the combustion temperature is high at 600 to 700 °C. This indicates that the combustibility of oil cokes (residual carbon equivalents) is better than that of the carbon element itself. The reason is ascribed to the combustion promotional action of trace amounts (0.12 %) of residual ash.

(2) **Evaluation by DSC of the combustibility of intermediate fractions**

- DSC measurements were taken of oil fraction after TBP cutting, and it was discovered that combustion temperature correlates with the boiling point range of the fraction. Taking calorification volume per unit weight (watt / gram) as a yardstick, it was observed that the lower the fraction boiling point, the greater the calorification volume; in other words, the faster the rate of combustion. (Figure 3.3.2)

- In order to investigate the impact of sulfur compounds on combustibility, thiophene derivative was used as a model compound for taking DSC measurements. It was found that the combustion temperature of sulfur compounds is drastically skewed to a point much higher than the boiling point. This fact suggests that the sulfur component in oil fractions elevates the combustion temperature; in other words, that it acts to reduce combustion speed. (Figure 3.3.3)

- An investigation was made of the impact on combustibility of changes in four types of container material, especially their surface conditions. With aluminum containers boiled in pure water, it was found that an increase in sulfur content did not lead to a rise in combustion temperature. This is in direct contrast to the trends noted with the other three types of container. On the other hand, with fractions containing oxygen compounds (phenol hydrocarbons), surface treatments had little impact. This indicates that the impact of different elements in oil fraction on DSC measurements varies with the element. With sulfur component in particular, there were cases in which the impact on combustion temperature depended on the surface treatment of the test container. These findings suggest that fractions containing different elements are important for improving accuracy in DSC measurements and for use as combustion indices. They also indicate that more data on such fractions should be accumulated. (Figure 3.3.4)
(3) Future issues

- As part of an effort to determine the combustibility (solid combustion) of residual carbon in heavy oil combustion, data are to be collected on oil cokes, as model substances, that are similar to residual carbon in composition and properties.

- The impact of various elements (e.g., sulfur, nitrogen, oxygen) in oil fractions is to be determined, and data are to be collected for improving the accuracy of such elements as indices of combustibility.

![Figure 3.3.1 DTA Combustion Curves of Oil Coke (Residual Carbon) Platinum Container, Rising Temperature Speed 10 °C / min](image1)

![Figure 3.3.2 DSC Combustion Curves of TBP Cut Fractions Aluminum Test Container: Hexane Washing 10 Times, Baking at 400 °C x 3 hr](image2)
Figure 3.3.3  DSC Combustion Curves of Various Sulfur Compounds
Aluminum Test Container: Surface Vapor Deposition of
Pyrophosphoric Acid Fluorine

Figure 3.3.4  DSC Combustion Curves Using each Type of Container
Phenol Group (MW=220)  2,6-di-t-butyl-4-methyl Phenol
Phenol Group (MW=341)  4,4-methylenebis (2,6-di-t-butyl Phenol)
3.4 Investigation of the Impact of Deterioration on Kerosene Combustibility

The purpose of this theme, which began from the year 2000, is to prevent trouble in combustion arising from kerosene that has been denatured (deteriorated) through long-term storage; for example, kerosene stored over an entire summer. Research was also conducted in order to elucidate the mechanism of kerosene deterioration, to investigate from multiple standpoints the relationship between kerosene deterioration and combustibility, as well as measures for preventing problems from deteriorated kerosene, and to provide consul and proposals to kerosene consumers, combustion equipment makers, oil companies and others.

This fiscal year, as part of a technological survey, the findings of studies conducted thus far on deteriorated kerosene and combustibility were investigated. Themes were abstracted and an outline of research up to the year 2004 was drafted (Figure 3.4.1). Specifications were also studied and decisions were made on equipment to be introduced. Two equipment pieces were introduced in 2000: an ultraviolet irradiation type accelerated deterioration unit (Figure 3.4.2) and a kerosene initial deterioration analyzer (chemiluminescence analyzer; Figure 3.4.3). The ultraviolet irradiation type accelerated deterioration unit was introduced for the purpose of fabricating, over a shorter time period than that of outdoor storage, samples of deteriorated kerosene that have uniform properties. Deteriorated kerosene thus produced can be used for analysis of deteriorated kerosene (deterioration byproducts) or for evaluation of the combustibility of deteriorated kerosene. The chemiluminescence analyzer detects chemiluminescence by radicals generated early in kerosene deterioration. Through determination of the time from oxygen introduction to peak detection, or of the peak gradient (oxidation reaction speed) or of emitted light wavelength, this analyzer can be used to investigate the behavior of kerosene oxidation deterioration reactions, to evaluate additives for curtailing deterioration, or to search for new deterioration indices.

