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ABSTRACT

The improvement of diesel engine performance and the reduction of exhaust smoke density by the method of auxiliary fuel addition into the intake air were experimentally investigated. This method was applied to three kinds of diesel engines and the useful results and also the matters which had to be considered to its practical application could be obtained.

1. Introduction

This paper presents the experimental investigations on the effects of auxiliary fuel addition into the intake air of diesel engines. Hereafter, we will call this method of auxiliary fuel addition the " bifuel method " for a simplification. The reduction of exhaust smoke density along with the improvements of the engine performance may be expected by the bifuel method. The attempts on such purposes have been studied by LYN (1954), PERRY (1954), SCHWEITZER (1958), HIRAKO (1970), SAITO (1966) and MATSUMOTO (1963) and some interesting results have been reported. However, those results can not always be applied generally to all kinds of diesel engines because each engine has a proper combustion chamber and combustion process. Therefore, we tried to apply the bifuel method to two kinds of four-stroke cycle diesel engines each having a pre-combustion chamber and to a uniflow-scavenged two-stroke cycle diesel engine.

As the main fuel the light oil was used in all of our experiments and as the auxiliary fuel the light oil which was the same kind of main fuel and two kinds of liquefied-petrol gas (LPG) (pure propane and pure butane) were used. Other fuels like gasoline and kerosene were also tried as auxiliary fuel; however, good results could not be obtained. In this paper the effects of light oil and pure butane are presented comparatively.

2. Experiments

2. 1 Engines and Fuels Used in the Experiments

Specifications of three kinds of diesel engines used in these experiments are listed in Table 1.

Table 1 Specifications of the engines used in the experiments

	engine I	engine II	engine III
cycle	4	4	2
bore (mm) × stroke (mm)	120×170	83×92	110×130
number of cylinders	1	4	1
total cylinder volume (cm^3)	1921	1991	1235
rated output (PS)	10	38.5	48 (maximum output)
rated speed (rpm)	900	2600	2000 (maximum speed)
maximum mean effective pressure (kg/cm^2/rpm)	5.2/900	6.89/2000	5.68/2000
compression ratio	17.3	21.0	16
combustion chamber or fuel injection system	pre-combustion chamber	pre-combustion chamber	direct injection

Engine I is one of the small medium-speed single-cylinder conventional engines with its injection timing gear reconstructed for the purpose of this experiment. This engine was used for basic research and most parts of these series of experiment were carried out by this engine. Engine II is a high speed diesel engine designed for vehicle use and it was used to investigate the practical adaptability of the bifuel method. Both of them are typical four-stroke cycle engines with a pre-combustion chamber. Engine III is a uniflow-scavenged two-stroke cycle engine which was specially reconstructed to single cylinder from a vehicle engine with 3 or 4 cylinders. This was used for an application of the bifuel method to the two-stroke cycle engine.

Characteristics of the main and auxiliary fuels used in the most parts of this experiment are shown in Table 2.

Table 2 Characteristics of the fuels used in this experiments

	light oil	propane C_3H_8	butane C_4H_{10}
maker	Shell Oil Co.	Esso Standard Oil Co.	Nippon Sekiyu Co.
specific weight	0.830 (15.4°C)	0.507 (15.6°C)	0.582 (15.6°C)
residuals	0.03%	0	0
cetane or octane No.	cetane No. 58	octane No. 125	octane No. 91
calorific value	10980 (kcal/kg)	11080 (kcal/kg)	10920 (kcal/kg)
Components	(vol. % liquid)		
$C_3H_8 + C_3H_6$		99.3	5.1
$C_4H_{10} + C_4H_8$		0	94.8

2. 2 Experimental Equipment

The general arrangement of the experimental apparatus is the same throughout three series of experiments and is illustrated in Fig. 1. The air is inhaled into the engine through a surge tank and the flow rate of air is measured by a nozzle and manometers. Between the surge tank and the engine inlet port the auxiliary fuel is supplied by a simple equipment. For the liquid fuel supply a reconstructed simple carbulettor of the conventional small kerosene engine was utilized and, on the other hand, the gaseous fuel was supplied from a simple nozzle installed in a part of the suction pipe as shown in Figs. 2 (a) and (b). The liquid and gaseous fuel consumption was measured by a measuring glass and a wet type gas-meter respectively.

To measure the exhaust smoke density the JSAE type exhaust gas sampling device and the Hartridge smoke meter with photo-cell were used according to the occasions. The exhaust gas was sampled from a gas sampling tap installed in the exhaust pipe as shown in Fig. 2 (c). Moreover, an electro-magnetic gas sampling valve was attached directly on the cylinder head. This sampling valve can be opened at a desired timing for a very short period by the activity of solenoid coil and electronic control system and the gas in the cylinder was sampled directly. The sampled gas was analyzed by a gas-chromatography or an Orsat gas analyzer.

