

3. Results of Combustion Test of Low-NO_x Burners in the 18 de Marzo Refinery

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Concerning the effects of low-NOx burners, the Government of Mexico requested to JICA to conduct a demonstration test because such burners are not commonly known in Mexico.

In response, the JICA Study Team began selection and preparation of a facility to be used for the demonstration test with steam-injection type low-NOx burners for heavy oil considering that heavy oil of high viscosity is consumed in AMCM by large amount. However, among the public enterprises appropriate for donation of the burners by the Japanese Government, two power plants and a refinery were in the course of fuel change to natural gas, and some of the large public enterprises were turned into private firms. In view of these facts and the number and capacity of burners, there was no eligible plant for the test. Therefore, in response to a request from the PEMEX headquarters, JICA decided to install four low-NOx burners for natural gas to one of the power generation boilers in the 18 de Marzo refinery, a sole oil refinery in AMCM.

The G3 boiler was selected from the four boilers, G1 through G4, which are the same type. This boiler is about 50 years old and rather outdated. At the same time as the demonstration test, substantial reconstruction works were conducted as required for NOx reduction.

The following three methods were adopted as NOx reduction measures:

- Low-NOx gas burners
- Steam injection
- Flue gas recirculation

Upon completion of burner installation and reconstruction work, operations with low-NOx combustion were conducted, and the data thus obtained from the G3 boiler were compared with the data for ordinary combustion with the G1 boiler which has the same shape and size as the G3 boiler. The successful results were obtained in NOx reduction and in operation, and are presented hereafter.

(1) Outline of the Boiler and NOx Reduction Works

The G3 boiler is operated with an evaporation rate of 55 ton/hr, steam pressure of 40 kg/cm², and super heated steam temperature of 380°C, and generates power used within the refinery.

The boiler is the water-tube type with four burners installed in the front. Drafting is made by balanced draft, and a blower to supply air and an exhaust blower to draw combustion flue gas are provided (see Figure 3.1).

The low-NOx burner is the off-stoichiometric combustion type which consists of a main burner and sub-burners. The entire amount of combustion air enters the combustion chamber from the center of the main burner (See Figure 3.2).

At the time of replacement of the existing ordinary burner by this low-NOx burner, a nozzle to inject steam into the flame was installed. This nozzle is used to decrease the flame temperature thereby reducing NOx generation. In addition, a duct was newly installed from the exhaust blower outlet to the blower inlet for recirculation of flue gas. This duct is also intended to decrease the flame temperature and to improve mixing in the combustion chamber so that uniform temperature distribution is attained. The arrangement described above is shown in a flow sheet in Figure 3.3. The hatched portion in the Figure shows reconstruction and new installation.

(2) Schedule for Installation on Testing of Low-NOx Gas Burners

Middle of October to November 15:

Removal of existing burners, repair of the boiler, and new installation of the flue gas recirculation duct

November 16 - 26: Installation of the low-NOx burners

November 26 - 30: Installation of gas piping and flame monitoring system, and wiring work

December 3: Ignition to the burners

December 4: Raising the evaporation rate to 50 ton/hr (90% load)

December 5: Combustion test with the low-NOx burners

December 6: Steam injection and flue gas recirculation tests

December 7: Test with the evaporation rate lowered to normal
36 ton/hr (65% load)

(3) Principle of NO_x Reduction of Low-NO_x Gas Burner

As shown in Figure 3.4 (a), highly fuel-lean and highly fuel-rich zones are simultaneously formed in the combustion chamber because the entire volume of air enters through the center of the main burner. Amount of the NO_x generation changes with a mountain-like curve pattern with respect to the air ratio as shown in Figure 3.4 (b). NO_x can therefore be reduced by, for example, producing flames corresponding to the base of the mountain-like curve, i.e., ① fuel rich and ② fuel lean in the Figure, and obtaining the state of ③ (average state of rich and lean) at the combustion chamber outlet.

This is the basic principle of this type of NO_x burner. In addition, it was designed to inject steam into the center of the flame of the main burner so as to lower the flame temperature.

Moreover, flue gas is recirculated to reduce the oxygen concentration of combustion air as well as to increase the volume of air entering the combustion chamber. In this way, the combustion flame temperature can be decreased and uniformly distributed, and NO_x generation can be reduced.

(4) Fuel Composition and Measuring Equipment

1) Composition of Fuel Used

Sampled at 9:00 a.m., November 29

Methane	88.4%
Ethane	9.7%
Propane	0.4%
Nitrogen (N ₂)	1.5%
Mercaptan	13.1 ppm
Specific gravity (air = 1)	0.611
LHV	8,665 kcal/m ³ (760 mmAq, 15.6°C)

2) Measuring Equipment

Basically, the measuring methods specified by JIS (Japan Industrial Standards) were used. The measuring equipment used is as follows:

NO _x	: Chemiluminescent analyzer
CO	: Non-dispersion infrared analyzer (NDIR)
CO ₂	: Non-dispersion infrared analyzer (NDIR)
O ₂	: Paramagnetic analyzer
Particulate matter	: Isosinetic sampling, gravitational analysis

(5) Result of Combustion Operation

1) Combustion with Normal Burners

Combustion with the main burners only was made without flue gas recirculation, steam injection, or gas injection to the sub-burners. In other words, this combustion mode is the same as that with ordinary burners and is not low-NO_x combustion. Operation in this condition was made on December 4. The result is shown in Figure 3.5. The result was nearly the same as that of G1 boiler obtained from the diagnostic survey made in September at the refinery with the NO_x concentration at 136 ppm for operation with 4% flue gas O₂. The CO concentration showed a tendency to increase sharply when the O₂ concentration decreases below 3%.

Hereafter, this set of data will be used as a reference for evaluation of low-NO_x combustion.

2) Low-NO_x Combustion (Simultaneous Combustion of Main Burner and Sub-burners) and Steam Injection

Figure 3.6 shows the result of combustion with the low-NO_x burners; 60% with main burner and 40% with sub-burner. In addition to this low-NO_x combustion, data were taken with steam injection with the rates at 1.5 and 2.5 kg/cm². Figure 3.8 shows a general relationship between steam amount and steam pressure for reference.

NO_x reduction of about 41 ppm (about 30%) was achieved by the low-NO_x burner operation with 4% O₂ in flue gas in comparison to the normal burner operation. But, NO_x reduction of only 10 to 15 ppm (7 to 11%) was achieved by further injection of steam, and the CO generating condition appeared.

3) Effect of Flue Gas Recirculation

Steam injection proved to be not very effective for reduction of NO_x, and an increase in steam injection caused undesirable CO generation. Accordingly, flue gas recirculation was made by setting the steam injection rate to 1 kg/cm². This test was conducted on December 6 and 7. The test on the first day was made with an evaporation rate of 50 ton/hr and a natural gas flow rate of 4,923 m³/hr (91% of the rated capacity), while the flue gas recirculation rate was set to provide 6% of the theoretically required amount of air. The NO_x concentration for operation with 4% O₂ in the flue gas can be read as 68 ppm from Figure 3.7. This corresponds to a reduction of 68 ppm (50%) from the normal burner. The test on the next day was made with an evaporation rate of 36 ton/hr (normal operation), natural gas flow rate was reduced to 3,587 m³/hr (65% of the rated capacity), and the flue gas recirculation rate was increased to provide 9% of the theoretical air amount. The NO_x concentration in the operation with 4% O₂ in the flue gas may be estimated at about 45 ppm from Figure 3.7. This corresponds to a reduction of 67% in the NO_x concentration from the normal burner.

(6) Summary

The NO_x concentration (converted to 5% O₂) during operation with 4% O₂ in the flue gas may be summarized as follows:

① Normal burner	136 ppm (reference level)
② Low-NO _x burner	95 ppm (30% reduction)
③ Low-NO _x burner, with steam injected at 1 kg/cm ² .and flue gas recirculated at 6%	68 ppm (50% reduction)
④ Low-NO _x burner, with steam injected at 1 kg/cm ² and flue gas recirculated at 9%	45 ppm (67% reduction)

The NO_x concentration was reduced more than expected by means of the low-NO_x burner and low-NO_x combustion (including flue gas recirculation).

Operation was also made at the rate of 50 ton/hr, nearly the rated capacity, without particular problems.