![Figure 3.4.1 Outline of Research on Kerosene Deterioration](image-url)
Figure 3.4.2  Ultraviolet Irradiation Type Accelerated Deterioration Unit (Outline Drawing)

Figure 3.4.3  Kerosene Early Deterioration Analyzer (Outline Drawing)
3.5 Development of a System for Evaluating Home Combustion Units

As part of an effort to provide test equipment to be used for the new theme launched this year, “Development of a System for Evaluating Home Combustion Units,” air-conditioned units were designed, constructed, adjusted and operated. Presented below is an outline of the equipment pieces introduced this year.

(1) Composition

- Air-conditioned room, control and data recorder
- Exhaust gas analyzer and data recorder
- Atmosphere analyzer and data processor / recorder

(2) Major specifications of air-conditioned room

- Temperature range: -20 + 40 °C (no-load time + / - 0.5 °C, at ambient temperature range: -5 °C + 40 °C)
- Humidity range: 20 % - 95 %RH (no-load time + / - 3 %, at 20 °C - 40 °C)
- Ventilation volume: Maximum 200m³ / h
- Floor emission speed: 0.5 m / sec or less

(3) Compound

Installed at the test preparation building, first floor (approx. 40 m² in area).
Layout

Top view of the air-conditioned room is shown in Figure 3.5.1.

Figure 3.5.1  Air-conditioned Room Layout
(First Floor of Test Preparation Building)
Elevation view

Elevation view of the air-conditioned room is shown in Figure 3.5.2.

Figure 3.5.2  Elevation View of the Air-conditioned Room
(First Floor of Test Preparation Building)
Development of Low NOx Combustion Technology for Oil Using High-temperature, Lean Air

High-temperature air combustion technology and its application to oil spray combustion

High-temperature air combustion technology is distinguished for being a low NOx combustion technology of high efficiency that can be used for downsizing, etc. It has spread primarily for gas combustion in furnaces in steel-related industries. In order for this technology, with its various special features, to become more widespread in the future, it will have to be applied not only to gas combustion, but also to combustion of liquid fuels such as oil, which accounts for the bulk of Japan’s energy, as well as coal and other solid fuels. It will also have to be made applicable in a wide variety of combustion facilities, not just heating furnaces or industrial furnaces for heat treatment.

In developing this technology, attention was initially focused on improvement of efficiency through exhaust heat recovery using heat accumulator. But under present conditions, as more attention is being devoted to environmental problems, the development of this technology as a low NOx combustion technology has become a vital issue. And for this purpose, it is crucial to elucidate the mechanism of low NOx combustion and to proceed with developments based on such elucidation. In addition, recent advances in R&D have been made, using high-temperature steam as well as high-temperature air, and this has captured attention as a new technology.

The objective in applying high-temperature air combustion to spray combustion of oil is as follows. By using high-temperature air in excess of 800 °C, combustion becomes possible at a very low oxygen concentration because atomized fuel is exposed to an atmosphere of much higher temperature than its self-firing temperature. Further, because combustion is slow, it becomes uniform without producing local, high-temperature areas, and thermal NOx is drastically reduced. Moreover, combustion of lower NOx than in gas combustion becomes possible because under these combustion conditions, fuel vaporization is rapid, there is thermal cracking/reformation, and the mixture with oxygen becomes uniform. There are numerous types of fuel oil, including kerosene, A heavy oil and C heavy oil, and they possess a wide variety of physical properties such as kinematic viscosity, density, distillation properties and chemical properties. In high-temperature air combustion, low NOx combustion is possible regardless of the type of oil, even if it is heavy oil or fuel oil difficult to burn. It is also possible to reduce fuel NOx because the combustion mechanism differs from that of regular combustion.

