Development of advanced combustion technology
for middle cut and heavy oil

1. Contents of R&D

1.1 Objectives of R&D

To secure stable supplies of petroleum fuel, which accounts for the majority of energy source demands in Japan, it is crucial to build relationships with the Middle East and other oil producing countries and with the countries of Southeast Asia. Moreover, petroleum ranks as the primary source of energy in these countries as well. Cooperative ties, including joint research, are being forged with research institutions in these countries covering external petroleum combustion technologies with the aim of atmospheric and environmental protection in these countries and energy conservation. In order to support these activities domestically, the following targets have been set and R&D on advanced combustion technology is being pursued.

First to be considered is the establishment of fundamental technologies to evaluate petroleum combustion performance of burners. They include: methods and technologies for evaluating characteristics of burners; technologies for measuring various combustion phenomena; simulation techniques for estimating and forecasting such phenomena, and methods for clarifying the relationships between the properties of oil fractions, combustion characteristics and NOx generation. In addition, based on these base technologies, advanced combustion technologies are being developed, targeted mainly at middle cuts, so that petroleum combustion can be carried out with greater cleanliness and efficiency. Examples include burner combustion, high temperature air combustion and catalytic combustion which will be able to meet long-term regulation values in the future.

1.2 Background of domestic support research

(1) In Japan, petroleum fuel accounts for the bulk of fuels not only for transportation but also for private consumption, commerce and industry. It plays a vital role in our national life, and in the 21st century, the most important mission for the petroleum industry will be to maintain stable supplies of petroleum. On the other hand, reduction of carbon gas, NOx and other exhaust gases produced by combustion of fossil fuels has become a global issue, and countermeasures against petroleum combustion, in view of their relevance in this respect, can be described as the most important topics.

(2) Petroleum fuel contains nitrogen compounds and, in contrast to city gas, LPG or other gaseous fuels, processes such as atomization and vaporization are required since it takes place in liquid form. For these reasons, petroleum combustion process is therefore complex and applications of technological developments have been late in coming. In recent years, environmental regulations on NOx, for instance, have been made stricter in large metropolitan centers, and fuel shifts are being made to gaseous fuels that can be easily applied. There are regional restrictions on the supply of city gas, and it is forecast that this will bring great confusion to national life in the future.
In its pursuit of application technologies for petroleum fuel, the petroleum industry has placed greatest emphasis on fuels for transportation. For combustion technologies employing burners, it is dependent upon the efforts of the equipment-related industries. Its results, as compared with those of the city gas industry, are far behind. As Japan's largest energy supply industry, the petroleum industry will have to prepare an R&D system and pursue development of combustion technologies. The equipment-related industry has a large number of small and medium-sized makers and their technological developments covering petroleum combustion are outdated. For commercial fields where regulations are the strictest, the industry will have to proceed with cooperation from the equipment industry.

With diversification of crude oil sources and changes in the structure of demand, the range of properties in fuel base materials is forecast to widen far beyond the conventional range, and this in turn will have an impact on combustibility. Accordingly, along with development of combustion technology for clean burning of these base materials, efforts will be directed toward determining the relationships between fuel properties and combustibility and toward creation of a combustibility index that is effective for designing products in which various fuel base materials are mixed.

1.3 R&D targets and contents

(1) Development of combustion based technologies: Establishment of technology for evaluating burner performance, for instance, using a combustion furnace; establishment of combustion diagnostic technology through measurements with laser of such things as temperature, atomized droplet diameters, droplet velocities and chemicals species in flames; establishment of base technologies covering combustion as far as those for the various processes involved in simulating combustion for the sake of optimization; and development of technology for burner combustion of higher performance which can be used in petroleum combustion equipment for commercial applications such as boilers, hot water suppliers and absorption-type hot and cold water units.

(2) Development of burner combustion technologies: Establishment of vapourizing combustion technology for kerosene which is equivalent to that of natural gas; and development of a burner combustion technology which surpasses the current low NOx emission technology through use of a high-temperature, internal exhaust-gas recirculation method and/or a low-pressure air support atomization method for heavy oil A. The intermediate goal for the end of fiscal year 1999-2000 is to reach NOx on the order of 50ppm (O2: 0% conversion, same hereinafter) with kerosene and on the order of 70ppm with heavy oil A, under a furnace load equivalent to that of a small boiler. Developments will be targeted at reaching NOx on the order of 30 ppm with kerosene and 50 ppm with heavy oil A by the final fiscal year. Along with clarifying the extent to which low NOx emission can be achieved with kerosene and heavy oil A, the exhaust characteristics of harmful substances including those not yet under regulation (e.g., N\textsubscript{2}O, dioxin, polycyclic aromatics) will be investigated.