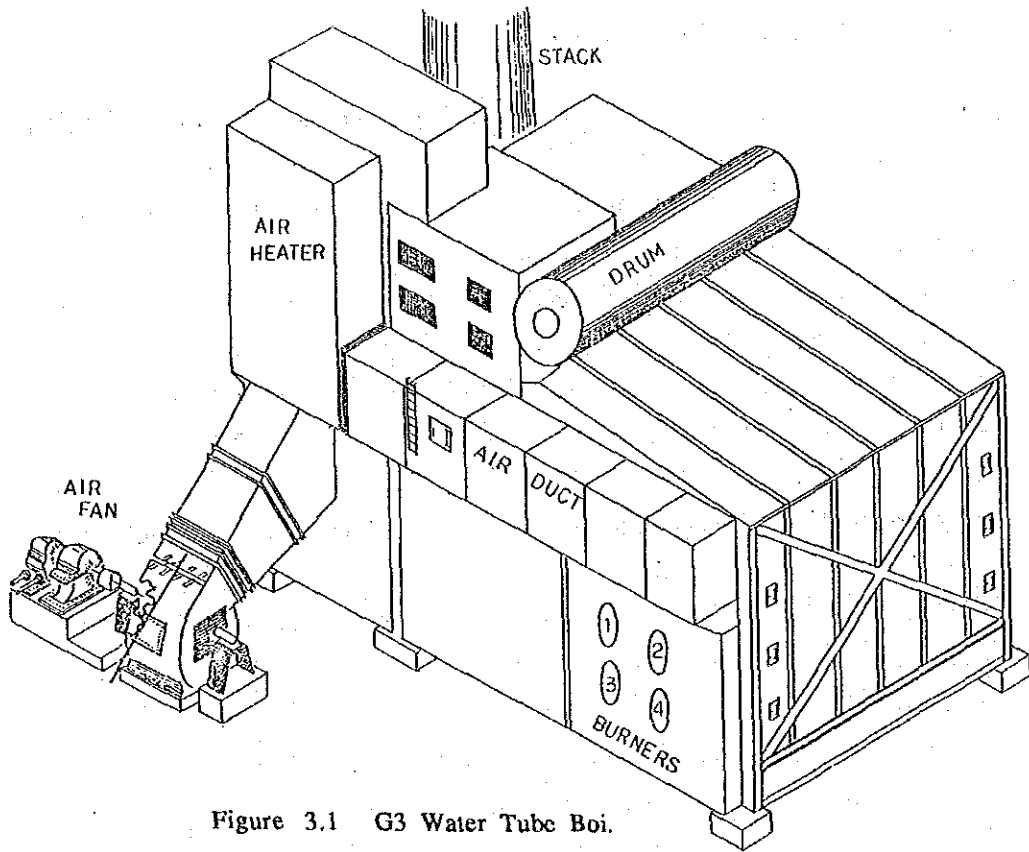


Figure 3.1 G3 Water Tube Boi.

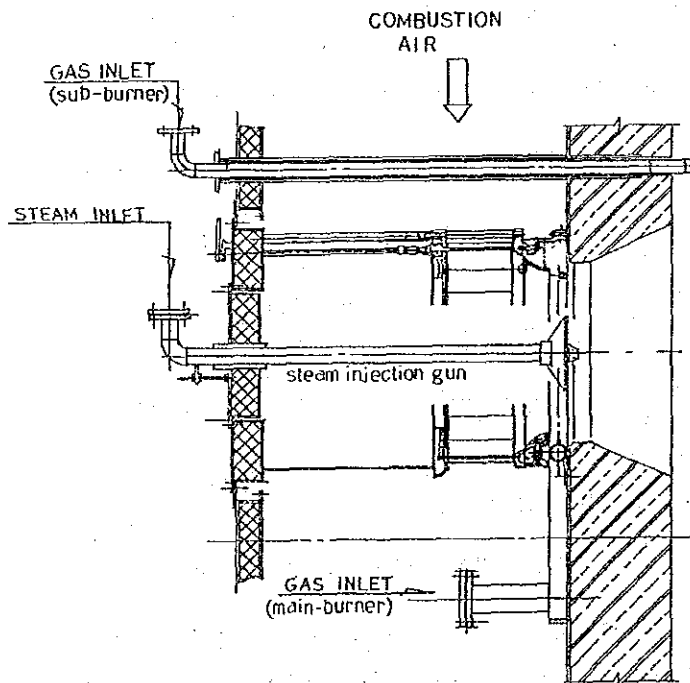


Figure 3.2 Low NOx Burner

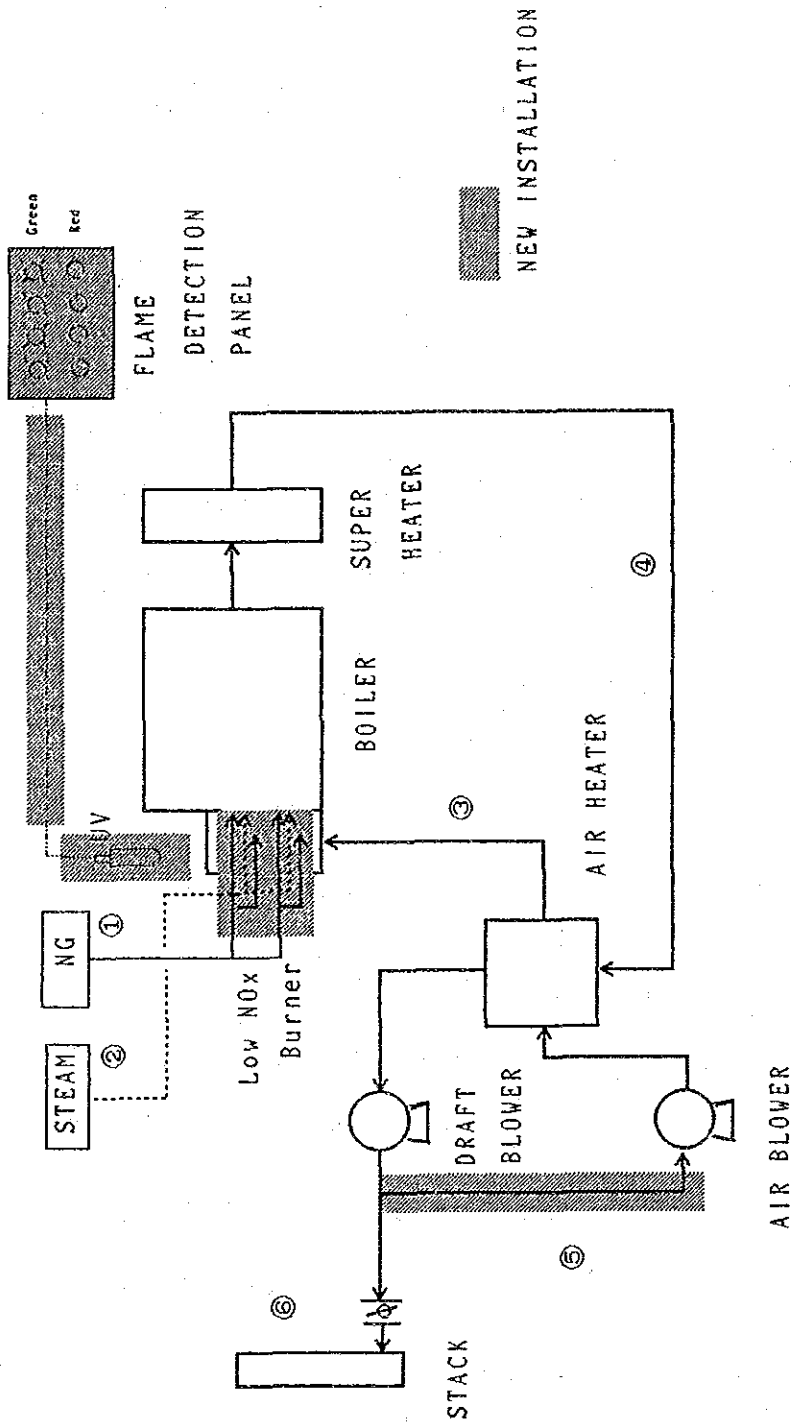


Figure 3.3 Low NOx System Flow Sheet

Low NOx Control	Boiler (ton/h)	N.G. (Nm ³ /h)	Steam (kg/h)	Air (Nm ³ /h)	Flue Gas (Nm ³ /h)	F.G.R. (Nm ³ /h)	Stack (Nm ³ /h)
Fuel Stage Low NOx B'nr	55	5,480	-	62,029	68,237	-	68,237
Steam Injection	55	5,480	1,390	62,029	69,967	-	69,967
Flue Gas Recirculation	55	5,480	-	74,435	80,643	12,406	68,237