At PEC laboratories, where progress is being made in the development of low NOx combustion using oil, attention has focused on high-temperature air combustion technology and studies are being done on applying this technology to oil spray combustion. By the last fiscal year, it was discovered that low NOx combustion, as found in the combustion of LPG or other gases, is possible also when burning liquid fuels such as kerosene. Differences in effect on the combustion of diluted gas producing air of low oxygen concentration were also elucidated. Findings from investigations made this year are presented below.
(2) Examination of the mechanism of low NOx combustion using high-temperature, lean air

(a) Measurement of temperature distribution in high-temperature air combustion flame

Figure 3.6.1 shows the distribution in temperature when kerosene has been burnt while changing its oxygen concentration. An R type thermocouple of element wire diameter 0.1mm was used for measurements. As shown in Figure 3.6.1a, measurements were taken at 9 points horizontally and 6 points vertically. The upper half (b to c) of the figure shows the distribution when nitrogen was used in dilution gas, and the lower half (dtof) represents the case of dilution with carbon dioxide. Since the oxygen concentration is 20.7 % in both cases, it was shown only in (d) below. As the figure indicates, at 20.7 % oxygen concentration, where a strong luminous flame is observed, the high-temperature portion is large. In contrast, whenever any of the gases is used for dilution, the high-temperature portion disappears as the oxygen concentration declines, and a uniform temperature distribution is manifested. What is more, the extent of low temperature and uniformity is greater with carbon dioxide than with nitrogen. At 11 % oxygen concentration, the maximum temperature in the case of nitrogen dilution is 1460 °C whereas in the case of carbon dioxide dilution, it is 1360 °C, or 100 °C lower. This temperature difference can be explained by the difference in specific heat of the dilution gas. It is understood that the scarcity of such local high temperature portions led to a drop in the production of thermal NOx, which is largely dependent on temperature. This does not conflict with the fact that the drop in NOx is actually greater with carbon dioxide than with nitrogen.
In the combustion flame, OH radical, CH radical or C₂ radical, for instance, can be observed. Flame color is determined by luminescence from these radicals. The green flame, for instance, which is observed exclusively in high-temperature air combustion, is assumed to be the Swan band of C₂ radical luminescence. By measuring these chemical species luminescence distributions, the combustion reactions occurring within combustion flame were assessed.
In taking measurements, flame luminescence was divided by spectroscope, and a luminescence spectrum was obtained from the producing radicals. Next, there was attached a band pass filter that transmits in the vicinity of luminescence from the radical to be measured, and a two-dimensional distribution image was measured. Figure 3.6.2 represents measurements of two-dimensional luminescence distribution from each radical when carbon dioxide is the dilution gas and oxygen concentration is changed.

As shown in the figure, at 20.7 % oxygen concentration, the luminescence of the flame from each radical exists near the center, but as the oxygen concentration diminishes, the distribution spreads outward and luminescence becomes weaker. Moreover, whereas there are a lot of OH radicals at the location where the flame begins to form, CH radicals and C\textsubscript{2} radicals are produced slightly downstream from this location. It is known that these radicals are produced where the combustion reaction becomes vigorous, and it was clarified that combustion as a whole takes place more slowly as the oxygen concentration declines. From observing such a chemical species luminescence distribution, it is suspected that in high-temperature air combustion, the chemical reaction takes place uniformly and NO\textsubscript{x} generation is curtailed.
(c) Effect of dilution gas percentage

Shown in Figure 3.6.3 is a photo of the flame observed when the oxygen concentration is held constant at 6 % and the percentages of carbon dioxide and nitrogen gas are varied; also shown is the self-luminescence spectrum. Going from left (a) to right (b), nitrogen gas declines and carbon dioxide increases. At (a) a green flame is observed, and from the self-luminescence spectrum also, it can be seen that the strength of the C₂ radical increases relatively. As nitrogen gas diminishes and the percentage of carbon dioxide increases, the flame color changes to blue and then to purple. From the spectrum it was discovered that, first of all, the relative strength of the C₂ radical diminishes, then the strength of the OH radical, and finally that of the CH radical, declines, while the luminescence, from ultraviolet to purple and blue in the visible spectrum, gains in relative strength. Absolute strength, however, grows weaker as the percentage of carbon dioxide increases. The NOx discharge values in these cases are represented in Figure 3.6.4. The value drops sharply as the carbon dioxide percentage escalates, and with carbon dioxide at 40 % or more, the NOx discharge value becomes low and does not change hardly at all. These results indicate that the NOx reduction effect of carbon dioxide is greater than that of nitrogen gas. By observing the flame color thus and measuring the self-luminescence spectra, the NOx exhaust characteristic of combustion flame can be determined, providing a major index for the development of low NOx combustion technology and combustion equipment.