(3) Development of new advanced combustion technologies: Concurrent with the aforesaid investigations, high temperature air combustion and catalytic combustion technologies will be developed as new, advanced combustion technologies which can comply with very long-term regulations.
(4) Creation of combustibility index: Using such things as a differential scanning calorimeter (DSC), differential thermal analysis (DTA) and a laminar flow reactor, efforts will be made to clarify the relationships between combustibility and the composition/properties of oil fractions and the NOx formation mechanism of combustion. A database will be constructed to serve as a reference for creating combustibility indices and for designing fuels.

(5) Construction of international cooperative relationships: In regards to the development of petroleum combustion technologies, a broad range of cooperative ties (including exchanges of information, sponsorship of symposiums, exchanges of researchers, and pursuit of joint research) will be constructed with oil producing countries and with various other countries in Southeast Asia and elsewhere that are relevant to the stable supply of petroleum.

2. Empirical research results and analysis thereof

2.1 Fundamental combustion research (1) Combustion technology development

Last fiscal year, the relationships between fuel pressure (atomization) and combustibility were investigated primarily in pressure spray burners, which are widely used in oil-burning boilers, along with fuel properties and combustibility by conventional burners. For the relationship between spray pressure and combustibility, kerosene and heavy oil A were tested as fuels. For fuel properties and combustibility, 14 fuel types were used, including kerosene (1), heavy oil A (2), high calorie heavy oil A (2), Light Gas Oil (LGO) (2), Light Cycle Oil (LCO) (2), Light fraction LGO, coker cracked LGO, and normal paraffin mixture (2). Typical properties of a number of oil types are listed in Table 2.1-1.

Table 2.1-1 Typical fuel properties

<table>
<thead>
<tr>
<th></th>
<th>Density</th>
<th>Viscosity</th>
<th>Carbon content</th>
<th>Hydrogen content</th>
<th>Nitrogen content</th>
<th>Aromatics content</th>
<th>Distillation properties</th>
<th>Gross heating value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/cm³</td>
<td>mm²/s</td>
<td>wt%</td>
<td>wt%</td>
<td>ppm</td>
<td>wt%</td>
<td>(°)</td>
<td>J/g</td>
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<td>Kerosene</td>
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<td>1.433</td>
<td>85.9</td>
<td>13.9</td>
<td>1</td>
<td>19.4</td>
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<td>201</td>
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<tr>
<td>Normal paraffin mixture</td>
<td>0.7484</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>0</td>
<td>0</td>
<td>193</td>
<td>202</td>
</tr>
<tr>
<td>LCO</td>
<td>0.8789</td>
<td>1.723</td>
<td>88.5</td>
<td>11.2</td>
<td>107</td>
<td>64.7</td>
<td>213</td>
<td>223</td>
</tr>
<tr>
<td>Heavy oil A</td>
<td>0.8767</td>
<td>4.766</td>
<td>87.4</td>
<td>12.2</td>
<td>294</td>
<td>43.1</td>
<td>250</td>
<td>290</td>
</tr>
<tr>
<td>LCO</td>
<td>0.9200</td>
<td>3.037</td>
<td>89.3</td>
<td>10.4</td>
<td>182</td>
<td>69.1</td>
<td>236</td>
<td>266</td>
</tr>
<tr>
<td>High calorie heavy oil A</td>
<td>0.9274</td>
<td>4.208</td>
<td>89.1</td>
<td>10.6</td>
<td>619</td>
<td>68.3</td>
<td>257</td>
<td>285</td>
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<tr>
<td>LCO</td>
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<td>89.3</td>
<td>10.4</td>
<td>182</td>
<td>69.1</td>
<td>236</td>
<td>266</td>
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</tbody>
</table>

3
(1) **Atomization and combustibility**

By changing fuel pressure under the prescribed flow rate, using a nozzle of different rated capacity with the pressure spray burner, the state of atomization was changed. From research conducted 2 years ago it became clear that the average droplet diameter after spraying depends upon fuel pressure and is almost totally unaffected by nozzle capacity. Figure 2.1-1 and Figure 2.1-2 show the spray droplet sizes (Sauter’s mean diameter) and NOx emissions for kerosene and heavy oil as a function of fuel pressures. Droplet sizes were measured using water and the NOx emissions were measured at 1:2 air-fuel rates and fuel flow rates of 40L/h and 50L/h.