The indicator diagrams in the main- and pre-combustion chambers were collected by a Fanborough-indicator or a strain-gauge type electronic indicator. The exhaust gas temperature was measured at the inlet of the exhaust pipe by a thermocouple and the temperatures of cooling water and lubricating oil were also measured and they were controlled within certain ranges throughout the experiment.

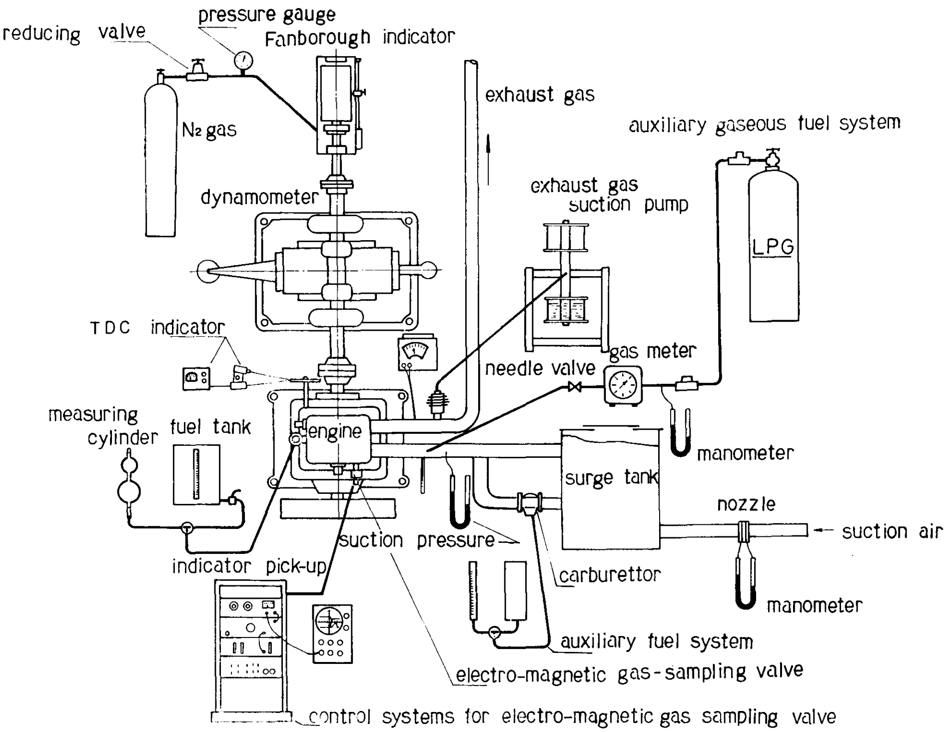
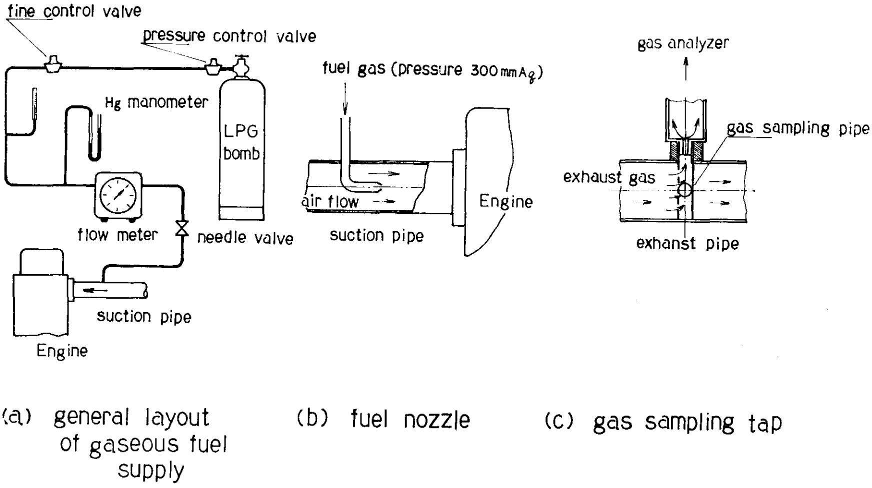


Fig. 1. General layout of experimental apparatus.



(a) general layout of gaseous fuel supply (b) fuel nozzle (c) gas sampling tap

Fig. 2. Auxiliary gaseous fuel system and exhaust gas sampling tap.

