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Combustion of Methanol and Liquefied Butane in a Gas Turbine Combustor

S. Kajita
Jet Engine Division

J. Kitajima
Technical Institute

T. Kimura
Technical Institute

Kawasaki Heavy Industries, Ltd.,
Akastii, Japan

Combustion tests with a gas turbine combustor were carried out to clarify the technical problems caused when liquefied butane was supplied and burned in the liquid phase in addition to evaluating methanol and liquefied butane as an alternative fuel. For methanol, a conventional dual-orifice type fuel injector, and for liquefied butane, the same dual-orifice type injector and two types of multi-hole injectors were tested. The results of combustion tests with both fuels were compared with those of conventional gas turbine fuels—kerosene and natural gas with respect to combustion performances and exhaust emissions. It was found that both fuels had some advantages over conventional fuels.

INTRODUCTION

The recent energy crisis has aroused much interest in the utilization of alternative fuels for gas turbine engines. Many fuels such as hydrogen, alcohols, liquefied petroleum gases, coal gas and ammonia etc. are considered as alternative fuels to conventional gas turbine fuels - kerosene and natural gas. In this paper methanol and liquefied butane were chosen from among these fuels, and combustion tests were carried out to evaluate both fuels.

Table 1 presents some physical and thermodynamic properties of both fuels in comparison with those of conventional fuels. Since methanol has some advantages, many experiments about its utilization for gas turbine engines have been carried out and several papers have been presented (1), (2). On the other hand, the utilization of liquefied butane has been rare because of complications resulting from its liquefied state, i.e. a complicated supply system was required. The supply system previously used included a pipe heating apparatus for the preventation of re-liquefaction and a vaporizer when liquefied butane was supplied to gas turbine engines in a gaseous phase. To avoid these technical difficulties, liquefied butane was supplied to the combustor in a liquid phase in the experiment.

The results of combustion tests with both fuels were compared with those of kerosene and natural gas.

APPARATUS AND PROCEDURE

Test Facility

The test facility is shown in Figure 1. Air is supplied from a compressor, metered by an orifice-meter, heated by an indirectly fired preheater and regulated at a constant pressure level by a butterfly valve in an exhaust duct.

The fuel facility is also shown in Figure 1. Kerosene is pumped by a plunger pump and metered by a turbine flow meter. Natural gas is supplied from commercial gas cylinders, regulated by a valve and metered by an orifice-meter. Methanol and liquefied butane are pressurized by nitrogen gas from commercial cylinders and metered by a turbine flow meter.

The exhaust gas temperatures are measured by 24 C-A thermocouples at the combustor exit. The following equipment is used for analysis:

Exhaust constituent	Instrument
NO, NOx	Beckman mod. 951A Chemi-luminescence instrument
CO	Yanagimoto mod. EIR-16 NDIR
HC	Beckman mod. 402 FID

Combustor and Fuel Injectors

A conventional can-type combustor of the industrial gas turbine engine, KAWASAKI M1A whose main particulars are shown in Table 2, was used to test four types of fuels without any modifications. It is shown in Figure 2.

Five types of fuel injectors as shown in Figure 3 and Table 3 were used in this experiment. For kerosene, a conventional dual-orifice type fuel injector (NO.1) was used. For methanol, the same type fuel injector (NO.2) was used, but its main passage was enlarged to permit adequate fuel flow. The same injector (NO.2) as was used for methanol and two types of multi-hole type injectors (N0.3,4) were used for

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Table 1. Fuel properties

	Methanol	Liquefied Butane	Kerosene*	Natural Gas (Methane)
Chemical Formula	CH_3OH	C_4H_{10}	$C_{12}H_{24}$	CH_4
Molecular Weight	32.03	58.1	168	16.0
Specific Gravity at 15 °C	0.796	0.585	0.800	-
Lower Heat of Combustion (MJ/kg)	20.1	45.7,	43.2	50.0
Boiling Temperature at 1 atm (°C)	65	-0.6	150 - 300	-161.5
Heat of Vaporization (MJ/kg)	1.101	0.386	0.306	-
Stoichiometric A/F by Mass	6.48	15.46	14.78	17.20
Flammability Limits (% vol, fuel)	7.3 - 36.0	1.8 - 8.4	0.7 - 5.0	5.0 - 15.0
Spontaneous Ignition Temperature (°C)	473	441	254	632
Viscosity at 20 °C (mm^2/S)	0.727	0.31	1.65	-

* The values represent averages.