![Droplet diameter and NOx emission as a function of fuel pressure (kerosene)](image1)

![Droplet diameter and NOx emission as a function of fuel pressure (heavy oil A)](image2)

Figure 2.1-3 shows the NOx and CO emission as a function of air volume for spraying at 50 L/h flow rate and air ratio of 1.26 in the case of internal mixture type burner.

![NOx emission and atomizing airflow rate (heavy oil A)](image3)

From these figures it can be seen that within the range of droplet diameter, as fuel pressure or spray air volume is reduced, fuel atomization worsens and NOx formation tends to decline. This is ascribed to the fact that as fuel droplet diameter became large, combustion velocity slowed down, and flame temperature dropped.
(2) Fuel properties and combustibility

Two years ago, because of limited facilities, fuel properties and combustibility were investigated at a low volumetric heat load of about 400,000 kcal/m³h. Last year, experiments were conducted in the range of 1,200,000 ~ 1,500,000 kcal/m³h, using conventional burners. The fuel types used are the same listed in Table 2.1-1.

Using heavy oil A and materials of heavy oil A, aromatics were adjusted within the range of 25 wt% ~ 70 wt%; pyridine was added as a nitrogen compound to LGO and these were burnt at a flow rate of 50L/h, 1.25 air-excess ratio and 1,200,000 kcal/m³h volumetric heat load. The results are shown in Figure 2.1-4.

![Figure 2.1-4](image)

**Figure 2.1-4** NOx vs. nitrogen contents in fuel oils of different aromatic contents

Given that the conversion rate of the nitrogen compound in fuel into NOx emission is about 70%, the aromatic hydrocarbons do not have a striking effect on NOx formation, but when aromatic contents are increased, NOx formation tends to be suppressed.

Figure 2.1-5 shows the NOx emission characteristics of kerosene, n-paraffin replicating the distillation properties of kerosene, and the light fraction of LCO, combined with the aforesaid emission results. At the same level of nitrogen in the fuel oil, NOx level is much higher in the combustion of kerosene than that of heavy oil A. In a comparison of n-paraffin with kerosene (taking the same distillation property), a blue flame was clearly observed with the normal paraffin and its combustibility was good, but no significant difference in NOx formation could be noted. The light fraction of LCO, with its higher aromatic content (64.7%) than kerosene (19.4%), produced luminous flame: almost no blue flame, unlike that manifested in kerosene combustion. NOx generation in this fuel was clearly lower than in kerosene to which pyridine was added to the same level of nitrogen content in LCO.
Figure 2.1-5  Effect of distillation properties on NOx generation

When the fuel has heavy distillation fraction or aromatic content, combustion speed slows down and NOx generation can be suppressed with conventional burners. Therefore, it can be inferred that if a combustion method can be developed in which fuel NOx is suppressed in this way, heavy oil and the oil with high percentage of aromatic compounds will definitely not be undesirable approaches.

2.2 Fundamental combustion research (II) Analysis of fuel spray atomization

Last year, spray characteristics were determined by cross-sectional measurements for pressure spray nozzle and calculations were made of spray droplet diameters.

(1) Two-dimensional cross-section analysis of spray

In a pressure spray nozzle, characteristics of the spraying state was measured over a two-dimensional cross section. A water spray system and a phase droplet particle analyzer (PDPA) purchased in 1996 were used in the experiments. Several types of nozzle sold on the market for general use were employed. The measurement method was as follows. The measurement cross-section was divided; spray droplets were measured at each measuring point and these measuring points were taken collectively as representing the planar surface. Measurement conditions were set so that the number of droplets measured exceeds 8000 at a data rate of 100 Hz or more on the PDPA.