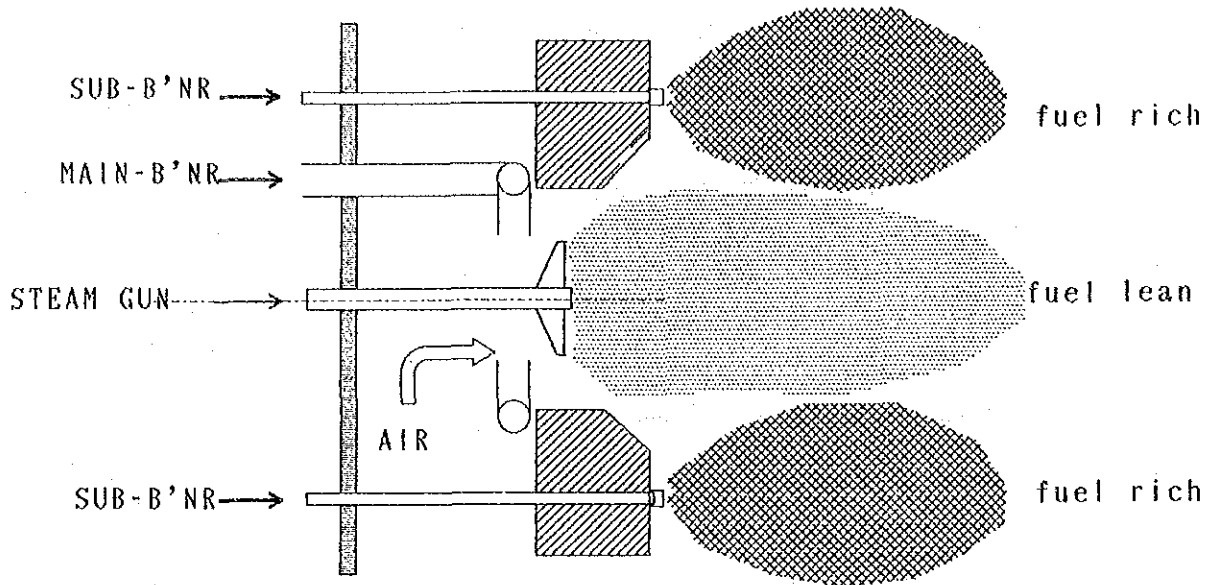


Figure 3.4 (a) Imaginary Picture of Low NOx Burner

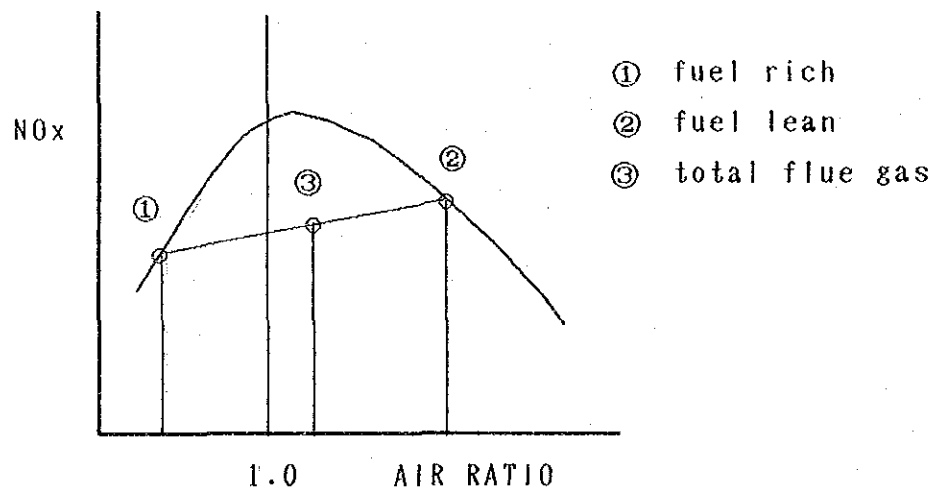


Figure 3.4 (b) Principle of Low NOx Burner

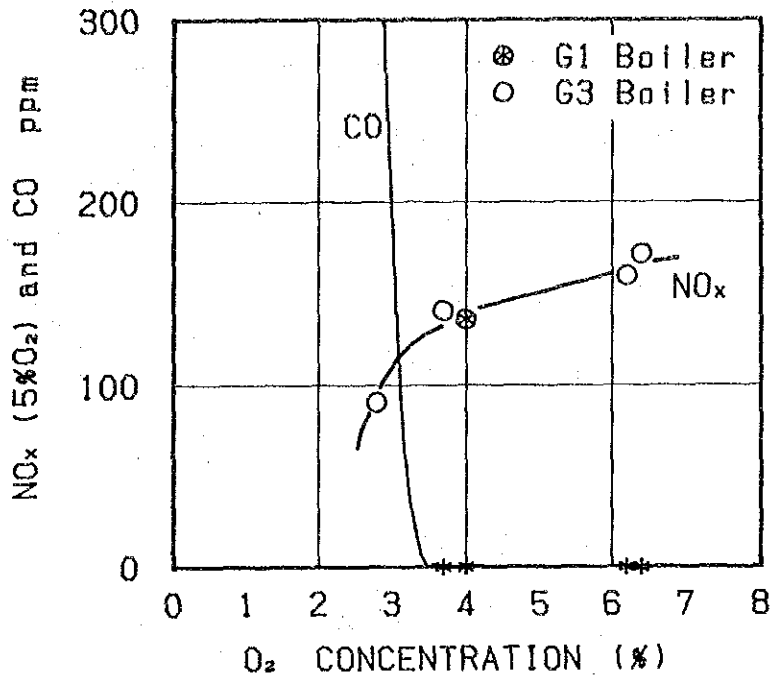


Figure 3.5 NO_x & CO Emissions by Original Burner

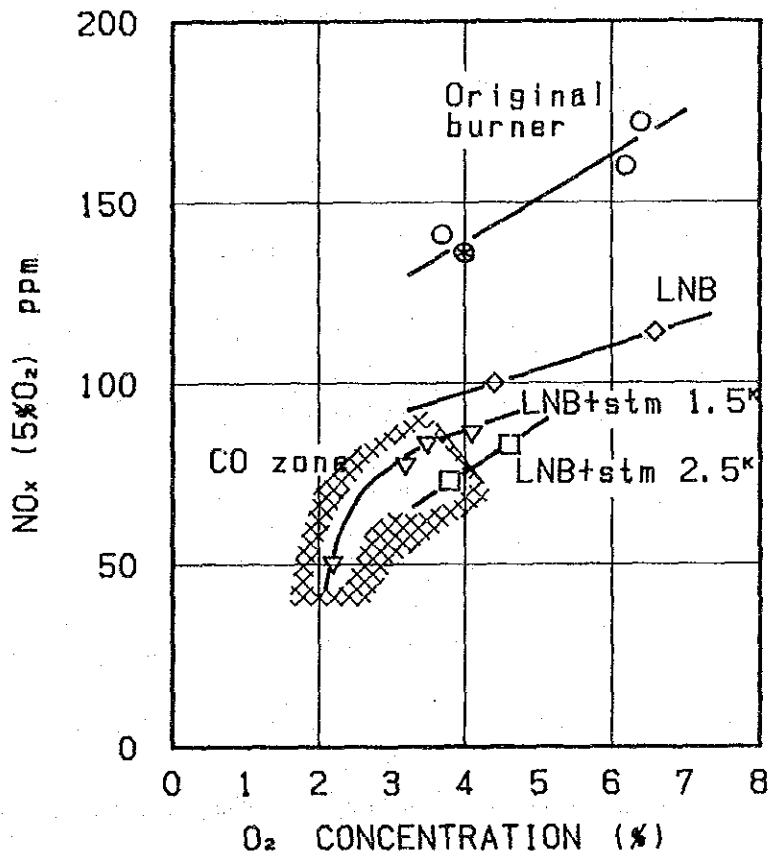


Figure 3.6 Effect of Low NO_x Burner (NLB) & Steam Injection

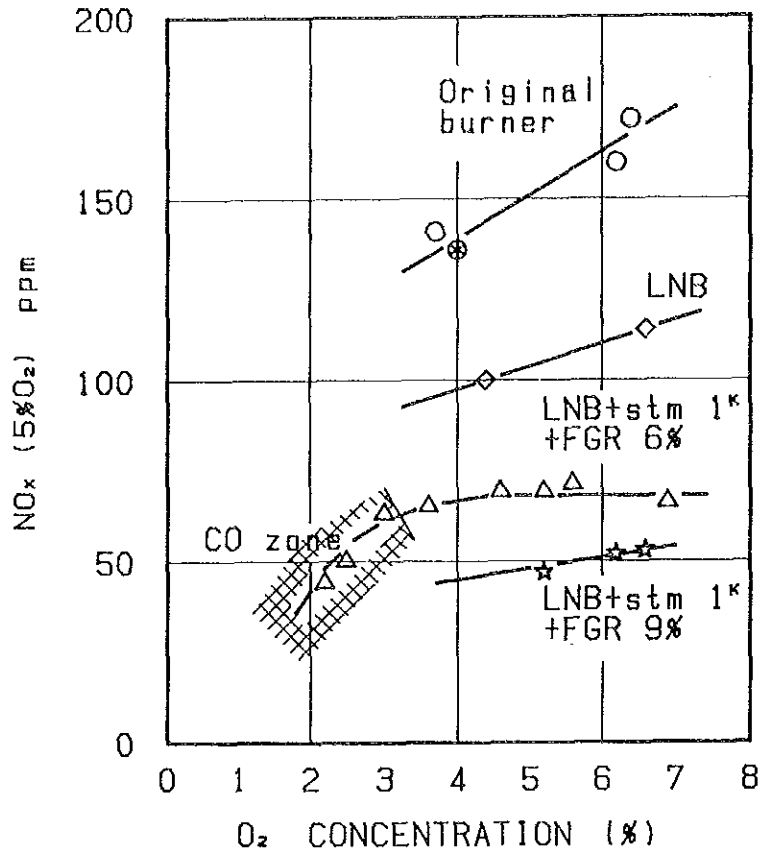


Figure 3.7 Effect of Flue Gas Recirculation
(Total Low NO_x Combustion)

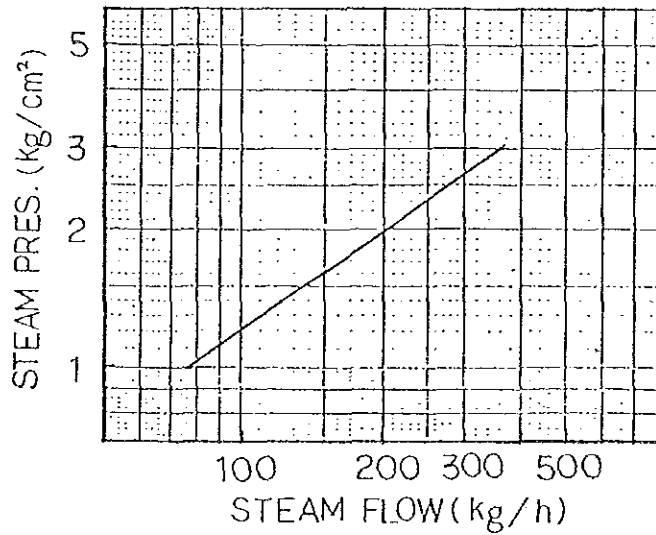


Figure 3.8 Relation Between Steam Flowrate and Steam Pressure

4. Results of Questionnaire Survey on Enterprisers' Minds Toward Environmental Pollution

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In order to understand enterprisers' critical minds toward environmental pollution, their mitigation measures and possible investments for environmental protection a simple investigation was conducted as a part of the Study by using a questionnaire to enterprisers.