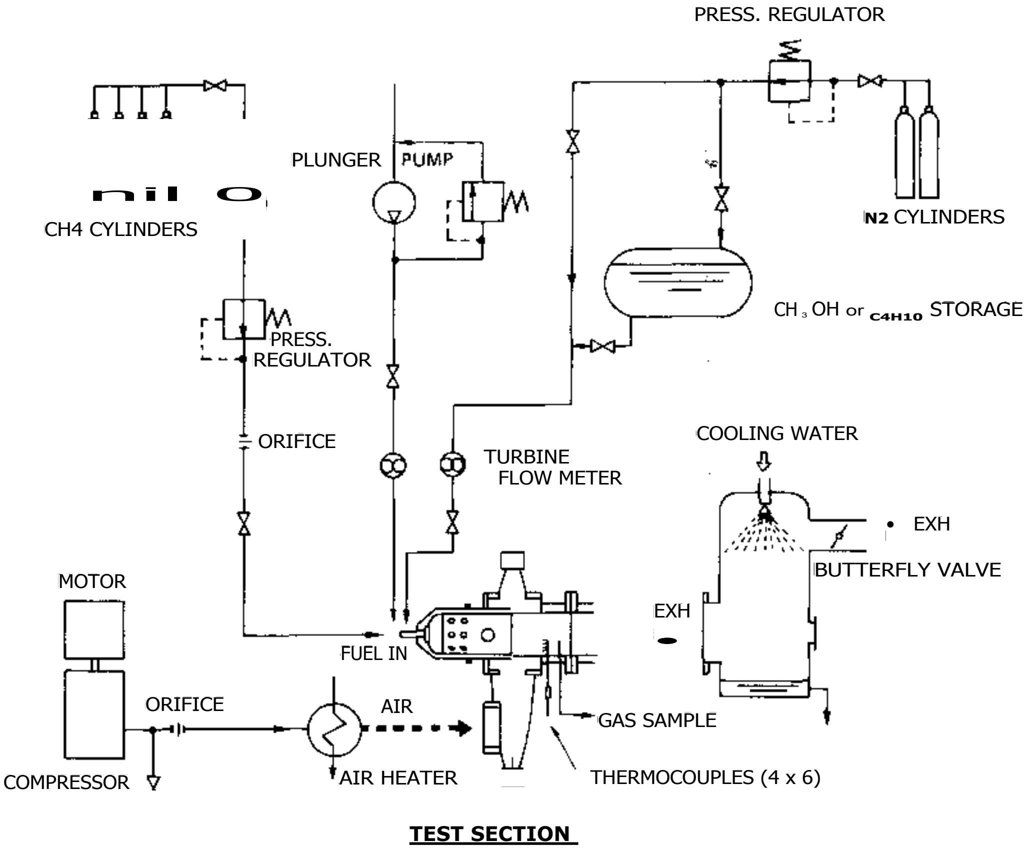


Figure 1. Schematic of the test facility

Table 2. Main particulars of KAWASAKI M1A

Type	Simple open cycle, Single shaft
Compressor	2-stage, Centrifugal
Combustor	Single, Can-type
Turbine	3-stage, Axial
Rated Output	1,177 KW at 15 °C and sea level
Rated Speed	22,000 rpm (main shaft)
	1,500 or 1,800 rpm (output shaft)
Compression Ratio	8
Air Flow Rate	7.7 kg/s
Use	Generator drive
Manufacturer	KAWASAKI HEAVY INDUSTRIES, LTD., AKASHI, JAPAN

Table 3. List of fuel injectors

No.	Injector type	Fuel	Remarks
1	Dual-orifice	Kerosene	
2	"	Methanol, Liquefied Butane	Enlarged Main passage
3	Multi-hole	Liquefied Butane	40.4 x 16
4	"	"	40.6 x 8
5	"	Natural Gas	45.6 x 6

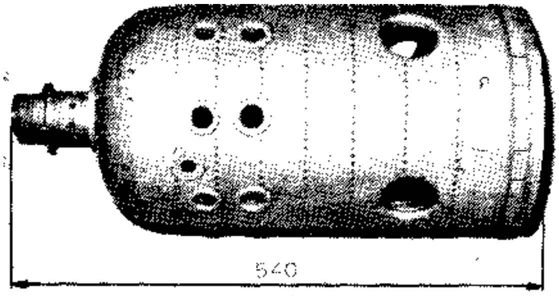


Figure 2. KAWASAKI M1A gas turbine combustor

Figure 3. Tested fuel injectors

liquefied butane. Another multi-hole injector (NO.5) was used for natural gas.

Test Conditions

Except for ignition performance tests, all tests were conducted under the following conditions: (1) the combustor inlet air temperature was 600 K and the combustor reference velocity was 20 m/S. These conditions are equal to the engine's operating conditions; and (2) the combustor inlet pressure was 2 atm which defined by the capacity of the facility. The range of air-fuel ratios was chosen from the operating range of the engine.

RESULTS AND DISCUSSION

Injector Performance

Spray Pattern. The spray patterns of the conventional dual-orifice type injector for kerosene, methanol and liquefied butane are shown in Figure 4. In this case, the same primary nozzle was used to clarify the differences of spary patterns with fuels.

The spray patterns of kerosene and methanol were almost the same, and spray angles of both fuels changed from 85 to 82 with increase of the spray pressure.