(a) Evaluation of spray characteristics by nozzle

Of the pressure spray nozzles sold on the market, and owned by the laboratory, a number of different sizes and by different manufacturers were freely selected. Cross-sectional measurements of the spray characteristics of each nozzle were taken and differences in spray conditions by nozzle were evaluated. Comparisons were made of spray droplet average diameter (arithmetic mean diameter, Sauter’s mean diameter), average velocity and maximum velocity, but no striking differences due to different nozzles, could be noted.
(b) Examination of spray characteristics by water flow rate

The characteristics of spraying was also investigated after injected water flow rates were changed. It was found that velocity distribution and droplet diameter distribution change when water flow rate is changed, and also that the position of the vortex formed on the outside of the spray changes. When the water flow rate is slight, droplet velocity slows down and the vortex size at the spray outer side grows smaller, but when it is accelerated, the vortex size becomes larger.

![Figure 2.2-1 Change in minimum droplet velocity due to water flow rate](image1)

(c) Comparison of spray visualization through cross-section image and of droplet measurement data

Thanks to expansions and augmentations implemented last year, it became possible to photograph cross-sectional images of spray. Data made visible by cross-sectional images was then examined. A spray image is shown in Figure 2.2-2.

The figure indicates that spray droplets are static at 0m/s, the point of minimum droplet velocity.

![Figure 2.2-2 Photo of spray cross-section](image2)

(2) Evaluation of spray droplet diameter

A search was made through the literature for a formula to calculate the droplet diameter of spray from a pressure spray nozzle (swirl spray nozzle), and comparisons were made between test results and calculated results. A number of formulas have been proposed for calculating average droplet diameter with the swirl spray nozzle, and of these formulas, the one proposed by Tanazawa and Kobayashi, which includes factors pertaining to nozzle internal shape and fluid physical properties, was used to conduct the investigation. The Tanazawa/Kobayashi formula, however, is intended for a completely hollow cone nozzle. It was assumed that calculation results would be slightly different for a semi-solid cone nozzle, and this point was also investigated.
(a) Evaluation of average droplet diameter

From research conducted in 1996, it was learned that the splitting from fluid sheet to droplet is nearly completed at a point about 20mm in axial direction from the nozzle tip. Accordingly, at a position 20mm from the nozzle tip along the axial direction, the spray in radial direction was measured, and the position for measuring average droplet diameter was investigated.

As a result of the investigation, the average droplet diameter at the highest point of the data rate assumed the closest value to the average droplet diameter over the spray cross-section. Thereafter, the average droplet diameter at the highest point of the data rate was treated as the average droplet diameter of the spray.

(b) Comparison of tests and calculations

A comparison was made between droplet diameter determined from calculations and results of spray tests. Among calculated values and measured values, the same trends were exhibited but differences could be noted in the values. Next, comparisons were made respecting the velocities of spray droplets determined from the formula. There was a difference between the maximum velocity of measured droplets and the spray velocity derived from calculations. The calculated velocities were lower than the measured. The spray velocities were matched and droplet diameters were calculated, but the calculated values still did not match adequately with the measured values (Figure 2.2-3). This can be ascribed to the fact that the calculation formula is for a completely hollow cone nozzle; the nozzle used in the tests was a semi-solid cone nozzle.

(c) Examination of spray droplet diameter according to fluid physical properties

A comparison was made for kerosene and for heavy oil A by means of water spraying and calculations. Spray conditions were used based on the tests conditions employed with the test combustion furnace. The physical properties of the sample fluids used in the calculations (kerosene, heavy oil A, water) are shown in Table 2.2-1, and calculated results are presented in Figure 2.2-4. Droplet diameter calculations are expressed as conversion percentages when water spray is taken as the standard of reference.
2.3 Fundamental combustion research (III) Simulation of combustion numerical analysis

(1) Development of combustion numerical simulation model

From the results of research conducted in 1997, it was found that a numerical simulation model for oil spray combustion must be developed independently. In 1998, a numerical simulation model of combustion was designed in outline and the fundamental components were developed. In this development, joint research was undertaken with Professor Takatoshi Miura of Tohoku University, who has distinguished himself in this field.