Figure 3.6.3 Changes in Flame Color and in Self-luminescence Spectrum due to Differences in N₂ / CO₂ Ratios Numerical Values are N₂ % / CO₂ %
In high-temperature air combustion, because the fuel is quickly exposed to a high-temperature atmosphere, the speeds of fuel evaporation and thermal cracking are rapid regardless of fuel distillation properties or chemical properties; a uniform combustion site is formed, and low NOx combustion can be expected. At this stage, fuel properties were varied and high-temperature air combustibility was evaluated. In addition to kerosene, LGO and HGO were examined as fuels. The properties of these fuels are presented in Table 3.6.1.

Shown in Figure 3.6.5 are the results of an examination of NOx emission characteristics using these fuel oils. In combustion with regular 21 % oxygen concentration, the NOx emission value increased in the sequence: LGO < kerosene < HGO. A higher NOx emission value was obtained with kerosene than with LGO. This might be explained by the fact that the evaporation speed of kerosene is rapid, since its boiling point range is lower than that of LGO, and by the fact that a violent reaction with oxygen takes place, and local high-temperature portions can be easily produced. With HGO, on the other hand, the spray for the available nozzle was not good because HGO has a high kinematic viscosity, and it is suspected that the NOx emission value was high because a luminous flame of uneven strength in brightness was produced.
Table 3.6.1  Test Fuel Properties

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Kerosene</th>
<th>LGO</th>
<th>HGO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [g / cm$^3$]</td>
<td>0.794</td>
<td>0.847</td>
<td>0.894</td>
</tr>
<tr>
<td>Kinematic viscosity [mm$^2$ / S]@50 °C</td>
<td>1.05</td>
<td>3.05</td>
<td>13.98</td>
</tr>
<tr>
<td>Distillation properties (°C)</td>
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<td></td>
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<tr>
<td>5VOL %</td>
<td>139</td>
<td>202</td>
<td>308</td>
</tr>
<tr>
<td>20VOL %</td>
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<td>262</td>
<td>370</td>
</tr>
<tr>
<td>50VOL %</td>
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<td>305</td>
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</tr>
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<td>347</td>
<td>431</td>
</tr>
<tr>
<td>95VOL %</td>
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<td>377</td>
<td>486</td>
</tr>
<tr>
<td>Nitrogen content percentage [ppm]</td>
<td>Less than 1</td>
<td>93</td>
<td>450</td>
</tr>
<tr>
<td>Chemical properties [%]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturation component</td>
<td>83.8</td>
<td>74.5</td>
<td>53.4</td>
</tr>
<tr>
<td>Aromatic component (1 ring)</td>
<td>15.7</td>
<td>14.1</td>
<td></td>
</tr>
<tr>
<td>Aromatic component (2 ring)</td>
<td>0.5</td>
<td>9.1</td>
<td>45.2</td>
</tr>
<tr>
<td>Aromatic component (&gt;3 ring)</td>
<td>0</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Lower calorific value [kJ / g]</td>
<td>46.0</td>
<td>42.8</td>
<td>42.2</td>
</tr>
</tbody>
</table>

Figure 3.6.5  NOx Emission Pattern of Each Fuel Oil

As indicated in Figure 3.6.5, in the domain of high-temperature air combustion with reduced oxygen concentration, low NOx combustion is obtained with any of the fuel oils. This also becomes evident from flame observation. As the oxygen concentration reduces, the flame becomes larger, portions of strong luminous flame are reduced, and uniform combustion is noted. Further, the combustion flame becomes more uniform with carbon dioxide than with nitrogen, and this is especially true in HGO combustion.

From the aforementioned, it has thus become evident that low NOx combustion is possible by burning in the domain of high-temperature air combustion with low oxygen concentration regardless of fuel distillation properties and even if fuel of high viscosity, such as HGO, is used.
(3) Synopsis

(a) Temperature distribution and chemical species self-luminescence distribution were measured. It was clarified that in the domain of high-temperature air combustion with low oxygen concentration, the temperature becomes low, distribution becomes uniform, and chemical species also exist uniformly. In this way, it became clear that low NOx combustion is achieved.