(1) Investigation Outlines

SEDUE, the executing agency, selected about 1000 companies of manufacturing and service industries in the metropolitan area. Those companies were visited by SEDUE and the questionnaire was dispatched to them. The answered questionnaires were sent back to the SEDUE office by messengers. The investigation was conducted during the period from September to November 1990.

A total of 140 questioners were collected, of which 129 were effective, or the rate of effectiveness was 12.9%.

Table 4.1 Dispatching and Collection of the Questionnaire

	Samples	Collection Rate
Dispatching	1000	
Collection	140	14.0%
Effective Answer	129	12.9%

The investigated items, as shown in Table 4.2, are: (1) Opinions to environmental pollutions in the Metropolitan Area, (2) Present mitigation measures, (3) Possible investments for environmental protection (vs added values of the products), (4) company size. The questions are relatively simple, but were requested to be answered by the company owners.

Table 4.2 Investigation Items

	Questions
Q-1	<p>What do you think about the environmental pollution in the Metropolitan area?</p> <p>A. the pollution problem is quite serious, and urgent measures should be taken.</p> <p>B. the pollution problem is serious, but urgent measures are not needed.</p> <p>C. the pollution problem is not serious.</p>
Q-2	<p>Is your company taking some mitigation measures?</p> <p>A. If yes, please describe concrete measures.</p> <p>B. If no, do you have any plan in the future?</p> <p>B1. If yes, please describe the measures.</p> <p>B2. If no, please give the reason.</p>
Q-3	<p>How many % of the added value gained by your company last year can you use for environmental protection?</p>
Q-4	<p>Which size of the sector does your company belong to?</p> <p>A. large size</p> <p>B. medium</p> <p>C. small</p> <p>D. individual (family)</p>

(2) Investigation Result

1) Opinions to Environmental Pollutions in the Metropolitan Area,

The first question Q-1 was "What do you think about environmental pollution in the Metropolitan Area?" The result is summarized in Table 4.3.

More than 90% of the enterprisers answered "the present situations are quite serious and urgent measures should be taken", while only 17% answered "the present pollution levels are serious, but there is no need for urgent measures." No company answered "the environmental problem is not serious." The result indicates the critical minds of the enterprisers. Most of the are thinking that the present environmental pollution is quite serious.

Table 4.3 Investigation on Enterprisers' Minds
Toward Environmental Pollution

Scale	Answers	Rate (%)	Q-1			Q-2		
			A	B	C	A	B (YES)	B (No)
Large	20	14.3	19 (95.0)	1 (5.0)	0 (0.0)	19 (100)	0 (0.0)	0 (0.0)
Medium	62	44.3	57 (91.9)	5 (8.1)	0 (0.0)	59 (95.2)	0 (0.0)	3 (4.8)
Small	40	28.6	38 (95.0)	2 (5.0)	0 (0.0)	35 (89.7)	1 (2.6)	3 (7.7)
Individual	2	1.4	1 (50.0)	1 (50.0)	0 (0.0)	2 (100)	0 (0.0)	0 (0.0)
Unknown	5	3.6	3 (100)	0 (0.0)	0 (0.0)	4 (100)	0 (0.0)	0 (0.0)
Effective	129	92.1	118 (92.9)	9 (7.1)	0 (0.0)	119 (94.4)	1 (0.8)	6 (4.8)
Ineffective	11	7.9						
Total	140	100.0						

Note Figures in parentheses are %.

2) Present Mitigation Measures

Table 4.3 also shows the result to the second question "Is your company taking some mitigation measures?"

94% of the companies answered that they were taking some measures. Most of the companies who had no mitigation measures answered that they would take some measures in the future. Those companies that had no plan to take any measures were sure that they were not generating any pollution.

This result reveals that most of the enterprises were taking some efforts to mitigate environmental pollution.

Air pollution control measures taken by the companies are shown in Table 4.4.

Table 4.4 Air Pollution Control Measures by the Companies

(1) Present Measures

Present measures	Number of enterprises
a) Fuel system control and fuel saving	50
b) Conversion of diesel burners to gas burners	1
a) Installation and improvement of filters and dust collectors	30
b) Installation of pollution control devices	7
c) Diagnostic inspection by consultants and plan to install pollution control devices	5
a) Conversion to low pollution fuels	16
b) Use of natural gas	13
c) Survey to convert to natural gas	1
a) Measuring pollutants emissions	6
a) Relocation of melting furnace out of the City	1
b) Removal of pollution source facilities	1
c) Less operating time of polluting facilities	1
a) Use of use of ammonium chrolides for soot prevention	1
b) Installation of watertrap for prevention of gas leakage from acid storage tanks	1
c) Use of water adhesives	1

(2) Future Measures Being Planned

Future measures	Number of enterprises
a) Installation of pollution control devices	2
b) Installation of dust collectors	5
c) Installation of economizer to boiler	1
d) Construction of solid waste incinerator with gas washing tower	1
e) Conversion of heavy oil to natural gas	1

There were 51 enterprises, the largest number out of collected answers, which took mitigation measures by combustion system control and fuel saving. The next group of the enterprises with 37 were to install filters, dust collection facilities and pollution prevention facilities. The third group of the enterprises with 29 were to convert their energy to lower pollution fuels including natural gas.

There were only 6 companies which answered that they were measuring their pollutant emissions by instruments. This shows that their monitoring levels are not high. Some companies are actively seeking measures to mitigate air pollution. Five companies are planning some environmental monitoring systems, assisted by professional consultants or their own committees. One company is studying conversion of the fuel to natural gas.

Among the mitigation measures being planned, the installation of dust collection facilities is the most in number with 5 companies. Others are installation of some types of pollution control devices, installation of economizers to boilers, and conversion of heavy oil to natural gas.

3) Possible Investments for Environmental Protection

Figure 4.1 and Table 4.5 summarize the result to the third question "How many percent of the added values gained last year can you use for environmental protection?"

A total of 56 enterprises answered the question. The possible investments compared with the last year's added values ranged from 0.01% to 50%. Those who answered less than 1% are the most with 16 enterprises, while 9 enterprises answered less than 2%, and 8 enterprises answered less than 0.5%. There are 33 enterprises, or 59%, who answered less than 2%. Those enterprises who answered less than 5% are 45 of the total 56, or 80%.

There were some answers that they could invest more than 30% of their profit to environmental installation investments. This seemed to be unrealistic. Excluding these answers, the average figure of 53 companies was 3.3%. This figure is almost the same regardless of the size of the companies, large, medium or small.

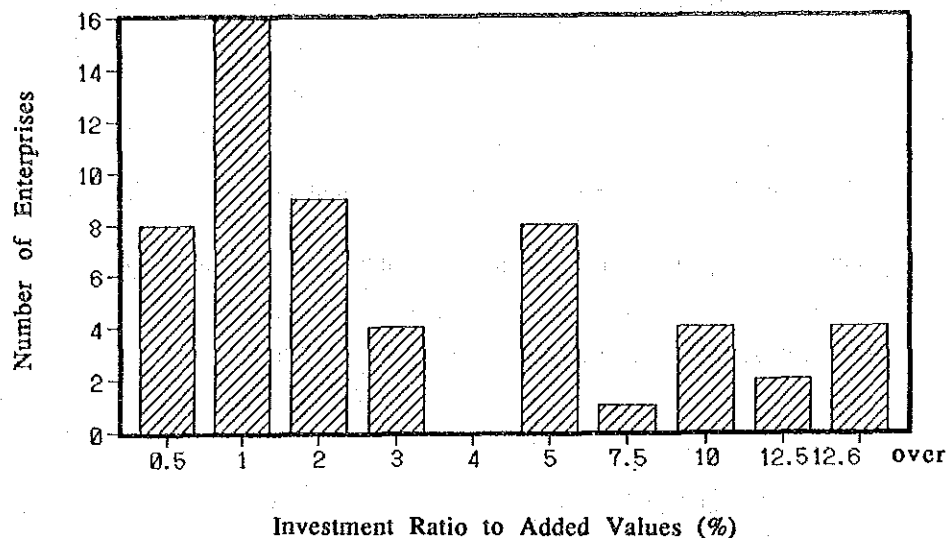


Figure 4.1 Possible Investment for Pollution control

Table 4.5 Possible Investments for Environmental Protection (Distribution of Enterprises)

Scale of Enterprises	Investment Ratio of Environmental Protection to Added Values										Average	
	0.5 under	1 under	2 under	3 under	4 under	5 under	7.5 under	10 under	12.5 under	12.6 over	Total (%)	Adjusted* (%)
Large	2	1	1			2			2		3.6	3.6
Medium	3	7	7			5		3		2	5.2	3.3
Small	3	7	1	3		1	1	1		2	5.8	3.3
Unknown		1		1							2.0	2.0
Total	8	16	9	4	0	8	1	4	2	4	5.1	3.3

Note: Adjusted figures were calculated excluding the answers of "possible investments are less than 30% of the added values."