First to be considered is the outline design. Research results in 1999 showed that the ideal approach is one in which physical models are incorporated with the flow analysis code of compressible fluid taken as the core. Accordingly, the following master formulas (fundamental formulas)--with the flow analysis code of compressible fluid taken as the core--were digitalized by the finite difference method, and a CFD code was created to conduct analysis by the mathematical methods shown below. In addition, each type of physical model was incorporated as a sub-model into this CFD code, which serves as the core, and a numerical simulation model of oil spray combustion was thus developed.

(a) Fundamental formulas

- Equation of continuity
- Chemical type conservation equation … Fick’s law was applied to cover diffusion.
- Energy equation … Fourier’s law was applied to cover heat conduction.
- Equation of motion…Stoke’s law of viscosity was applied on the assumption of a Newtonian fluid.
- State equation

(b) Mathematical methods

With respect to calculation lattice and digitalization method, from the standpoint of improving the approximate accuracy of the configuration, either a boundary applicable coordinate system should be used with a structured lattice or a non-structured lattice should be used. In the case of the former, however, it takes time to generate the lattice and in the case of the latter, the calculation scheme must be developed independently. For the present research, the regular coordinate system of a structured lattice was selected because often the internal configuration of boilers, etc., used in this research is relatively simple. For digitization, the differential equations were adopted in consideration of calculation load and speed, and a staggered grid was used to prevent erroneous convergence. Moreover, in consideration of the non-linearity of combustion phenomena and calculation load, the SIMPLE algorithm was selected for binary calculation of pressure--flow location. Various improved editions of this format exist for elevating stability, but if there are no special conditions such as supersonic combustion, calculations can be made to adequate stability with the original SIMPLE method. In the solution of multi-dimensional digitalization equations, a line-by-line method was employed in which a triple diagonal matrix algorithm (TDMA) was applied.
(c) Physical sub-model

A standard k-ԑ model was used as a turbulence model. Since swirling flow in the combustion chamber is not so forceful, isotropic turbulence was assumed in this model, and results with it matched well with test results. However, for analyzing in detail the forced swirling flow regions near the burner nozzle, other approaches such as the Reynolds stress model must be investigated. For turbulent flow combustion model, an eddy dissipation model was used, but the PDF model is also being studied for improving accuracy in forecasts of NOx generation volumes. A Lagrangian model was selected for covering spray, and the PSI-Cell model was adopted for mutual action with the gaseous phase. The wall function model of Chieng et al was used to correct for the impact of walls.

(2) Analysis by numerical simulation model

Presented below are simulation results of furnace internal gas flow as an example of analysis conducted using the newly developed numerical simulation model. Used as the target of analysis was a cylindrical test combustion furnace (800mm internal diameter) in our laboratory. With this furnace it was confirmed that swirl effect has a major impact on combustion status, but direct measurement of the strength of swirl near the nozzle is problematic. Accordingly, a forecast was made of swirl count by comparing measurements of furnace internal flow speed during non-combustion with the results calculated after assigning a swirl number (s) at the burner throat inlet. Calculated results and test results are shown in the figures below. For measurements, the distribution in radial direction from the furnace central axis was measured at 223 mm and 688 mm from the burner tile. Here, axial speed along the cylindrical test combustion furnace is denoted as u; radial speed is v, and swirl speed is w. Since a hot-wire flow velocity meter of single wire was used, the 3 components of speed could not be separated, and the measurements were expressed in terms of u + v and v + w. A comparison with results calculated after changing the swirl count diversely reveals that the result of s = 1.16 matches well in any case. For this reason, it was found that under the test conditions a fairly strong swirl was generated at a swirl count of about 1.2 at the burner throat inlet.
2.4 Fuel properties and combustibility

(1) Evaluation of combustibility by thermal analysis

With respect to heavy oils having different properties, combustibility was evaluated using thermogram/differential thermal analysis (TG-DTA). As a result, a correlation was found between residual weight at prescribed temperature in the course of temperature rising and the quantity of asphaltene and residual carbon in the test fuel (Figure 2.4-1).

Since asphaltene and residual carbon are the main causes of the formation of soot during combustion, it has been suggested that residual weight by thermal analysis can be taken as an index.