On the other hand, the spray pattern of liquefied butane was considerably different from those of kerosene and methanol. The spray angle changed from 73 to 66 with increase of the spray pressure. In addition, the extension of the spray was extremely narrow, particularly for higher spray pressures as can be seen in Figure 4. Therefore, a longer flame length is to be anticipated for the combustion with liquefied butane by a conventional dual-orifice type injector.

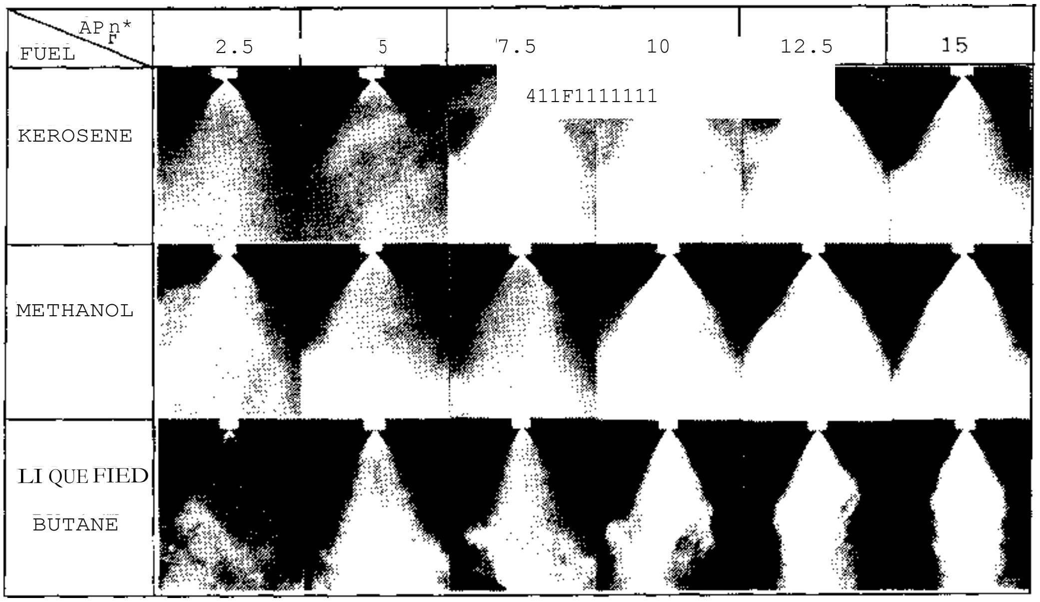
Flow Characteristics. The flow characteristics of NO.2 dual-orifice type injector are shown in Figure 5. The flow rates of kerosene and methanol were proportional to the differential spray pressure by the power of 0.5 for both main and primary nozzles. However, the flow rate of liquefied butane was proportional to the power of 0.71 for the main nozzle and 0.74 for the primary nozzle, and rapidly decreased for lower spray pressures.

Figure 6 shows the flow characteristics of multi-hole type injectors. For kerosene, the flow rate was also proportional to the differential spray pressure by the power of 0.5. Whereas, it was proportional to the power of 0.88 for liquefied butane.

The results indicate that the flow of liquefied butane became a two-phase flow in the pipe for lower spray pressures.

Ignition Performance

Figure 7 presents the ignition performance test results. Flammability limits and the stoichiometric ratio in the primary combustion zone are also shown in the figure. For kerosene and natural gas, the ignition occurred when the air-fuel ratio in the primary combustion zone reached the stoichiometric ratio. Whereas, the ignition performances of methanol and liquefied butane were better than those of the above fuels; for methanol, it occurred near the lean flammability limit; for liquefied butane, it occurred between the lean flammability limit and the stoichiometric ratio,



* APF : differential spray pressure (kgf/cm^2)

Figure 4. Effect of fuel on the spray characteristic of the dual-orifice type fuel injector. Conversion factor: (kgf/cm^2) = (0.0980665)(MPa)

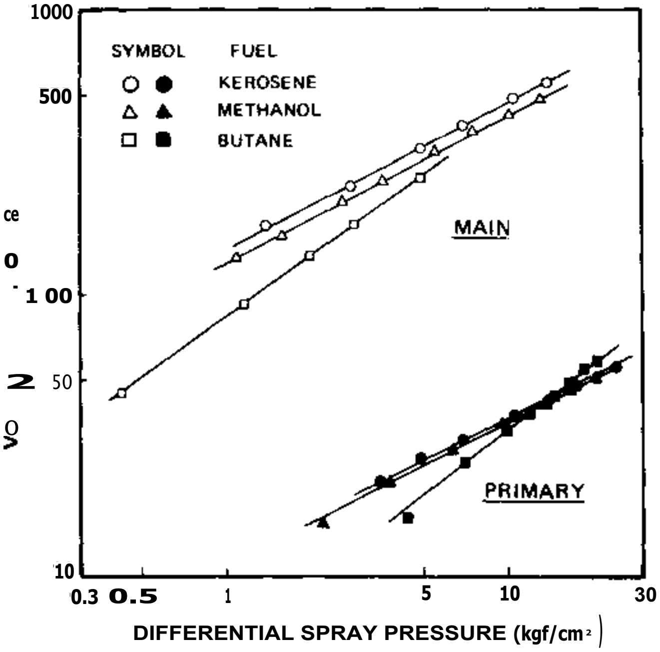


Figure 5. The flow characteristics of the NO.2 dual-orifice type fuel injector. Conversion factor: (kgf/cm^2)=(0.0980665)(MPa)

but was considerably scattered because the flow became a two-phase flow at the injector orifice.