(b) In terms of low NOx combustion, carbon dioxide has a greater effect as a dilution gas than nitrogen. By varying the mixture percentages, the flame can vary between green and purple, but combustion status can be assessed and low NOx combustion can be determined by measuring the self-luminescence spectra.

(c) High-temperature air combustion of kerosene, LGO and HGO, all with different distillation properties, was evaluated. At the regular oxygen concentration of 21%, NOx emission values vary, but in the realm of high-temperature air combustion at low oxygen concentrations, it was clarified that low NOx combustion is possible in all cases.

(4) Future schedule

(a) Evaluate high-temperature air combustion with A heavy oil, C heavy oil and other fuel oils.

(b) Take steps to establish fuel NOx reduction technology.

(c) Introduce high-temperature steam into combustion furnace and realize low NOx combustion even with C heavy oil.

(d) Install a high-temperature air combustion furnace of about 400,000 kcal / hr and evaluate high-temperature air combustion.

(e) Continue basic research on such things as oxygen concentration measurement and chemical species measurement in order to establish even lower NOx combustion technology.
3.7 R&D on Home System Using Closed Vaporizing Bunsen Burner

Shirane No.1 Combustion Laboratory

1. Objective of R&D

There are approximately 26 million units of oil fan heater in use throughout Japan, and its role as the main heater has become established. Yet as living environments become more and more air-tight, concern about indoor exhausts has begun to surface.

The purpose of the present R&D is to develop a closed vaporizing Bunsen burner, by using a closed vaporizing combustion format, which accounts for roughly half of total sales volume, and by reducing to a very minimum emissions of nitrogen oxides and trace amounts of substances not fully burnt.

The final target of this R&D is to achieve the following values in a kerosene burner for 5 to 10 kw oil fan heater.

- NOx emission value: 60 ppm or less (CO2: 15.2 % conversion result)
- CO emission value: 20 ppm or less (CO2: 15.2 % conversion result)

2. R&D Contents and Results

2.1 Investigative research on current fan heater

An investigation of fan heaters currently on the market revealed that most of such heaters employ a flame holder (component that covers like a ring the perimeter of the flame hole surface) and simplified two-stage combustion. Standard NOx emissions is about 100 ppm and CO emissions is about 50 ppm.

2.2 Evaluation of effectiveness of various low NOx combustion formats

Two-stage combustion, thick and thin combustion and ceramic burner, each of which is considered effective in reducing NOx, was trial produced, and a comparative evaluation was made of exhaust gas properties.

Of these, the properties of exhaust gas from two-stage combustion are presented in Figure –1.

The test conditions were as follows. The primary air percentage was fixed at 0.9 and NOx and CO emissions were measured after secondary air was introduced at a height of 0 to 150 mm with flame holder present (20 mm in height) and with no flame holder.

The following findings were obtained

a) While secondary air was introduced at a height of up to 50 mm, the NOx emissions value dropped sharply, then declined slowly.

b) When secondary air was introduced at a height of 100 mm or higher, the CO emissions value rose easily.

c) In a comparison with and without flame holder, it was found that with the holder present, the NOx emissions dropped slightly while the CO emissions rose slightly.
d) Under test conditions in which the primary air percentage was fixed at 0.9, a flame holder (20 mm in height) was present and the secondary air was introduced at a height of 100 mm, the NOx emissions value was recorded at 58 ppm and CO emissions was at 74 ppm.

![Graph showing measurements of exhaust gas properties](image)

**Figure 3.7.1** Measurements of Exhaust Gas Properties in Two-stage Combustion Format

**Table 3.7.1** Overview of Exhaust Gas Properties in Two-stage Combustion, Thick and Thin Combustion and Ceramic Burner Format

<table>
<thead>
<tr>
<th>Combustion format</th>
<th>NOx emission value (ppm)</th>
<th>CO exhaust value (ppm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard burner</td>
<td>113</td>
<td>2</td>
<td>No flame holder and secondary air introduced at 0 mm height.</td>
</tr>
<tr>
<td>Two-stage combustion</td>
<td>Secondary air introduced at 100 mm height 58</td>
<td>74</td>
<td>When the height at which secondary air is introduced exceeds 100 mm, the merits are few.</td>
</tr>
<tr>
<td>Thick and thin combustion</td>
<td>$\lambda = 1$ 93</td>
<td>29</td>
<td>It is difficult to establish two types of thick and thin combustion with one kerosene vaporizer.</td>
</tr>
<tr>
<td>Ceramic burner</td>
<td>$\lambda = 0.6$ 82</td>
<td>44</td>
<td>Because combustibility is good, combustion appears possible where primary air percentage is low.</td>
</tr>
</tbody>
</table>
From a comparison of two-stage combustion, thick and thin combustion and ceramic burner, it appears that two-stage combustion offers the greatest chance of achieving low NOx.