Table 3 Items measured in the experiments

items	notation	
engine speed	n.	(rpm)
torque	T	(kg m)
rate of main fuel flow	G_m	(kg/h)
rate of auxiliary fuel flow	G_a	(kg/h)
rate of suction air flow	G_s	(kg/h)
exhaust smoke density (reflectivity of filter paper)	R_e	(%)
exhaust temperature	t_g	(°C)
sampling of combustion gas		
indicator diagram		

2. 3. Procedure of the Experiments

Items measured in all of these experiments are listed in Table 3. The experiments were carried out by a following procedure:

1) During a series of measurements the engine was operated under a constant rotating speed and a constant loaded condition.

2) At first the engine was driven without the auxiliary fuel, namely, this was a normal operating condition, and the measurements on the arranged items listed in Table 3 were carried out. These measured results are used as the standard values to compare the effects of bifuel method.

3) In the second process the flow rate of auxiliary fuel was set to a certain value G_a and consequently the flow rate of the main fuel G_m had to be decreased to maintain a constant speed and loading condition which was set at the beginning. The arranged measurements were then carried out.

4) Owing to the increase of the flow rate of auxiliary fuel, the main fuel was decreased and such operations were repeated until a limit was reached in which the engine could be operated without great trouble.

3. Experimental Results and Discussions

3. 1. Correlations of the Experimental Results

To indicate the rate of auxiliary fuel addition, the auxiliary fuel ratio is defined here and is written:

$$\xi=\frac{H_{ua}G_a}{H_{ua}G_a+H_{um}G_m}\times 100\% \qquad (1)$$

Moreover, the equivalent total fuel consumption G_e is defined by the following formula:

$$G_e = G_m + \frac{H_{ua}}{H_{um}} G_a$$

$$= G_m + \bar{G}_a \qquad (2)$$

where, $\bar{G}_a$ (kg/h) = an equivalent value of the auxiliary fuel consumption reduced by the calorific value, G_e (kg/h) = the sum of the main fuel consumption G_m and the equivalent auxiliary fuel consumption $\bar{G}_a$, H_{um} (kcal/kg) = calorific value of main fuel, H_{ua} (kcal/kg) = calorific value of auxiliary fuel. Then ξ means the ratio of the auxiliary fuel to the total fuel consumption reduced by the calorific value and hereafter engine performances and other characteristics are plotted against ξ.

Exhaust gas sampled from the exhaust pipe was adsorbed by a filter paper conforming to the JSAE system on the measurement of exhaust smoke density, and the reflectivity R_e of the adsorbed filter paper was measured by a photoelectric spectro photometer. This R_e value was used as an indicator of the exhaust smoke density.

3. 2. Experiment I

Experiment I was carried out by engine I (four-stroke cycle single-cylinder diesel engine) to obtain the basic data. The typical results are shown and discussed here.

(1) Engine Performances and Exhaust Smoke Density

In Figs. 3-7 the effects of the bifuel method to the engine performances and exhaust smoke density are shown. Both effects by the liquid auxiliary fuel and by the gaseous auxiliary fuel are shown as (a) and (b) in each figure respectively for comparison purposes. From these figures the main effects of the bifuel method are summarized as follows:

1) The bifuel method brings favorable effects to engine performances and the exhaust smoke density. But these effects are seen only at high loaded and high speed operating conditions. On the contrary, at low loaded and low speed operating conditions the engine performances become worse.

2) When the light oil is used as the auxiliary fuel, about 10% of auxiliary fuel ratio brings the engine performance to maximum efficiency and gives the best smoke density. On the other hand when LPG is used as the auxiliary fuel there is no optimum ratio of ξ to the efficiency, and the more auxiliary fuel results in better thermal efficiency and exhaust smoke condition.

3) If the smoke limited power output is set up at $R_e = 60\%$ for the present, we can read from Fig. 6 that the increase of maximum output by butane addition is about 10%, and by light oil addition it is about 15%. This tendency is more remarkable at high-loaded operating conditions.

4) The optimum injection timing of this engine is about 5 deg before top

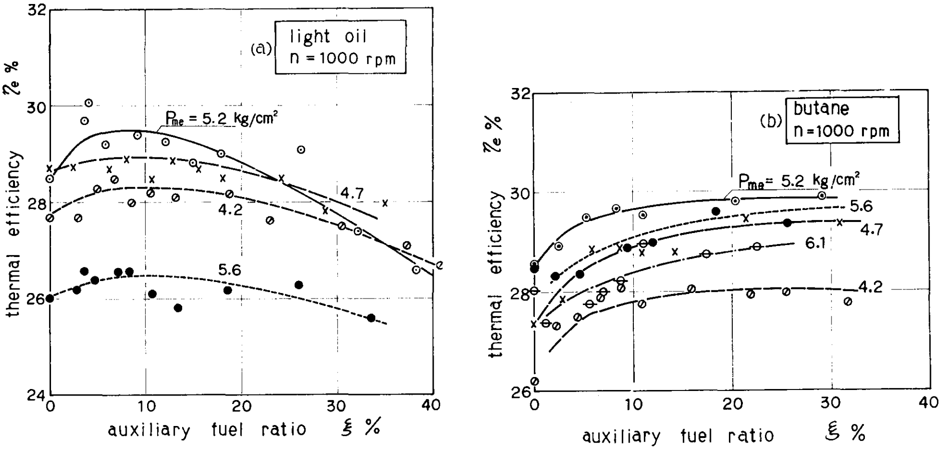


Fig. 3. Thermal efficiency.