Visual Observations of the Flame

To clarify the characteristics of the flame for various fuels, visual observations of the flame were carried out preceding the combustion performance test. The color of the flame changed with the fuel type as follows,

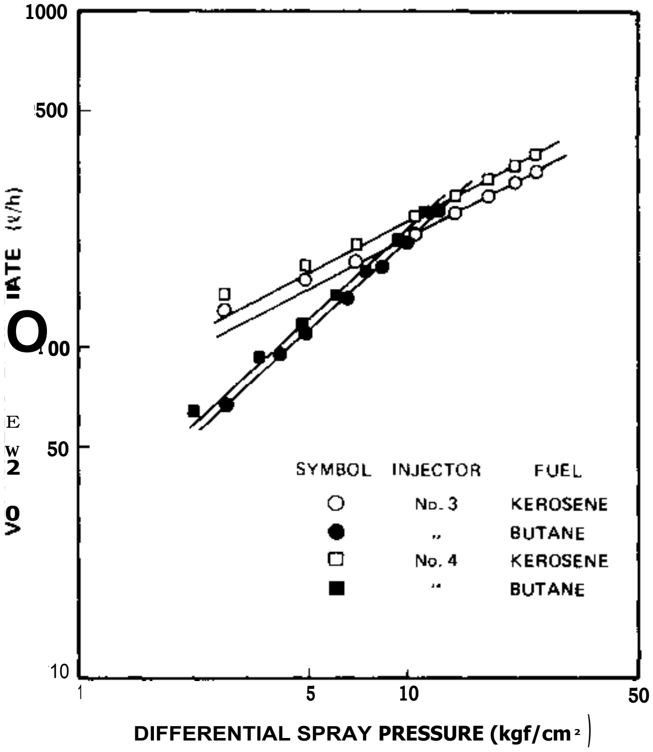
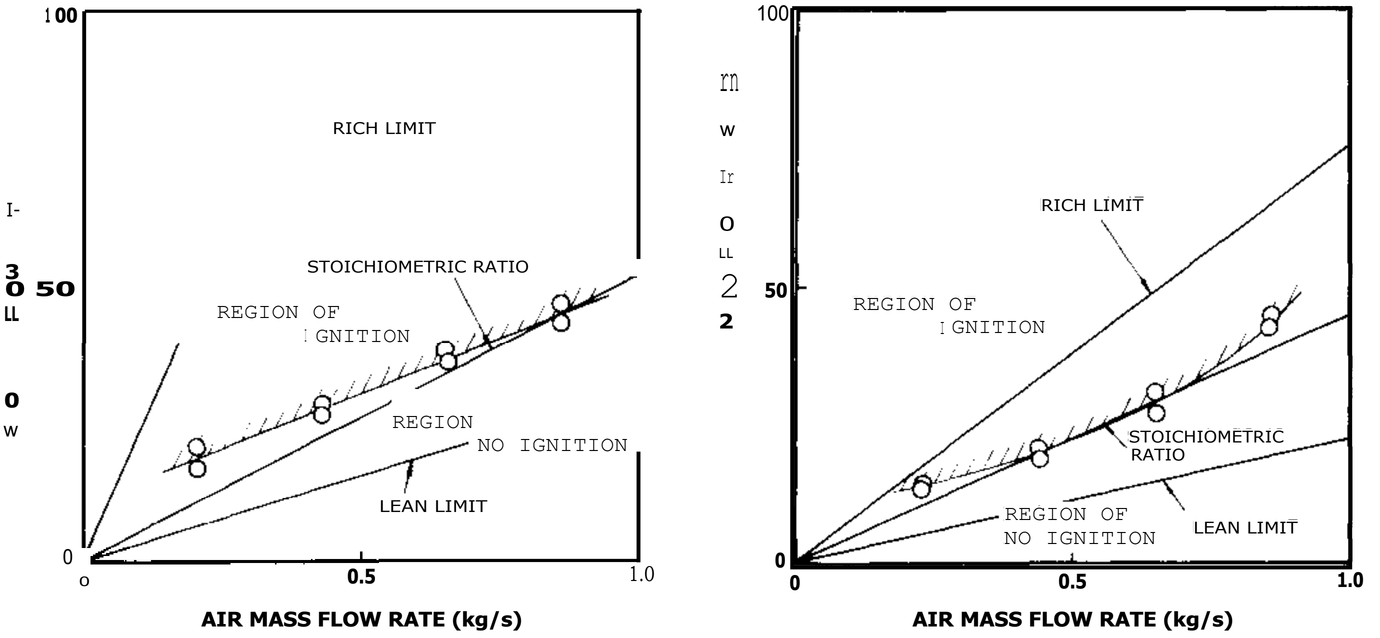