4) Enterprisers' Minds Reflected by the Investigation

The results of the investigation can be summarized as follows:

- i) 90% of the answered enterprisers recognize that the pollution problem in the Metropolitan Area is quite serious, and think that this would require urgent measures.

- ii) Most of the companies are taking some measures for environmental protection by themselves.

Measures many of them are taking are: (a) combustion system control and fuel saving, (b) installation and improvement of filters and dust collectors, and (c) conversion to better quality fuels. Some of them are claiming that regular inspection of boilers would be enough. There are also some enterprises that are planning to convert the fuel to natural gas, to have inspections by professional consultants, and to install pollution control devices.

- iii) The limit of investments for environmental protection, 80% of the enterprises think, should be less than 5% of the added values of the last year. 60% of the answered enterprises said that such investments for pollution control should be less than 2%.

In conclusion most of the enterprisers think that the present environmental problem is quite serious, but realistically they can afford 1 to 3% of the profits to invest in environmental protection.

5. Emulsion Combustion

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(1) History of Development of the Emulsion Combustion System

Development of emulsion fuel in Japan dates back more than ten years ago when a few laboratories began studying emulsion fuel when they learned that NASA was studying gelled emulsion fuel for rockets.

Initially, development was directed to fuel for rockets, solid fuel substitute for camping, and briquette substitute. Then, in response to a proposition by the fire fighting laboratory, it was directed to a safe fuel that prevents fire when a household oilstove is overturned in an earthquake. As regards the safe fuel, the development was deadlocked because of other measures made available to prevent fire and problems such as development of a combustion unit, price increases for kerosene due to gelling, and marketing methods.

In the course of combustion tests of gelled fuel, however, it was confirmed that NO_x and smoke and soot in flue gas could be reduced. Demonstration tests were continued using various oils ranging from asphalt to kerosene in order to achieve industrial application of gel fuel.

Emulsion fuels are now practically used in industrial boilers and furnaces. An emulsion fuel of the particle size at a few microns is produced by adding water and a small amount of a surfactant to a petroleum liquid fuel and by mixing them with a specially designed stirrer. Combustion of the emulsion fuel in a boiler or a furnace enables reduction of NO_x generation and smoke and soot generation as well. Production unit for emulsion fuels is compact in size. The fuel can be easily applied to combustion facilities such as packaged boilers and industrial furnaces whose NO_x generation control has been considered difficult.

(2) Emulsion Fuel

Emulsification refers to dispersion of one of two liquids which are not usually mixed together such as oil and water into another in small drops; their diameters are normally a few microns.

Figure 5.1 shows a microscopic photo of emulsion.

Emulsion is roughly classified into two types as shown in Figure 5.2 : 1) water-in-oil (W/O) type (water drops dispersed in oil), and 2) oil-in-water (O/W) type (oil drops dispersed in water).

The emulsion state differs depending on the kind of stirrer used, the stirring method, and the kind of surfactant. The oil-water ratio can be freely chosen for both emulsion types. Figure 5.3 shows a general relation between the oil-water ratio and the viscosity. In the case of the water-in-oil type, the viscosity of emulsion increases gradually with an increasing number of water drops, and then to become a gel state of low fluidity. The viscosity of the oil-in-water type, on the other hand, decreases greatly with increasing water content.

Figure 5.4 shows the relation between temperature and viscosity of emulsion fuels from the result of the experiment on the O/W type emulsification conducted in this Study in Mexico using Mexican heavy oils. A 28% addition of water reduced the viscosity from original 1,100 cSt (50°C) to 40 cSt (50°C), a decrease to 1/26. In this state, atomized combustion is possible even at room temperature. In the experiment, satisfactory results were obtained in atomized combustion without need of oil preheating.

In the selection of a surfactant and additives for the emulsified combustion system, the following consideration shall be made:

- i) They must not contain sulfur, nitrogen, and harmful heavy metals which are causes of secondary pollution.
- ii) Emulsion must be stable, particularly free from separation due to temperature change.
- iii) They are inexpensive.
- iv) Emulsions must not be broken by acid or alkaline.
- v) Due attention must be paid to prevent rusting of combustion equipment.

(3) Mechanism of NO_x and Smoke and Soot Control in Emulsion Combustion

Figure 5.5 shows an outline of mechanism of emulsion combustion.

Mechanism of reduction in generation of NO_x and smoke and soot is described below.

- i) Combustion with low excess air through promotion of atomization into fine particles

Fuel particles atomized to 30 - 150 μ m are broken into still finer particles through evaporation of water contained in the emulsified fuel. As emulsion particles of 0.5 - 5 μ m are dispersed in atomized fuel drops, the oil drop - air contact area increases rapidly, thereby enabling reduction of smoke and soot and NO_x through the low excess air combustion.

- ii) Removal of local high-temperature zones by water droplets in emulsion fuel

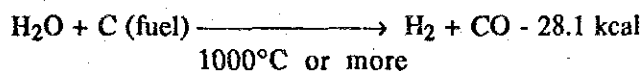
Water is uniformly dispersed in fuel, which leads to a uniform flame as a whole, thereby suppressing appearance of local high-temperature zones.

- iii) Heat absorption through evaporation of water

Thermal NO_x can be reduced by lowering the combustion temperature. The latent heat of evaporation of water in the emulsion fuel lowers the combustion temperature, thereby reducing generation of thermal NO_x.

- iv) Heat absorption by water gas reaction

At a high temperature of over 1,000°C, the water gas reaction occurs between water in emulsion and carbon in fuel. This reaction is endothermic and favorable for removal of local high-temperature zones.



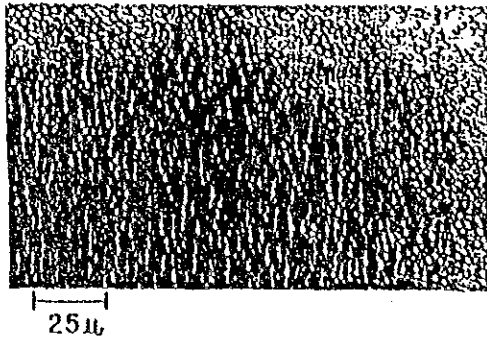


Figure 5.1 Microscopic Photo of Emulsion

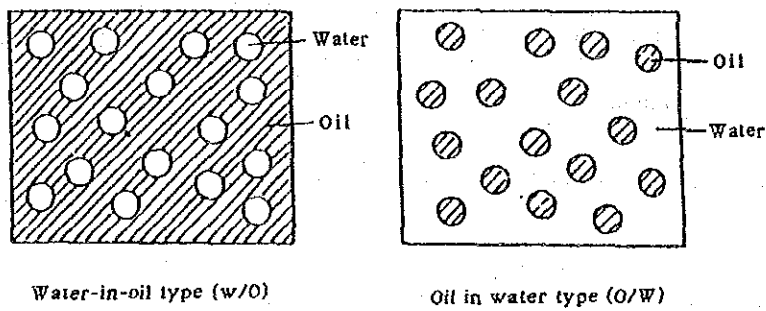


Figure 5.2 Types of Emulsion

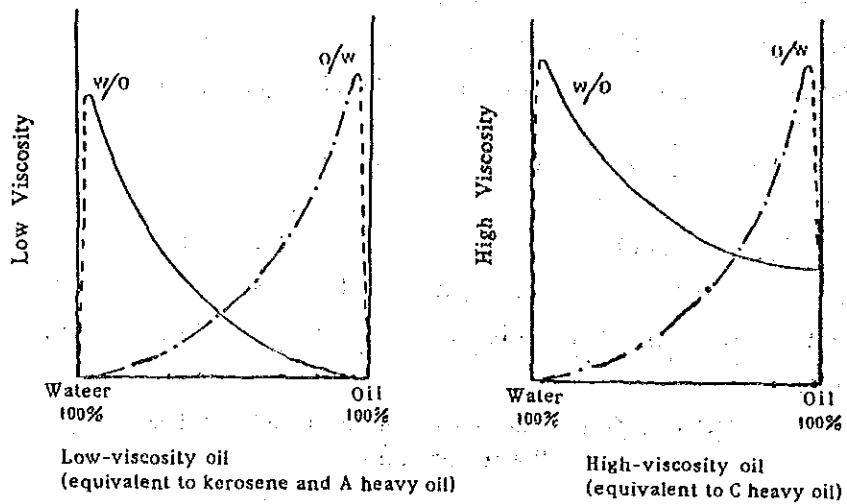


Figure 5.3 Change of Viscosity of Emulsion

Source: "Combustion System Utilizing Emulsion," Japan Oil Chemistry Association, Kansei Division, Text for the 39th Meeting of the Interfacial Chemistry, 1976.