With respect to intermediate fraction, in an evaluation of combustibility, using a differential scanning calorimeter (DSC) under high-pressure atmosphere, the exothermic peak configuration in the process of temperature rise varied with the type of oil. With kerosene, a peak configuration similar to that of paraffin was observed, but with LCO, the peak was similar to that of tetralin. In the future, correlations with combustion test data will be examined, and peak configurations will be investigated to see if they can serve as an index of combustibility.
(2) NOx formation with flow reactor

Using a laminar flow reactor, a combustion reaction was instigated with lean fuel (hydrocarbon: 3% as C1, equivalence ratio 1.0, balanced with nitrogen gas, flow rate: 1.01/min). Last year, formation of prompt NOx was investigated using different structures of hydrocarbon (Figure 2.4-2). As a result, the amount of prompt NOx formed became large in the sequence: paraffin > naphthene > aroma.

2.5 Investigation of new combustion technologies (I) High temperature air combustion technology

(1) High temperature combustion technology: present status and issues

Advancements in the development of high temperature air combustion technology, which has many advantages, have been based mainly on the use of gas fuels, but more recently, other novel advances are also being made. Examples include a newly developed system which achieves high power generation efficiency as a whole. In this system, solid fuels such as coal or wastes are melted over pebbles using high temperature air and gasified, and the gas thus synthesized is used to drive boilers or turbines. In addition, basic phenomena are becoming clarified, and the mechanisms involved are being approached little by little. Nevertheless, the mechanism of low NOx combustion, for instance, has not yet been fully elucidated in many respects, and further studies are required.

In this way, various advances have been made in the application of high temperature air combustion technology, which possesses diverse characteristics, to practical furnaces. However, its application to liquid fuels such as petroleum, which accounts for the majority of our energy sources, still remains virtually absent. If a high temperature air combustion technology using petroleum fuel can be developed and directed to various applications, exceedingly great advantages will be gained in terms of energy supply. What is more, there is a possibility of achieving NOx emission as low as gas with high temperature air spray combustion. Low NOx combustion independent of the quality of the petroleum fuel can also be expected. Thus the development of high temperature air combustion technology using petroleum fuel has become a major issue and R&D for the development of an advanced petroleum combustion technology has been inaugurated at our laboratory.

(2) High temperature air supply methods

With the apparatus initially introduced, the time in which high temperature air of 800°C or higher could be delivered was short, at 3 to 7 minutes. For this reason, major problems arose in the continuous supply of high temperature air: testing efficiency was poor; the time period in which the temperature remained constant was short, and data accuracy was problematic. Consequently, the equipment was expanded this year as shown in Figure 2.5-1, and continuous supply of high temperature air was made possible.
(3) Measurement of flame structure

Differences in flame structure and color were observed when supply air temperature and oxygen concentrations are changed. The results are shown in Figure 2.5-2. It was observed that at each oxygen concentration, the luminous flame diminishes and the blue flame grows larger as the temperature drops. At low oxygen concentrations, a green flame was observed instead of the blue flame, which is the same as in the combustion of LP gas.

![Flame structures observed in high temperature air combustion](image)
(4) Radical measurement

A distinctive green frame is observed in the high temperature air combustion. This is ascribed to light emission from the Swan band of C₂ radicals generated from the fuel when the oxygen concentration is lean. Accordingly, measurement of the C₂ radicals can serve as an index of whether or not high temperature air combustion, (a low NOx combustion mode), is taking place. Since laser measurements, in particular, are outstanding in spatial resolution, a two-dimensional distribution image can be measured. Figure 2.5-3 shows the two-dimensional distribution image of C₂ radicals measured with a high temperature air combustion flame when the supply air temperature is changed. The flame is formed from the lower left to the upper right, and the laser beam is irradiated to its lower half. It was observed that, as the temperature drops, intensity of the signal weakens.

Figure 2.5-3 Two-dimensional distribution image of C₂ radicals observed in high temperature air combustion

2.6 Investigation of new combustion technology (II) Catalytic combustion

In catalytic combustion, fuel undergoes oxidation over catalyst. In comparison to the conventional combustion method, the combustion temperature is low at combustion sites because thermal NOx is not formed. Catalytic combustion has thus gained attention as an extremely low NOx combustion technology. In order to develop a high-efficiency, low NOx combustion system for petroleum fuel with catalytic combustion, a test equipment was manufactured. This is for obtaining fundamental data (e.g., effect of fuel properties, best combustion condition, exhaust gas analyses) to determine the unique features of catalytic combustion of petroleum fuel.