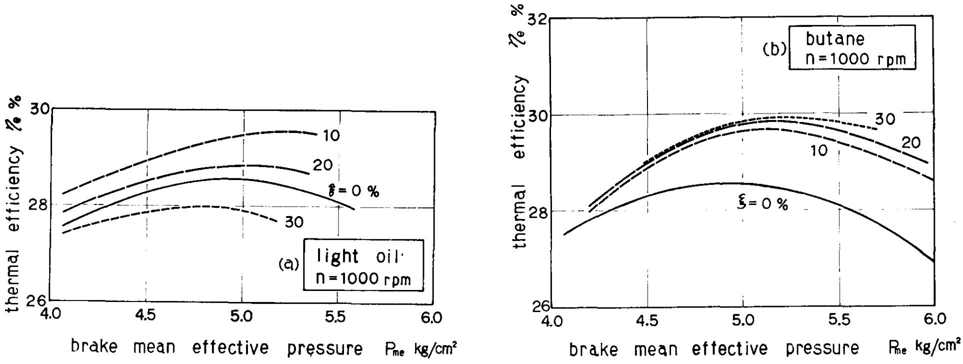


Fig. 4. Thermal efficiency.

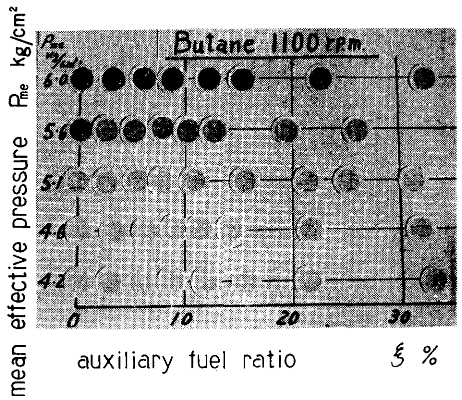


Fig. 5. Exhaust smoke density.
(photograph of filter paper)

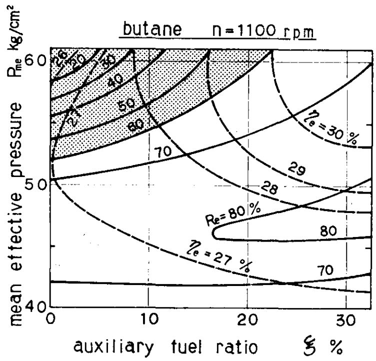


Fig. 6. Exhaust smoke density
and thermal efficiency.

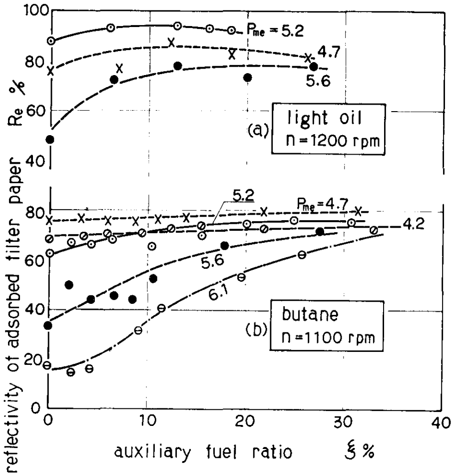


Fig. 7. Exhaust smoke density.

dead center and by the operation with bifuel this optimum value is unchanged. Therefore, the most part of the experiments were carried out by this injection timing.

(2) Analyses of Indicator Diagrams.

Figs. 8-11 show the typical indicator diagrams and their analyzed results. From these figures the following are made clear:

1) When light oil is used as the auxiliary fuel, ignition delay is reduced and combustion is completed quickly.

2) By addition of LPG the combustion progresses very rapidly and the more auxiliary fuel added produces higher explosion pressures.

3) Figs. 11 (a) and (b) show the rate of heat generation $dq/d\theta$ (cal/deg) in the cylinder. From these figures we can see the following:

(a) When light oil is added as the auxiliary fuel, a slight heat generation may begin without significant ignition delay and main reaction continues slowly. It means there is some rate of pre-reaction of auxiliary fuel.