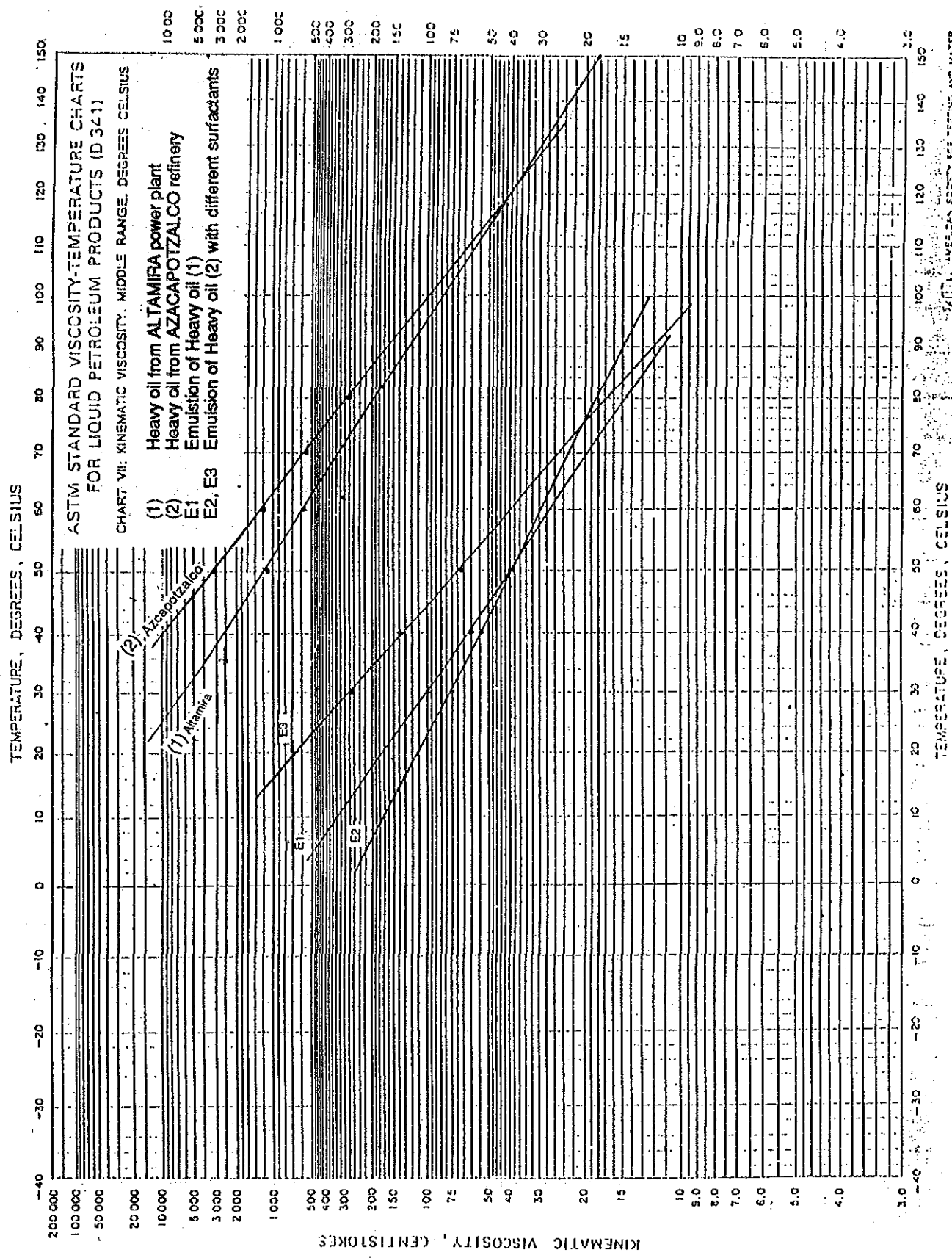
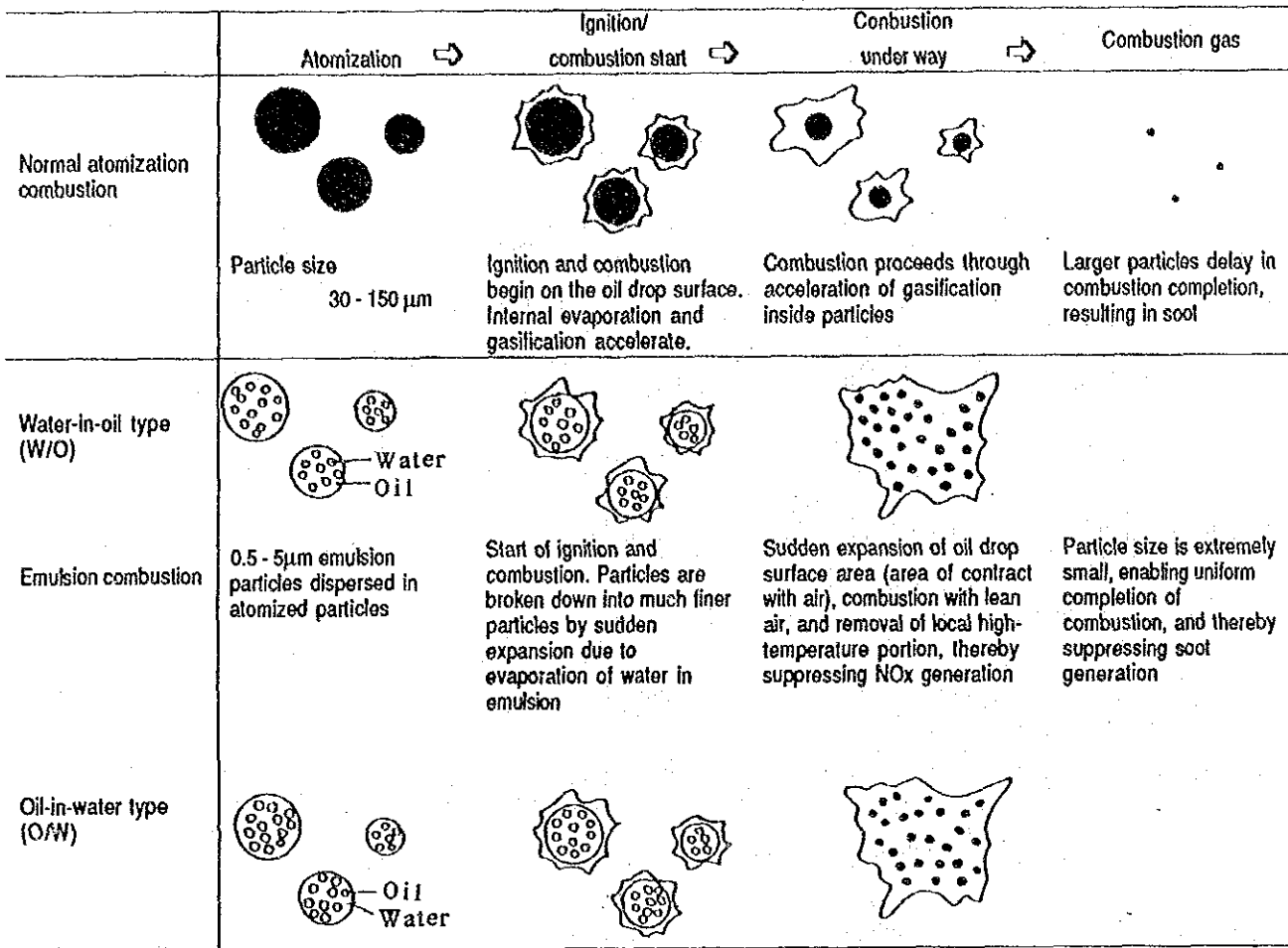


Figure 5.4 Relationship Between Temperature and Viscosity for Heavy Oil and Its Emulsion



Source: *ibid.*, 1976

Figure 5.5 Mechanism of Emulsion Combustion

(4) Examples for Effects of Emulsion Combustion on Control of NO_x and Smoke and Soot Generation

i) Examples in Japan

Actual measurement data in Japan on reduction of NO_x and smoke and soot by the water-in-oil type emulsion combustion in boilers are shown below.

Figure 5.6 shows the NO_x reduction effect when a BS-70S water tube boiler of the evaporation rating at 6.35 ton/hr with a steam atomizing burner was used and emulsion fuels of A-class heavy oil with various water contents were burnt at the rated operation.

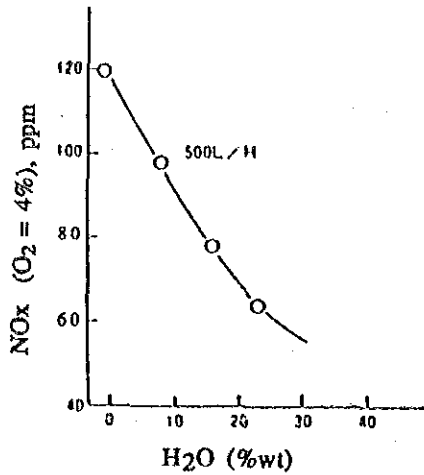
Figure 5.7 shows NO_x reduction effect for the same BS-70S boiler by emulsion of kerosene, by exhaust gas recirculation (EGR), and by both of them coupled. Figure 5.8 shows the same except that A-class heavy oil was used instead of kerosene. In these emulsion fuels, water was added by 20%. The EGR rate was 20 - 25% in volume.