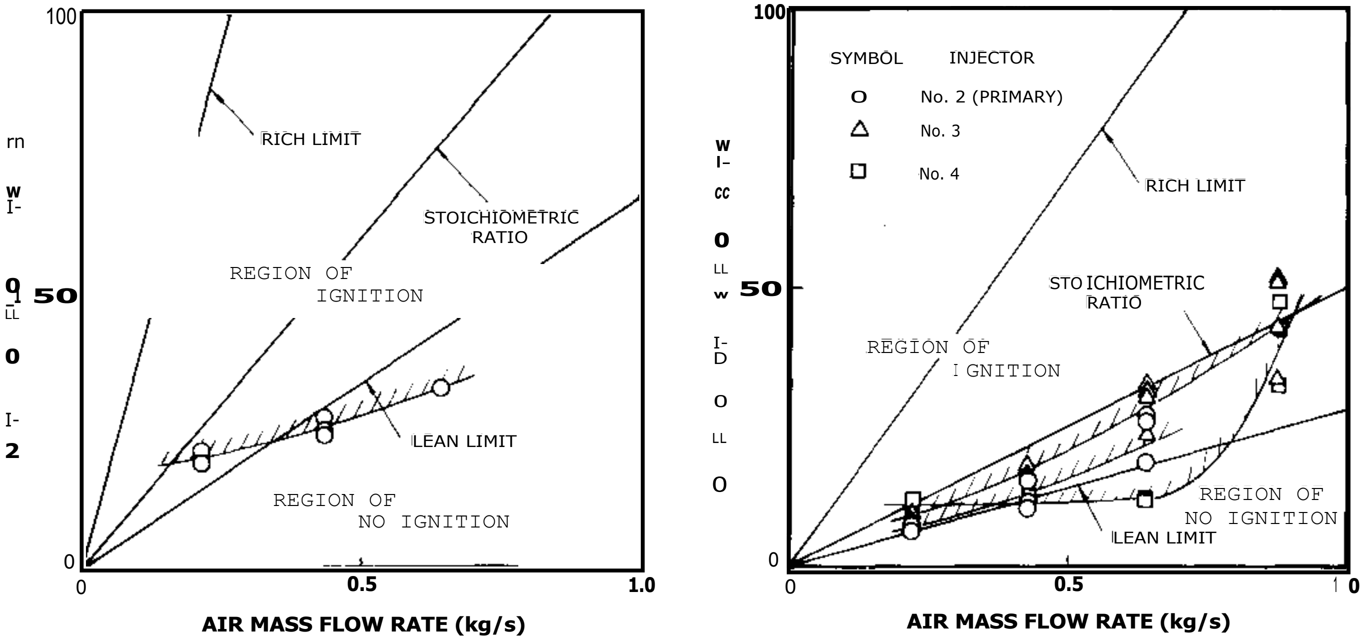
Figure 6. The flow characteristics of multi-hole type fuel injectors. Conversion factor: (kgf/cm^2)=(0.0980665)(MPa)

Under atmospheric conditions, the flame of kerosene was almost yellow, and those of natural gas and methanol were blue. For liquefied butane, it was light blue, but with a yellow flame front.



(a) KEROSENE

(b) NATURAL GAS



(c) METHANOL

(d) LIQUEFIED BUTANE

Figure 7. Comparison of ignition performances

On the other hand, under the preheated and pressurized condition, the flame of kerosene was an extremely bright radient yellow. Almost the same result was obtained for liquefied butane, but its flame was considerably transparent. For natural gas, the flame was blue with a yellow front. For methanol, the flame was blue-pink.

From these results, it was expected that the radiation from the flames was extremely low for methanol and natural gas.

Combustion Performance

Combustion Efficiencies. The combustion efficiency data calculated from emission measurements are shown in Figure 8. In this paper, the flow rate of methanol, liquefied butane and natural gas is converted into that of kerosene with its lower heat of combustion to directly compare the results of the four types of fuels.

The combustion efficiencies with kerosene and methanol were greater than 99% for lower air-fuel ratios. While for higher air-fuel ratios, the efficiency fell off because of deteriorating spray conditions. This tendency is significant for methanol because of its lower combustion temperature and the increased amount of combustibles quenched by the film-cooling air on the combustor wall.

The combustion efficiencies with natural gas were greater than 99% for all air-fuel ratios. For liquefied butane with the dual-orifice type injector, almost the same result was obtained. Even for multi-hole type injectors, the efficiencies were over 99%. These results exhibit that the atomization of liquefied butane is extremely easy.