(b) On the other hand, by the addition of LPG, a symptom of pre-reaction can not be seen and the ignition delay increases followed by a very quick explosion.

4) Fig. 12 shows the change of exhaust gas temperature. Exhaust temperature decreases according to the increase of auxiliary fuel because of the quick completion of the combustion processes by the auxiliary fuel addition.

(3) The Results of Exhaust Gas Analyses.

Figs. 13 (a) and (b) show two examples of combustion gas analyses. The gas was sampled from the cylinder between approximately 10 deg. before TDC and 3

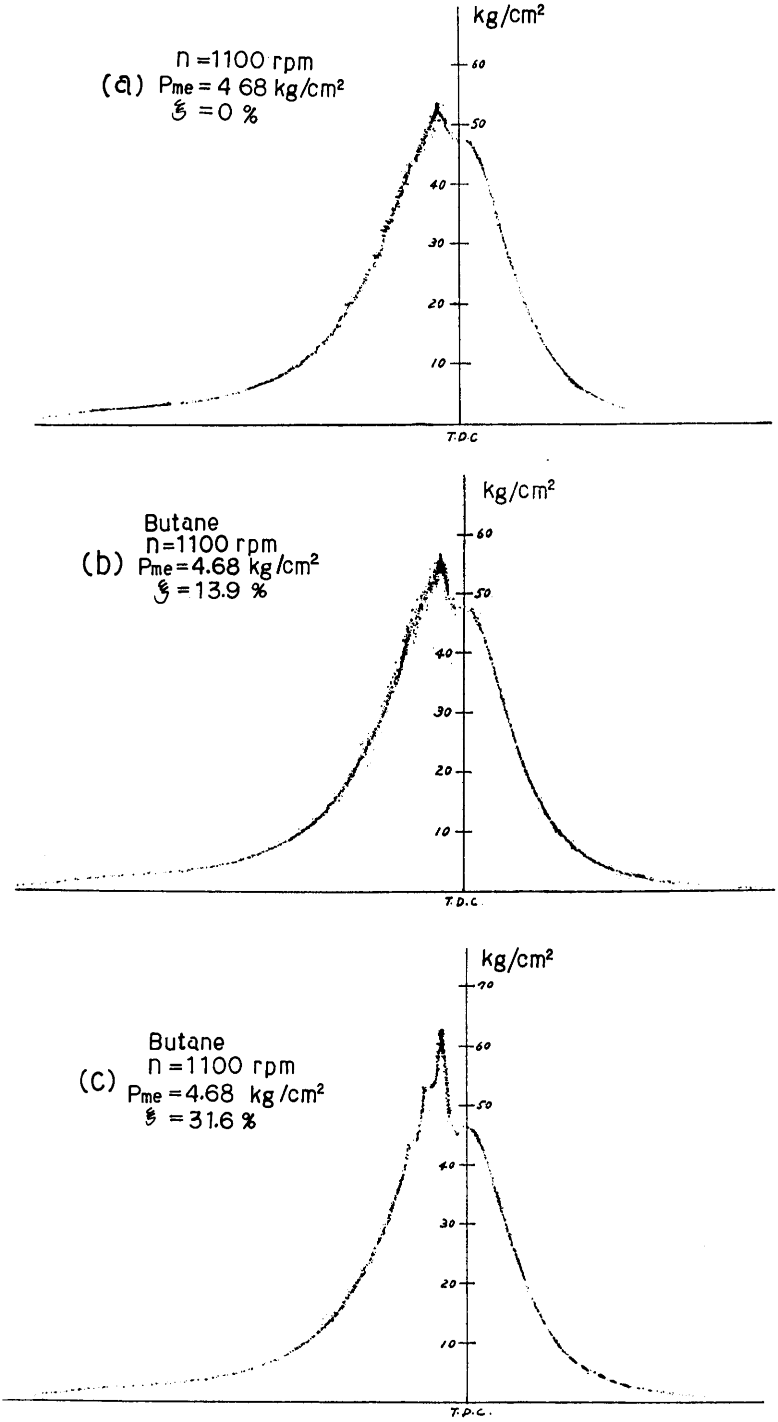


Fig. 8. Indicator diagrams by Fanborough indicator.