An outline of the equipment can be summarized as follows: A 300 mm catalytic combustion part, a 600 mm gas-phase combustion part and up to 3 units of 50 × 50 mm catalyst can be set into the equipment. In the case of 1 catalyst unit, a maximum space velocity of about 300,000 can be secured. With maximum fuel supply rate of 1.2L/h, air and fuel are mixed using a Venturi type premixer.

Test results using the catalytic combustion evaluation equipment are presented in Table 2.6-1. These results were obtained under relatively low space velocity and the combustion temperature was varied by changing the feed amount of kerosene with almost constant air volume for combustion. At the present stage, data are insufficient and adequate analysis cannot be made, but more data will be collected in the future and detailed analyses will be conducted.
Table 2.6-1 Operating sample of catalytic combustion evaluation

<table>
<thead>
<tr>
<th>Parameter / No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<td>Kerosene flow rate (ml/min)</td>
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<tr>
<td>Air temperature before catalyst (°C)</td>
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<td>450</td>
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<tr>
<td>Exhaust gas temperature (°C)</td>
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<td>18.59</td>
<td>17.89</td>
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<td>16.23</td>
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</table>

3. Summary
3.1 State of progress up to the present

(1) Development of combustion based technology

1) The relationship between combustibility support factors around burners or combustion units and combustibility or exhaust gas characteristics was investigated.

2) The characteristics of each type of low NOx burner were clarified and work was begun on development of a new low NOx burner.

3) The spray characteristics of each type of spray nozzle were measured and relationships to combustibility were investigated.

4) The chemical species in flames were measured using laser diagnostics and the combustion characteristics of petroleum types were clarified.

5) In cooperation with Tohoku University, a simulation of petroleum combustion was constructed and its applicability was investigated.

(2) The combustibility of various base materials and of pure substances, and the characteristics of NOx formation, were inspected under thermal analysis or combustion furnace. Relationships with properties were investigated, and it was discovered that there are differences in combustibility and in NOx formation characteristics depending upon fuel components.

(3) In an effort to achieve high efficiency and low NOx, work was begun on development of high temperature air combustion and catalytic combustion technologies.

(4) As an international cooperative effort, an investigation was made into the building of cooperative ties with China and the various countries of Southeast Asia, and an evaluation of combustibility was made by means of thermal analysis of H-Oil bottom used at an oil refinery in Kuwait. In addition, a study team on combustion from China and trainees from PTT of Thailand were received.
3.2 Research schedule for fiscal year 1999-2000

(1) Development of combustion base technology

1) With the aim of reaching intermediate targets (NOx level on the order of 50 ppm with kerosene and 70 ppm with heavy oil A), a low NOx burner of pressure spray method with internal exhaust gas recirculation or low-pressure air spray method will be investigated. For the development of burners, cooperative efforts with burner manufacturers and universities will be eagerly pursued in addition to independent research. In the developmental efforts, laser technic measurements of burner spray accumulated thus far will also be used, together with flame spectral measurements and simulation technology.

2) The burners to be developed are expected to be of high performance, and they will be applied to small boilers and other practical equipment.

(2) Data from instrumental analysis and combustion furnace will be accumulated respecting the correlations between the properties, compositions and combustibility of fuel oils and the characteristics of NOx formation. This is also in reference to heavy oil A of high aromatic content, which can be assumed for the future, and creation of an index of combustibility will be further investigated.

(3) Advances will be made in the development of high temperature air combustion and catalytic support combustion technologies in order to acquire technologies of higher efficiency and lower NOx than conventional technologies. In cooperation with Tokyo Institute of Technology, further studies will be done on the applicability of high temperature air combustion to petroleum fuels. With respect to catalytic support combustion, studies will be pursued in cooperation with the PEC support project "Development of an Advanced Very Low NOx Combustion Technology (provisional title)," which is scheduled to begin in the fiscal year 1999-2000.

(4) As part of an international cooperative undertaking, cooperative ties will be built with combustion research institutions in Southeast Asia (e.g., Thailand, Malaysia, and Vietnam). This year, information exchange, symposiums and other steps will be taken to investigate implementation details and so on. The possibilities for accepting researchers will also be explored.

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