Figure 5.9 shows NO_x reduction effect for a BS-300FII-C20 boiler of the evaporation rating at 20 ton/hr with a steam atomization type burner by emulsion of kerosene, by the two-stage combustion (TSC), and by both of them coupled.

Figure 5.10 shows a NO_x reduction effect for the same boiler by emulsification of A-class heavy oil, by EGR, and by both of them coupled.

Table 5.1 shows concentration of smoke and soot of the exhaust gas from the same BS-300FII-C20 boiler under the rated operation using C-class heavy oil and its emulsion, and kerosene and its emulsion. For C-class heavy oil fuels, TSC, TSC + EGR, and TSC + emulsion are compared. For kerosene fuels, EGR, emulsion, and the both coupled are compared.

In Table 5.2, concentrations of smoke and soot from a BS-50 water tube boiler (evaporation rate: 5 ton/hr, burner type: compressed air atomization) using C-class heavy oil and its emulsion are shown.



Source: *ibid.*, 1976

Boiler type: BS-70S (evaporation rate 6.35 T/H)
 Burner Type: Steam injection type kps burner
 Fuel: A heavy oil

Figure 5.6 Water Addition Amount and NOx Reduction Effect

Boiler type: BS-70S (Rating: 6.35 ton/hr)
 Fuel: Kerosene

- No measure taken
- ☆- EGR
- Kerosene emulsion fuel
- ★- Kerosene emulsion fuel + EGR

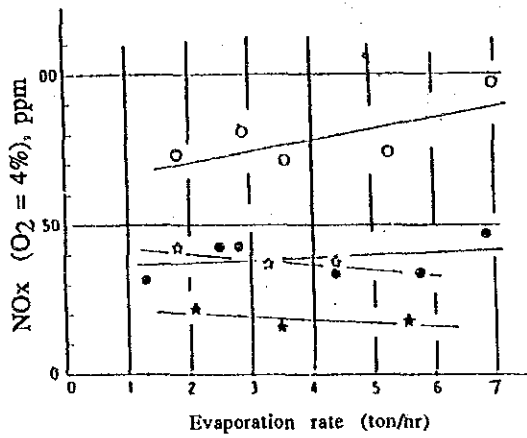


Figure 5.7 NOx Reduction by Kerosene Emulsion

Boiler type: BS-70S (Rating: 6.35 ton/hr)
 Fuel: A-class heavy oil

- No measure taken
- A-class heavy oil emulsion
- ★- A-class heavy oil emulsion + EGR

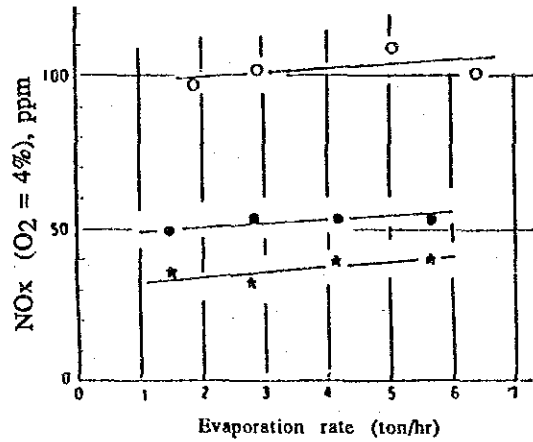


Figure 5.8 NOx Reduction by A-class Heavy Oil Emulsion

Boiler type: BS-300FII-C-20 (Rating: 20 ton/hr)
 Fuel: Kerosene

- No measure taken
- △- TSC
- Emulsion
- ★- Emulsion + TSC

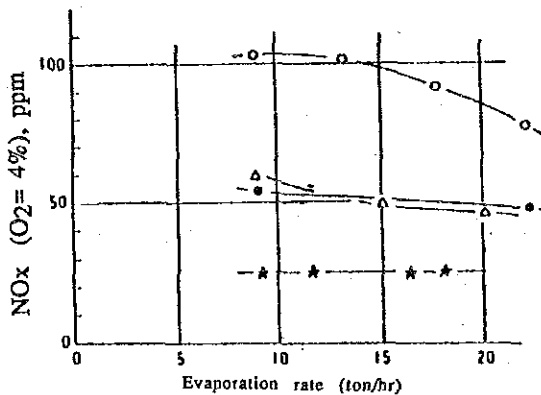


Figure 5.9 NOx Reduction by Kerosene Emulsion

Boiler type: BS-300FII-C20 (Rating: 20 ton/hr)

- Fuel: A-class heavy oil
- No measure taken
 - Emulsion
 - ☆- EGR
 - ★- Emulsion + EGR

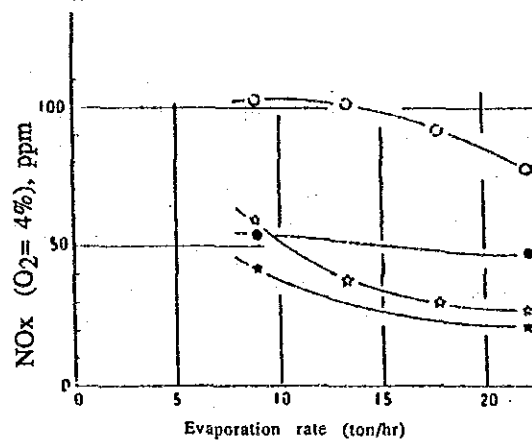


Figure 5.10 NOx Reduction by A-class Heavy Oil Emulsion

Table 5.1 NOx Control Measure and Smoke and Soot Concentration for a 20 ton/hr Boiler

Fuel	Oil Combustion Rate (l/hr)	Flue Gas O ₂ (%)	NOx Reduction Measure	Smoke and Soot Concentration (g/m ³ N)	Measurement Method
C-class Heavy Oil	1,750	3.3	No measure	0.108	JIS Z 8808
		3.3	TSC	0.149	Dust tube method
		3.2	TSC + EGR	0.069	
		2.9	TSC+Emulsion	0.076	
Kerosene	2,000	3.0	No measure	0.022	JIS Z 8808
		2.6	EGR	0.013	
		2.7	Emulsion	0.009	
		2.5	Emulsion+EGR	0.009	

TSC : Two staged combustion
 EGR : Exhaust gas recirculation
 Source: ibid., 1976.

Table 5.2 Particulate Matter Concentration Measurement for a 5 ton/hr Boiler

Fuel	Water Mixing Ratio (%)	Oil Combustion Rate (l/hr)	Flue Gas O ₂ (%)	Smoke and Soot Concentration (g/m ³ N)	Measurement Method
C-class Heavy Oil	0	250	6.8	0.21	JIS Z 8808
	0	180	9.6	0.20	
C-class Heavy Oil	10	250	7.0	0.081	
	10	180	9.8	0.082	
Emulsion	20	250	6.8	0.089	
	20	180	9.6	0.084	

Source: ibid., 1976

These Figures and Tables show the effect of emulsion combustion as follows.

The concentration of smoke and soot is reduced to less than a half when combustion is made with emulsion fuel.

Thermal NOx is reduced by about 50% as compared with the case in which there were no NOx reduction measures. The concentration of NOx is around 40 ppm (O₂ 4% conversion) for the boiler burning

kerosene and 50 - 60 ppm for boiler burning A-class heavy oil.

When this fuel is used together with exhaust gas recirculation or two-staged combustion, synergistic effect can be achieved, with NOx reduced by 65 -75%: reduction to 20 ppm for kerosene and 35 ppm for A-class heavy oil. For C-class heavy oil, reduction of NOx by 20 - 30% is possible, and if water mixing ratio is increased above 30%, NOx can be possibly reduced by 40 - 50%. In summary, the emulsion combustion has a large effect in reduction of NOx and smoke and soot.

In Table 5.3, effects of emulsion combustion and other method on reduction of NOx are compared, and some information on running costs is given.

Table 5.3 Comparison of Various NOx Reduction Methods

Reduction Method	Condition	NOx (4% O ₂) Concentration	Running Cost	Remarks
Emulsion Combustion	Kerosene, Heavy oil A	40-60ppm	Cost of additives around 10-20% of fuel	Particulate matter reduced to one half or less Applicable to industrial furnace
	Kerosene, Heavy oil A coupled with EGR or TSC	25-35ppm		
	Heavy oil C	130 ppm		
Exhaust Gas Recirculation (EGR)	Kerosene, Heavy oil A	40-60ppm		Boiler capacity reduced by 20 - 30%
Two-staged Combustion (TSC)	Kerosene, Heavy oil A	60-90ppm		Unapplicable to existing facilities
	Heavy oil C	140-180ppm		
LPG	Burner improvement	50-70ppm	30 - 100% higher as compared with kerosene	
	No measure	140-160ppm		
City Gas	Burner improvement	50-70ppm		
	No measure taken	100-120ppm		
Exhaust Gas Denitration	Kerosene A-class heavy oil C-class heavy oil	10-30ppm	US\$15 - 77 per kl of fuel	Large equipment area. Waste water treatment system necessary for the wet type.

Source: *ibid.*, 1976.

ii) Result of the emulsion combustion test in Mexico

Samples of emulsion fuels were prepared using Mexican heavy oil and the combustion test was carried out using a test equipment in the Institute of Electrical Investigation (IIE) of Mexico.