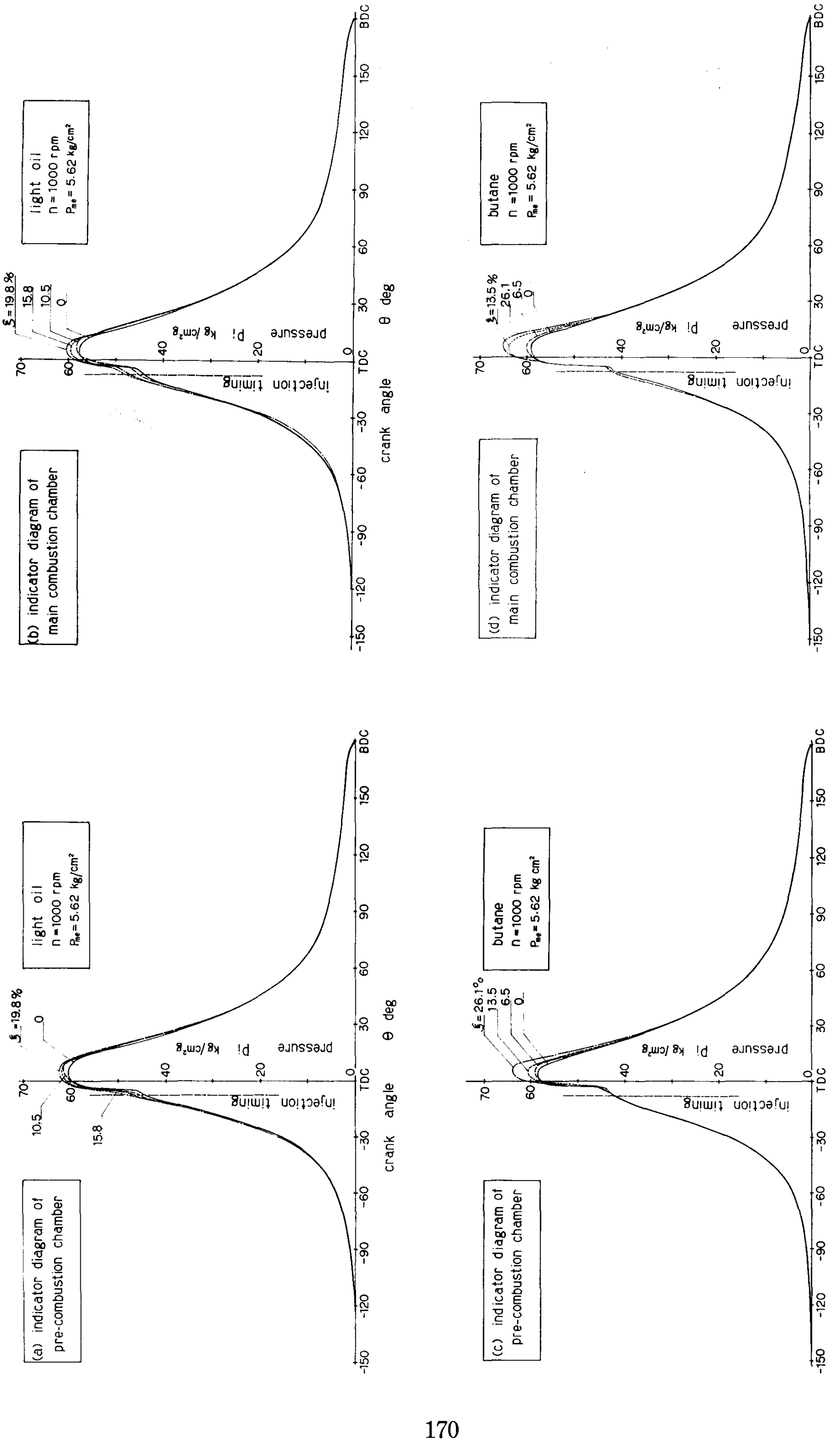


Fig. 9. Indicator diagrams.

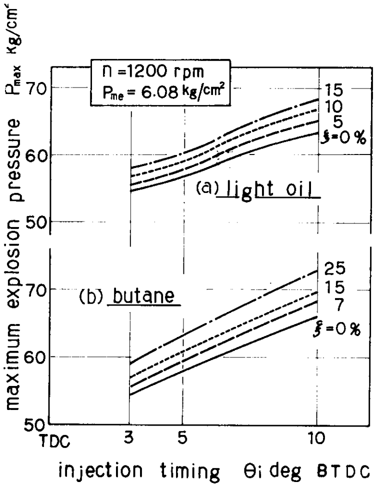


Fig. 10. Maximum explosion pressure.