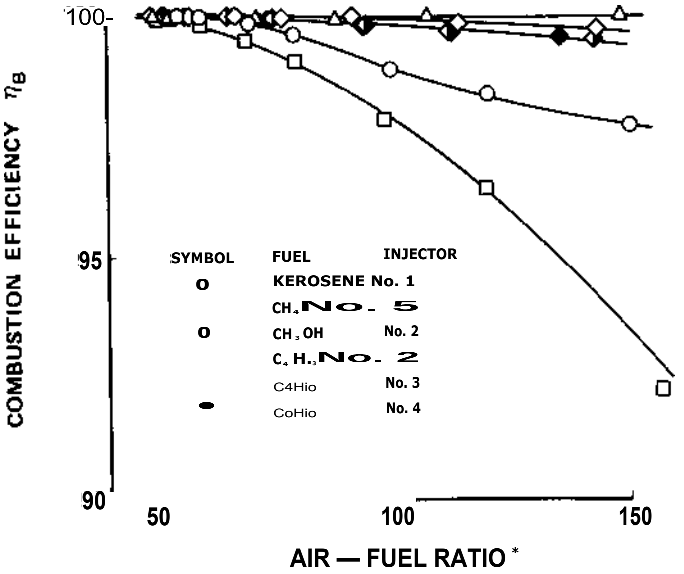


Figure 8. Combustion efficiencies

(*All air-fuel ratios in this paper are converted to kerosene's air-fuel ratio.)

Exit Temperature Pattern Factors. The exit temperature pattern factors are shown in Figure 9. The exit temperature pattern factor 8t in the figure is defined by the following equation

$$t - \frac{Tmax - Tmean}{Tmean - Tin}$$

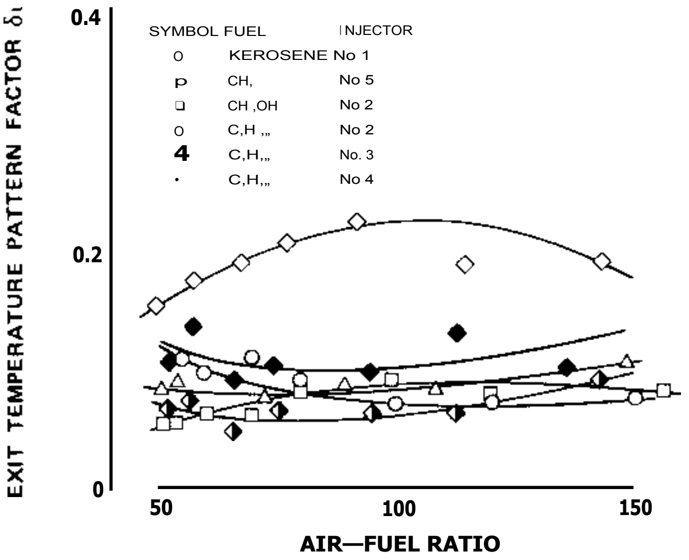


Figure 9. Exit temperature pattern factors

where T_{max} is the maximum exhaust gas temperature measured at the combustor exit; T_{mean} is the weighted average temperature of the exhaust gas; Ti_n is the air temperature at the combustor inlet.

As can be seen in Figure 9, 8t with methanol and natural gas for lower air-fuel ratios is considerably lower than that with kerosene. While for liquefied butane, large differences were found among the three types of injectors; eft with the NO.3 injector was almost the same as that with natural gas. oft with the NO.4 injector was larger than that with kerosene, especially for higher air-fuel ratios. While drt with the NO.2 dual-orifice type injector was extremely high compared with those of the above two types of injectors because the spray angle and extention were significantly narrower as previously described.

Combustor Wall Temperatures. The combustor wall temperatures, measured by a temperature indicating paint, are shown in photographs in Figure 10. As expected, with methanol and natural gas, the combustor wall temperatures were extremely low. Most of the combustor wall was covered with region B of 410 C - 490 C. For liquefied butane, the combustor wall temperature changed slightly with fuel injectors; with the NO.4 injector, the result was almost the same as that with methanol and natural gas: with the NO.2 dual-orifice type injector and the NO.3 injector, the combustor wall temperatures were slightly higher than that with the NO.4 injector. With kerosene, the temperatures were extremely high, and most of the combustor wall was covered with region C of 490 C - 575 C and region D of 575 C - 800 C.