Two-stage combustion alone, however, is limited; it must be integrated with other combustion formats and investigated.

3. **Future Issues**

At present, it appears that two-stage combustion offers the greatest possibilities, but interest has also focused on the merits of ceramic burner combustibility; these two formats could also be integrated.

Evaluations will continue to be made and efforts will focus on the optimum combustion method, with integration also taken into consideration.
3.8 Development of Low NOx Burner of Pre-volatilization, Pre-mixing Format for the Home

Sanjo No.1 Combustion Laboratory

1. Measurement of Self-luminescence Spectrum at Combustion Site

The self-luminescence spectrum of secondary flame from a 5 kW kerosene burner made by the Corona Company was measured.

Spectra corresponding to the OH radical, CH radical and C\(_2\) radical were observed, and it was found that the strength of these spectra were roughly dependent on combustion volume.

2. LIF Measurement at Combustion Site

In order to investigate the distribution of radicals at the combustion site, the LIF of secondary flame from a 5 kW kerosene burner made by the Corona Company was measured. Sample measurements are shown below.

![LIF image of OH at irradiation position (1) →](image)

3. Flame Temperature Measurement by Polar Thermocouple (Preliminary Test)

In order to obtain accurate measurements of flame temperature, measurements by polar (0.025 mm element wire diameter) thermocouple were investigated. As a preliminary test, measurement values and responsiveness were examined upon measurement of the temperature of secondary flame from a 5 kw kerosene burner made by the Corona Company, using R thermocouple of element wire diameters: 0.025 mm, 0.1 mm and 0.3 mm.

As indicated by the right-hand figure, there are great differences among measured values and responsiveness.
Secondary flame temperature measurement (with coating)

<table>
<thead>
<tr>
<th>Temperature [℃]</th>
<th>1500</th>
<th>1450</th>
<th>1400</th>
<th>1350</th>
<th>1300</th>
<th>1250</th>
<th>1200</th>
<th>1150</th>
<th>1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elapsed time [seconds]</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>14</td>
<td>16</td>
</tr>
</tbody>
</table>

- Ø0.3mm
- Ø0.1mm
- Ø0.05mm
3.9 Development of Broad Turndown Ratio - Low NOx Oil Burner

Matsuyama No.1 Combustion Laboratory

1. Development of Broad Turndown Ratio - Low NOx Oil Burner

There are various possible methods of expanding burner turndown ratio. One method is to install a multiple number of burners and switch among them according to load requirements; another method is to expand the range of stable combustion to the low-load region by improving the burner itself. In the present research, turndown expansion was investigated by using a fuel spray nozzle that takes a large turndown ratio together with an integrated format in which combustion by pilot burner was added to the existing burner with three positions: HIGH – LOW – OFF.

Used as the base burner in the study was a burner for boiler with vaporization volume equivalent to 2000 kg / h, as shown in Figure 1; the combustion volume was 1390 kW (1.2 million kcal / h). Due to the limitations of the pressure spray fuel nozzle on the market, the cubic capacity of the pilot burner mounted on the base burner was 46.5 kW (40,000 kcal / h), and A heavy oil was used in test combustion.

Two types of pilot burner structure were investigated. One is the main coaxial type burner in which the pilot burner is set at the center of the main burner for simplified overall burner structure. The other is the separate pilot burner type in which a general-purpose pilot burner is installed separately from the main burner so that interference with the main burner can be minimized. For improvement of the main burner itself, improvements using a binary fluid spray nozzle were investigated.

1.1 Development of Main Coaxial Type Pilot Burner

Pilot burner configuration and installation method are shown in Figure 2, where we can see that the pilot burner is installed at the center of the main burner. The flow of air for combustion is divided into two categories: primary air which flows through the center of the main burner as air for main burner combustion, and secondary air which flows over the outer periphery of the primary air. In this structure, primary air is used both as the primary air for the pilot burner shown in Figure 2 and as secondary air.
The combustibility of this type of burner is represented in Figure 3. It can be seen that although good combustibility can be obtained when there is no air (main secondary air) from the main burner (Figure a), combustibility becomes poor when main secondary air is introduced as shown in Figure b. This is ascribed to the cooling action of the secondary air. It was also found that during main burner combustion, the flame from the pilot burner goes out and a stable flame cannot be maintained.