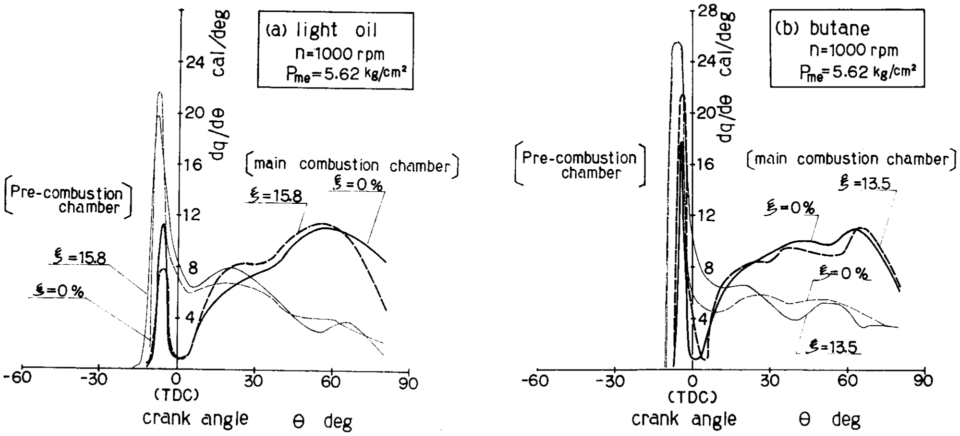


Fig. 11. Rate of heat generation in cylinder.

deg. after TDC. There may be seen little change of CO concentration by the addition of LPG, however, when the light oil is added over $\xi=10\%$, the CO concentration is increased slightly.

2) When butane was added in the suction air some concentration of hydrocarbon (C_3H_8, i-C_4H_{10}) and (n-C_4H_{10}) remained in combustion gas in the cylinder and was directly proportional to the auxiliary fuel ratio ξ. From this result it may be considered that, against expectation which is assumed by Lyn, auxiliary fuel is unlikely to be oxidized completely before the ignition of main fuel.

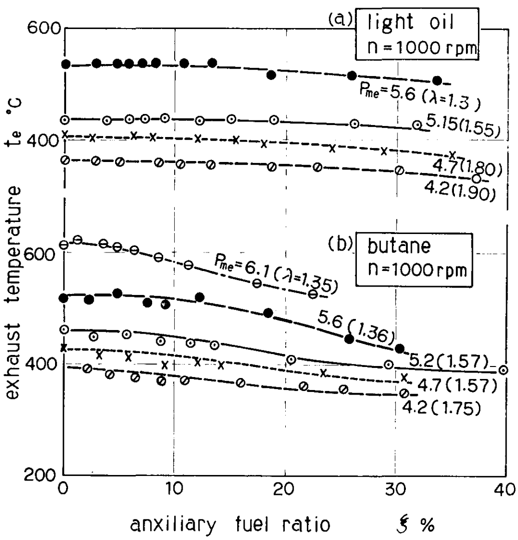
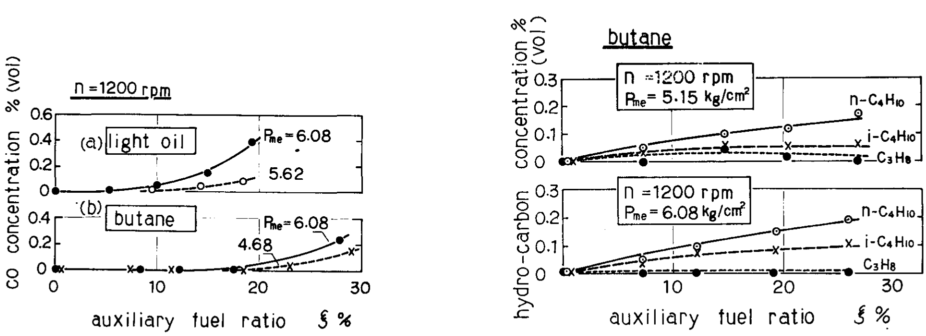


Fig. 12. Exhaust gas temperature.



(a) CO concentration (b) hydro-carbon concentration

Fig. 13. Analyzed results of combustion gas in cylinder.

(timing of sampling valve; open BTDC 10-12 deg
close ATDC 2-3 deg)

3. 3. Experiment II

This series of experiments were carried out on the practical standpoint by using a four-stroke cycle high-speed diesel engine of vehicle use. Therefore, general performances and the exhaust smoke density were measured mainly. The typical results of these experiments are shown in Figs. 14 and 15. In these figures the effects of auxiliary fuels are shown by the ratio Γ_A defined by the following formula.

$$\Gamma_A=\frac{A}{A_0} \tag{3}$$

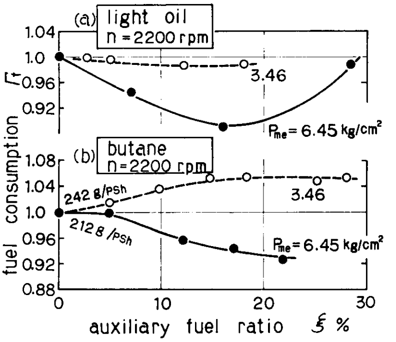


Fig. 14. Fuel consumption.
(Engine II)