Emission Results

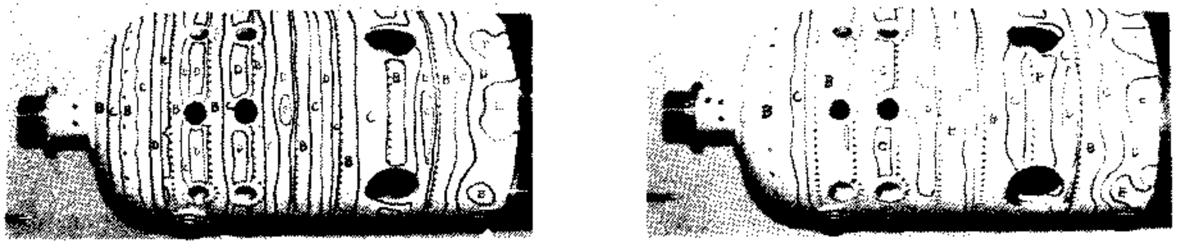
Unburned Hydrocarbons. The emissions of hydrocarbons are presented in Figure 11. The hydrocarbon emissions with natural gas were nearly zero for all air-fuel ratios. For liquefied butane, the hydrocarbon emissions changed somewhat with the type of injector; with multi-hole type injectors, the results were almost the same for all air-fuel ratios and 75 - 80% less than that with kerosene for higher air-fuel ratios; with the NO.2 dual-orifice type injector, the hydrocarbon emissions were less than half that obtained with multi-hole type injectors.

The "hydrocarbon" emissions resulting from combustion with methanol were extremely higher than with kerosene. The reason for this is thought to result from the quenching on the combustor wall by film-cooling air. Since the required methanol flow rate was more than twice that of kerosene, the amount of combustibles reaching the combustor wall was increased.

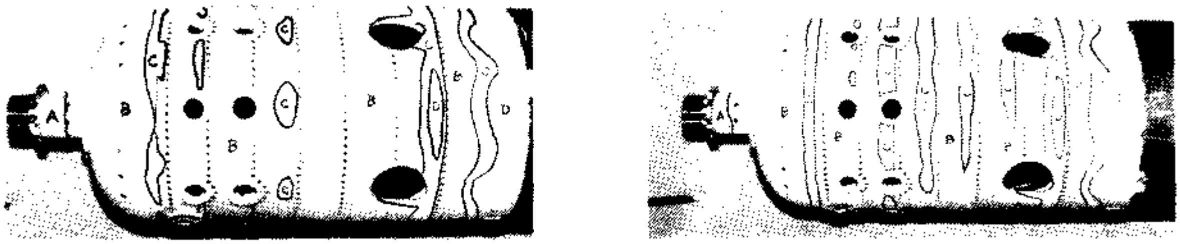
Carbon Monoxide. Combustion with liquefied butane produced less carbon monoxide than with kerosene for all air-fuel ratios as shown in Figure 12; with multi-hole injectors, the results were approximately half that with kerosene; with the NO.2 dual-orifice type injector, the results were 65 - 70% less than that with kerosene. But all results were slightly more than that with natural gas.

Combustion with methanol produced extremely higher carbon monoxide than with kerosene resulting from the quenching by film-cooling air and the lower combustion temperature as previously mentioned.

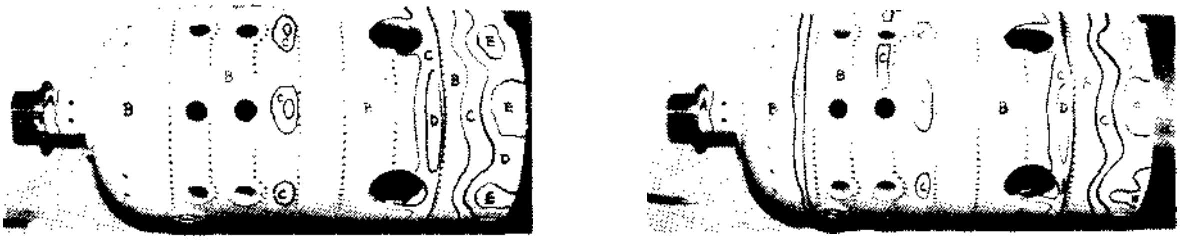
Oxides of Nitrogen. Combustion of liquefied butane with the NO.2 and NO.3 injectors produced slightly lower nitrogen oxides emissions than that of kerosene at low air-fuel ratio, but 7 - 10% higher for higher air-fuel ratios because the combustion efficiency of kerosene rapidly decreased. These results are shown in



(a) KEROSENE (d) LIQUEFIED BUTANE (NO.2 INJ.)



(b) NATURAL GAS (e) LIQUEFIED BUTANE (NO.3 INJ.)



(c) METHANOL (f) LIQUEFIED BUTANE (NO.4 INJ.)