When emulsified, Mexican heavy oils (analytical values shown in Table 5.4), which are heavier in quality than those produced in other countries, undergo large decrease in viscosity to the similar level of Japanese A-class heavy oil (viscosity 20 cSt at 50°C).

Table 5.5 shows the result of the combustion test in comparison with the actual emissions of NO_x from some industrial boilers in AMCM measured during the diagnostic survey. The result of the combustion test shown in the part (2) of the Table indicates a large reduction of the NO_x emission. A decrease in viscosity by emulsification enabled smooth atomization and improved combustion efficiency.

Through the experiment in I.I.E, it was confirmed that in addition to the substantial decrease in the NO_x concentrations, appropriate choice of an additive would decrease the SO_x concentration considerably.

Table 5.4 Results of Analysis of Mexican Heavy Oil by IIE

Origin of heavy oil	C.T.ALTAMIRA (Power plant)	18 de MARZO Refinery
Date of Analysis	Nov. 23, 1990	Nov. 28, 1990
Specific gravity	0.999	0.999
API gravity (degree)	9.75	9.75
Flash point (°C)	72.0	86.0
Water distilled (% vol)	0.20	< 0.10
Water and sediment (% vol)	0.30	0.10
Conradson carbon (% wt)	16.80	14.61
Asphaltenes in nC5 (% wt)	20.02	17.26
Viscosity, SSF at 50°C (sec)	545.0	-
Viscosity, SSF at 60°C (sec)	276.0	486.0
Viscosity, SSF at 82.2°C (sec)	84.0	123.0
Viscosity, SSF at 98.9°C (sec)	-	58.0
Total ash (% wt)	0.065	0.071
Total sulfur (% wt)	3.97	3.8
Gross calorific value (kcal/gr)	10.058	10.142
Net calorific value (kcal/gr)	9.577	9.661
C (% wt)	82.3	84.1
H (% wt)	10.2	10.35
N (% wt)	0.46	0.47
O (% wt)	3.07	1.28

Table 5.5 Comparison Between Heavy Oil Combustion and Emulsion Combustion

(1) Heavy Oil Combustion (Measured at Factories in AMCM)

Name	Boiler Rating (ton/hr)	O ₂ (%)	CO ₂ (%)	NO _x (ppm)			NO _x Generation	
				Measured	O ₂ 0% conversion	O ₂ 2% conversion	NO _x kg Oil m ³	NO _x kg 10 ⁶ kcal
Kimex	28	6.9	10.0	283	422	361	8.46	0.87
Uniroyal	10	6.2	10.5	250	355	304	7.04	0.72
Modero	63	4.3	12.0	242	304	261	6.61	0.61
Fibras Sinteticas	40	5.2	11.0	247	328	281	7.15	0.73
	13	5.8	12.0	319	441	338	8.64	0.89
Quimica Lucava	2.6	4.2	11.5	265	331	284	7.08	0.73
Anderson Clayton	45	4.8	11.5	205	266	228	5.00	0.51
Empaques y Carton	9.5	5.2	10.8	191	254	218	5.13	0.53
Average		5.3	11.2	250.3	337.6	284.4	6.89	0.70

(2) Emulsion Combustion (Test in IIE)

Emulsion test A	3.8	12.8	143	175	150	3.41	0.37
Emulsion test B	2.5	14.3	160	182	156	3.56	0.37
Average	3.2	13.6	151.5	178.5	153.0	3.49	0.37

Note: 1) When the average values of (1) and (2) in the Table are compared, generation of NO_x in (2) is reduced by about 50%. In general, the reduction rate should be assumed more conservatively at 20% - 50% since it is influenced by many factors such as combustion temperature, shape of combustion chamber, chamber loading, and appropriateness of atomization.

2) The calculated reduction ratio for SO₂ is as follows:

Emulsion test A	48%
Emulsion test B	22%

(5) Advantages of the Emulsion Combustion Method

Advantages of the emulsion combustion method are summarized below:

i) Substantial reduction in NO_x and smoke and soot

As described above, the emulsion combustion exhibits large effects in reducing generation of NO_x and smoke and soot when applied to petroleum fuels such as heavy oil. The effect becomes larger when

emulsion combustion is coupled with exhaust gas recirculation or two-staged combustion.

ii) Easy application to existing combustion equipment

Since combustion with emulsion fuel only requires connection of the emulsion production system to the fuel supply system, it can be applied easily to new and existing facilities alike without decreasing the combustion equipment capacity. The size of the equipment is small, e.g., 4 m³ or less for a 40 ton/hr boiler (exhaust gas of about 40,000 m³N/hr). If this unit is to be applied to an existing boiler, only a short time is required and the time for suspension of operation can be minimized.

iii) No decrease in combustion efficiency

Some point out that heat loss due to the water content may be a problem. As shown in Table 5.6, however, the theoretical calculations show only about a 2% heat loss due to a 20% water content by volume in emulsion fuel. Because of lean air combustion and less particulate matter generation, the heat transmission efficiency rises and the total efficiency becomes higher over a long period.

Table 5.6 Heat Loss due to Water Content in Emulsion Fuel

A-class heavy oil (net calorific value of 10,000 kcal/kg) emulsion of water/oil = 2/8 (volume ratio) burnt and flue gas discharged at 250°C.	
Heat required for water in fuel to turn into steam of 250°C	
$2 \times \left\{ 100 - \frac{\text{(Room temperature)}}{20^\circ\text{C}} + \frac{\text{(Evaporation Latent heat 539)}}{\text{8 x (Fuel specific heat 0.85)}} + (250 - 100) \times \frac{\text{(Steam Specific heat 0.5)}}{\text{8 x (Fuel specific heat 0.85)}} \right\}$	
= 204 kcal/kg	
204 ÷ 10000 × 100 = 2% (Heat loss due to water content of the fuel)	

iv) No decrease in combustion equipment capacity

The increase in volume of exhaust gas due to a 20% water content in emulsion fuel is calculated to be 2.6%, as shown in Table 5.7. This means that there is no need of enlargement of the capacity of

combustion equipment such as that required in the flue gas recirculation method.

Table 5.7 Exhaust Gas Increase due to Water Content in Emulsion Fuel

<p>A-class heavy oil (C=85%, H=12%, others=3% by weight) emulsion of water/oil = 2/8 (percent by volume) burnt at the air ratio of 1.2</p> <p>Amount of steam from water in fuel = $2 \times 22.4 + (8 \times [\text{Specific weight } 0.85] \times 18)$ = $0.37 \text{ Nm}^3/\text{kg}$</p> <p>Increase in exhaust gas = (Steam amount from water in fuel) + (Wet combustion gas amount) = $0.37 + (11.7 \times 1.2) \times 100 = 2.6\%$</p>
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v) Slight increase in running cost

The cost to produce emulsion is around 10-20% of the price of oil fuel.

vi) Less trouble in the fuel feeding system, with high durability

vii) Atomized combustion of high-viscosity fuel at room temperature

When the viscosity of a highly viscous oil is reduced by applying the oil-in-water type emulsification, the fuel can be transported in piping at room temperature and can be finely atomized for burner combustion.

(6) Problems in Emulsion Combustion

- i) Since the flame temperature decreases by the elimination of local high temperature zones associated with evaporation of water droplets and by the endothermic functions, emulsion fuels can not be used in furnaces such as cement kilns and glass melting furnaces in which a high temperature of $1,400^\circ\text{C}$ or more is required.
- ii) When a fuel of a high vanadium (V) content is emulsified with certain types of surfactant, the melting point of V_2O_5 is decreased and furnace materials may be corroded. Therefore, a prior investigation is necessary.

iii) While the water content of the flue gas from ordinary heavy oil combustion is 10 - 11%, it increases to 14 - 15% when the fuel is emulsified with addition of water by 30%. Although the difference is rather small, possible influences of the increased water content should be investigated beforehand when applying to metal heating furnaces or ceramic furnaces.

(7) Further Studies Required

In order to adopt the emulsion combustion system in industries in Mexico, further studies are needed as described below.

i) First phase - Basic study

- a. Selection of surfactant which is the most stable over an extended period of time for emulsion of Mexican heavy oil
- b. Selection of additives to reduce emission of NO_x and SO_x and measurement of the reduction ratio during combustion
- c. Study of long-term stability of emulsion
- d. Secular change of status of oil drops in emulsion
- e. Change of water content in emulsion
- f. Test of temperature effect on emulsion
- g. Corrosion test of combustion equipment and facilities
- h. Re-emulsion test of broken emulsion fuel
- i. Selection of burner atomizing conditions for satisfactory combustion (Setting of the air or steam atomizing pressure, air ratio, air-blow method, and fuel pressure, and fine atomization test of emulsion fuel)

ii) Second phase - Pilot-scale study

- a. Long-term storage test in a pilot-scale tank
- b. Transportation test with a tank lorry

- c. Forced feeding test with a pump
 - d. Combustion experiment (pilot scale) with emulsion of hydro-desulfurized heavy oil and combustion tests in facilities in two or three plants in Mexico
- iii) Third phase - Study on small-scale industrial facility
- a. Study on NOx reduction ratio and economy on a practical application scale
 - b. Cost estimation and feasibility study for construction of a large-scale emulsion fuel production plant

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