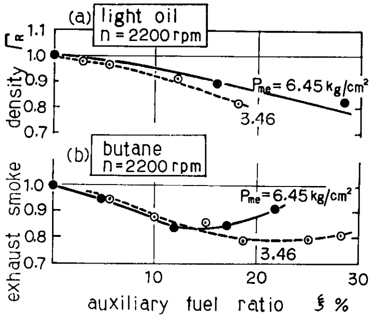


Fig. 15. Exhaust smoke density.
(Engine II)

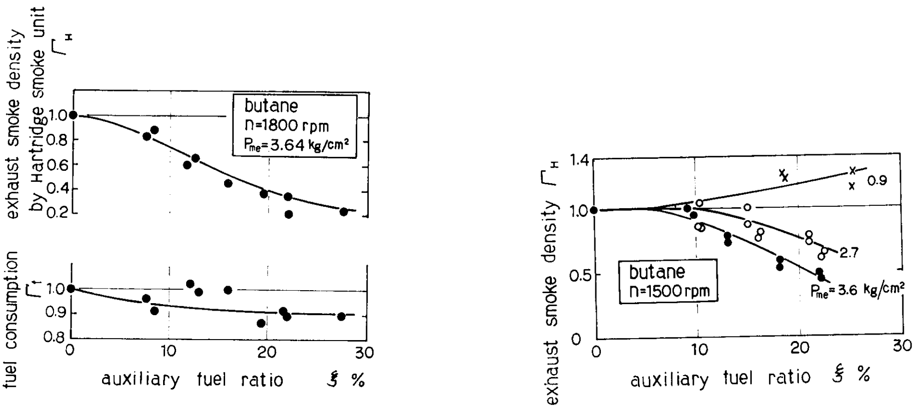
Here A_0 is a measured value of A at a reference condition which is selected at the point of $\xi=0$ in every case, and A is a measured value at given auxiliary fuel ratio ξ.

From these figures it follows that the basic effects of the bifuel method are the same as compared with the results of previously mentioned experiment I and favorable effects to the thermal efficiency can be taken at high loaded operating conditions with the bifuel method, also creating exhaust temperaturs decreases. However, exhaust smoke density change worsened by auxiliary fuel addition. This is contrary to the first expectation, but it may be caused by the bad distribution of the auxiliary fuel in each cylinder due to the simple device used for auxiliary fuel addition. In fact, unbalanced combustion noise and vibration was observed during the operations with auxiliary fuel. Therefore, if bifuel method will be applied to the multi-cylinder engine of practical use, some special device to distribute auxiliary fuel uniformly into every cylinder must be used.

3. 4. Experiment III

This series of experiments were carried out to find out the effect of the bifuel method to a direct injection type uniflow scavenged two-stroke cycle high speed diesel engine. Moreover, the analyses of combustion processes from the indicator diagrams were also tried. However, operations at the high-loaded condition with auxiliary fuel were impossible, because in such condition the engine was discordant and sometimes scuffing of piston and cylinder liner occurred. This was due to the oil-dilution by the auxiliary fuel and this must be taken care of in the practical application of this system.

Figs. 16 (a) and (b) show the examples of experimental results. There is only a little effect on the fuel consumption because this experiment was carried out in only limited small output conditions On the other hand, a splendid effect to the exhaust smoke density could be taken in spite of low-loaded condition. In high-loaded operation more effective results may be expected, however, it could not be verified by the above mentioned reason.



(a) fuel consumption and exhaust smoke density (b) exhaust smoke density

Fig. 16. Fuel consumption and exhaust smoke density.*
(Engine III)

4. Conclusions

On three kinds of diesel engines the effects of auxiliary fuel addition into the intake air were investigated From these experiments it can be concluded that this method is generally useful to the conventional diesel engine, however, the following attention must be paid from the practical point of view:

1) As the auxiliary fuel the light oil which is the same as the main fuel is adequate and about 10% of auxiliary fuel ratio brings the most favorable effect.

2) The contribution of this method is remarkable for the reduction of exhaust smoke density and additionally the improvement of fuel consumption can also be expected.

3) This method should be applied only to the high-speed and high-loaded condition. Therefore, to apply the bifuel method effectively a control device which operates the bifuel system only at such a high-loaded and high-speed condition should be developed.

4) In these experiments only a simple device of auxiliary fuel addition was used. It will be satisfactory in the practical use, however, if more adequate injection system which atomize the fuel to smaller droplets and distribute them uniformly into the suction air is to be used. By using such atomizer more effective results may be expected.

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* The ratio Γ_H is calculated from the measured results of Hartridge smoke unit. Therefore, small value under unity shows the better effect.

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