Figure 2. Detailed View of Main Coaxial Burner

Figure 3 (a) Main Air Absent

Figure 3 (b) Main Air Present
1.2 Separate Pilot Burner

As shown in Figure 4, the separate pilot burner is detached from the main burner and its position is determined, in consideration of main burner flame position, flame configuration, and position relative to furnace internal waterwall, etc., so as to have minimum adverse effect on firing and combustibility. In principle, its size and configuration match those of the coaxial type pilot burner.

Combustion with this type of pilot burner is represented in Figure 5. Combustibility of the separate pilot burner is affected by auxiliary burning or cooling action of air for main burner combustion. It was found that with the present-day pilot burner, air for combustion from the main burner must be reduced to about one-third for initiating combustion. Test results with the pilot burner under these conditions are presented in Figure 2. The targeted combustion performance of CO < 100 ppm, smoke < 1 could be reached.

Variations in the combustibility of main burner when the pilot burner is burning and not burning are shown in Figure 6 (a) and Figure 6 (b), respectively. There was no problem in transfer of flame from pilot burner to main burner, but it was confirmed that the presence of the pilot flame had an adverse effect on combustibility. In the future, in conjunction with targeting low NOx, ongoing efforts will be directed toward resolving this problem.

Figure 4. Separate Pilot Burner Installation View

Figure 5. Pilot Burner Combustibility
1.3 Binary Fluid Spray Nozzle

An evaluation was made of spray characteristics using a binary fluid spray nozzle (Figure 7) made by the Ikeuchi Company. Measurements were taken of flow characteristics at each flow volume and at each discharge pressure of fuel fluid and spray assist air.

From measurement results (Figure 8), it was confirmed that a turndown ratio of 1:10 or above can be attained.
Figure 8. Flow Characteristics of Binary Fluid Spray Nozzle

2. Establishment of Combustion Simulation Technology by Combustion - Heat Flow Dynamics Analysis

Combustion and heat flow dynamics analysis software available on the market was investigated and screened with the aim of establishing combustion simulation technology for application to other types of equipment.

As a result of the screening, STAR-CD Ver3.1 by CD-ADAPCO JAPAN Company was purchased, models were created and analysis methods were acquired.

3.10 Analysis of Advanced Combustion Burner Firing Mechanism and Development of Firing Unit

Honatsugi No.1 Combustion Laboratory

1. Analysis of Pressure Vibration Waveform Upon Firing

A pressure transducer was used to measure and analyze window box internal pressure during firing with a 129 kW trial-produced burner, furnace internal pressure and the vibration waveform produced by the difference in these two pressures.

It was discovered that pressure vibration during firing can be reduced by elevating window box internal pressure.
2. Verification of Decline in Pressure Vibration Upon Firing

Using a 129 kW trial-produced burner (2) with elevated window box internal pressure, repeated tests of time-limited firing were conducted up to 5,500 times, and the practical advantages of reduced pressure vibration during firing were verified.

As a result, it was determined that soot adherence to fuel spray nozzle or ignition electrode, which are important indices for securing reliable firing performance, was slight and that pressure vibration is reduced upon firing.
3. Analysis of Firing by High-Speed Photography

Firing with a 129 kW trial-produced burner (3) was photographed at high speed (10,000 frames / second) and analyzed. It was discovered that the position of initial flame formation was not close to the ignition electrode tip but in a region where oil and air flowing downstream along the burner main axis are mixed for a suitable air-fuel ratio.
4. Analysis of Wind Velocity Distribution Near Position of Initial Flame Formation

Wind velocity distribution near the position of initial flame formation by a 129 kW trial-produced burner (3) was measured, using two-dimensional hot-wire anemometer, and analyzed.

![Figure 3.10.6 Distribution of Average Wind Velocity Along Burner Main Axis](image1)

![Figure 3.10.7 Distribution of Turbulence Strength Along Burner Main Axis](image2)

It was discovered that the area around the position of initial flame formation was one of relatively low average wind velocity along the burner main axis or low turbulence strength.

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