TEMPERATURE CODE ON COMBUSTOR WALL

A	< 410°C
B	410 - 490 °C
C	490 - 575 °C
D	575 - 800 C
E	> 800°C

Figure 10. Combustor wall temperatures

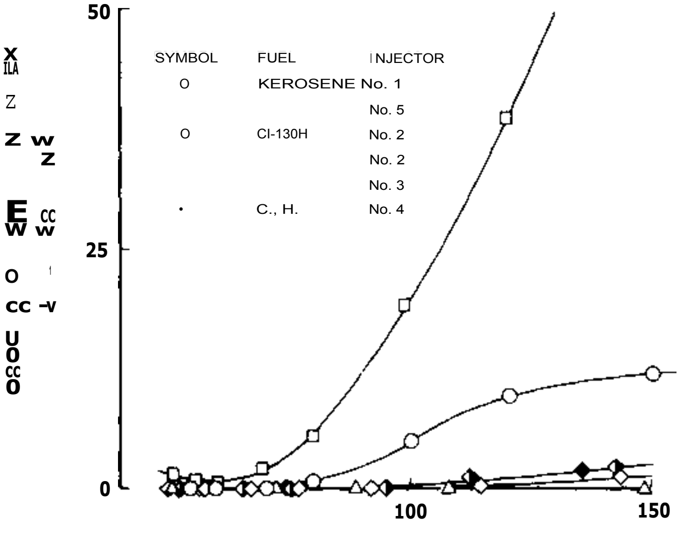


Figure 11. Hydrocarbon emissions

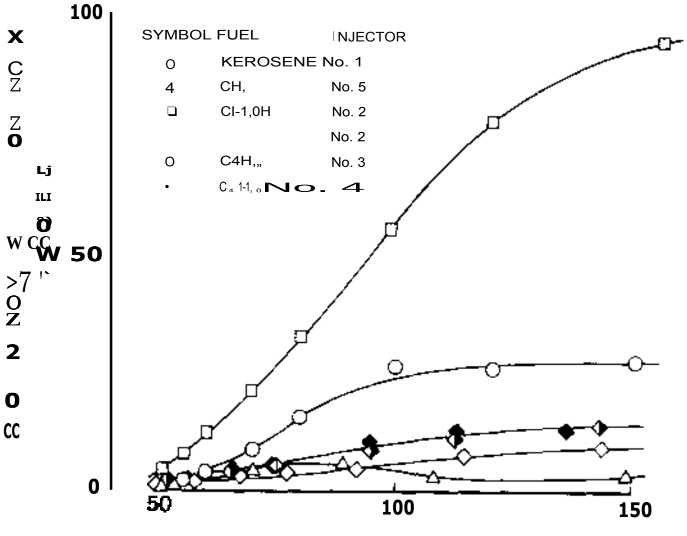


Figure 12. Carbon monoxide emissions

Figure 13.

Combustion of liquefied butane with the NO.4 injector produced approximately 15% lower nitrogen oxides emissions than with the above two injectors, but those emissions were 7-14% higher than those from natural gas.

The emissions of nitrogen oxides resulting from combustion with methanol were 70% lower than those produced from kerosene. The reduction in nitrogen oxides emissions results primarily from the lower combustion temperature of methanol.

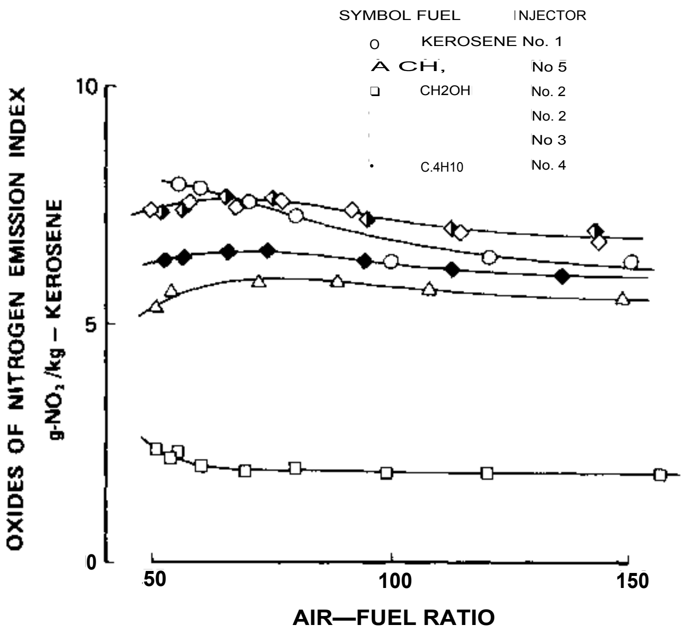


Figure 13. Oxides of nitrogen emissions

CONCLUSIONS

The results of combustion tests on methanol and liquefied butane indicate that both fuels have some advantages over a conventional fuel - kerosene; good ignition performances, reduction of pollutant emissions and lengthened combustor life will be expected. However, in using these fuels, the following points are significant:

1. Combustion with methanol produces higher carbon monoxide and "hydrocarbon" emissions, so it is necessary to use a suitable atomization method, such as an air assisted fuel injector.

2. A conventional dual-orifice type fuel injector is unsuitable for liquefied butane because it causes an extremely poor temperature distribution at the combustor exit.

3. For liquefied butane, a multi-hole type fuel injector is suitable, but an optimum number of holes and their diameters have to be determined from experiments.

   The injector with a large number of holes has a good temperature distribution but it also produces a high level of nitrogen oxides emissions.

4. Since liquefied butane vaporizes easily, pressurizing it at least over its saturation pressure is necessary to prevent its vaporization in pipes.

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