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A STUDY ON THE CHARACTERISTICS OF COMBUSTION VARIATIONS OF COMPRESSION IGNITION ENGINE

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This paper describes the results of a study of the variation of combustion characteristics in a precombusion chamber type water-cooled diesel engine. Statiscal analysis on cycle-by-cycle variation of combustion characteristics such as rate of pressure rise, heat release rate, and mass burning rate from combustion pressure-crank angle data of one thousand cycles were made under several operating conditions.

The influence of engine speed and coolant temperature upon maximum frequency of combustion characteristics are discussed also.

Key Words : Diesel Engine Combustion, Heat Release Rate, Pressure Rise Rate, Engine Combustion Variations

NOMENCLATURE

BDC : Bottom dead center
BR : Mass burning rate
CA : Crank angle
F.D. : Frequency distribution
H_O : Stagnation enthalpy
HR : Rate of heat release($=dQ/d\phi$)
$(HR)_{max}$: Maximum rate of heat release
k : Total number of sample
n : Engine speed
$(P)_{max}$: Maximum pressure
$(P_{max})_m$: Mean value of peak pressure
PR : Rate of pressure rise($=dP/d\phi$)
$(PR)_{max}$: Maximum rate of pressure rise
S : Standard deviation
T_c : Cooling water temperature
TDC : Top dead center
U : Internal energy
W : Work
V : Cylinder volume
Q : Heat
$\triangle$: Time interval of measurement
$\phi(HR)_{max}$: Crank angle at maximum rate of heat release
$\phi(PR)_{max}$: Crank angle at maximum rate of pressure rise
κ : Specific heat ratio
τ : Time

1. INTRODUCTION

The combustion characteristics of compression ignition engine are mainly affected by the properties of injected fuel, type of combustion chamber and operation conditions of engine. The problem of engine effiency, power output, exhaust emissions and noise are closely related to the rate of pressure rise and heat release. On the other hand, the cyclic variation of combustion characteristics have an effect on the power variations, engine vibration and the concentration of exhaust emissions. The solution of these problems may be considered in two parts. The one is to determine the requirement of performance in terms of combustion characteristics, and the other is to obtain what operation conditions will give the required characteristics of combustion. Therefore, the investigation of combustion variation in diesel engine is important to the improvement of combustion characteristics. In this point, statistical analysis of pressure-time data of engine cylinder is necessary to estimate the combustion characteristics and engine performance.

Many studies on cyclic variations of combustion characteristics of engine were made with spark ignition engine (Hori & Sowa, 1979 ; Toda, et al. ; Nohira, et al., 1977 ; Sanda, et al., 1984 ; Sowa, et al., 1975), however, there are scarceley such studies for compression ignition engine (Yamada & Mitome, 1985. ; Sawa, et. al, 1981). The work of Peters and Borman(1964) has shown that mass burning rate for a single cylinder engine based on experimentally obtained pressure-time diagrams was used to analyze the effect of fuel-air ratio, engine speed, load, and cyclic cylinder pressure variations on mass burning rate and output. A statistical indicator data analyzer has been developed by Toda et al.(1976), which is able to analyze various combuston characteristics of engine. Statistcal analysis on cycle-to-cycle variation indicated mean effected pressure are investigated by Sanda et al.(1982).

Recently, Yamada et al.(1985) have shown that cycle-to-cycle combustion variations in diesel engine are reported for ethanol heavy oil blended fuel. Combustion variation of fuel-air mixture within cylinder of the diesel engine has a strong influence on the combuston characteristics and on engine performance. Most of the previously reported work has been done regarding the cyclic variations of combustion in gasoline engine, but there are scarcely any the effect of engine variables of combustion variations on diesel engine.

The aim of this paper is to present the results of the effect of operating conditions on the combustion variations in a four-stroke cycle diesel engine. In this study, the effect of engine variables such as engine speed and cooling water temperature on the variations of combustion characteristics are investigated by using the combustion analyzer system.

2. EXPERIMENTAL APPARATUS AND METHOD OF INVESTIGATION

2.1 Experimental Apparatus

Arrangement of experimental apparatus is shown schematically in Fig.1, and the specification of test engine and apparatus are shown in Table 1. The engine used is a single-cylinder four-stroke cycle diesel engine with swirl and precombustion chamber, as shown in Fig.2.

Combustion analyzer was composed of the crank angle position detector, input amplifier, A/D converter of pressure signal, and microprocessor with graphic printer. Pressure-time data in cylinder were measured by a combustion analyzer and crank angle detector with optical projector. Cylinder pressure was obtained by using a Kistler type 601A

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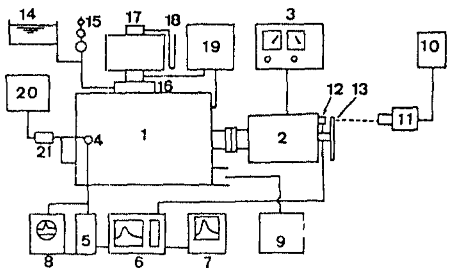

1. Test engine
2. Dynamometer
3. Dynamometer controller
4. Pressure transducer
5. Input amplifier
6. Combustion analyzer
7. Graphic printer
8. Oscilloscope
9. Exhaust gas analyzer
10. Power supply
11. Optical projector
12. Photo receiver
13. Slit disc
14. Fuel tank
15. Fuel burette
16. Fuel injection pump
17. Nozzle of surge tank
18. U-manometer
19. Multi-channel digital thermometer
20. Cooling water tank
21. Flow meter

Fig. 1 Schematic diagram of experimental apparatus

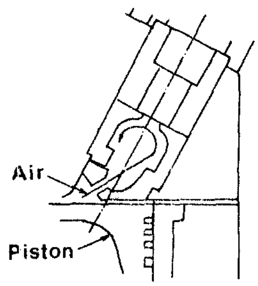

Fig. 2 Combustion chamber

pressure transducer connected with the input amplifier and A/D converter. Crankshaft position was determined by using photo-receiver along with a 200mm diameter slotted disc mounted on the rear end of crankshaft. The output of the engine was measured by the eddy current type dynamometer.

Table 1 Specifications of experimental equipment

Engine	
Cylinder bore	85mm
Stroke	90mm
Clearance volume	$2.6\times10^{-6}m^3$
Compression ratio	21
Maximum output	9PS/2200rpm
Dynamometer	
Type	eddy current type
Maximum power absorbed	10PS/2200rpm
Combustion analyzer	
Function	P-ϕ, dP/dϕ-ϕ, dQ/dϕ-ϕ, BR(ϕ), frequency distribution
Crank angle detector	photo-receiver with projector

2.2 Method of Investigation

The engine was investigated under the following experimental conditions :
engine speed, 1400,1600,1800,2000rpm; inlet air temperature, 15℃; cooling water temperature, 40, 50, 60, 70, 80℃.

The cyclic variations of the combustion characteristics, which were represented by the variation of maximum pressure P_{max}, maximum rate of pressure rise$(dP/d\phi)_{max}$, the combustion pressure P at each crank angle, were anlyzed statistically under the above mentioned conditions. By utilizing the combustion analyzer system, one thousand cycles of pressure and crank angle data were stored simultaneously. Mean value and standard devitiation of cylinder pressure rise, rate of heat release, etc. were obtained by combustion analyzer. Cyclic variations of maximum pressure, maximum rate of pressure rise and the frequency of P_{max} and $(dP/d\phi)_{max}$, etc. were evaluated by the pressure data for each cycle and crank angle at which it occured. In this experiment, automotive light oil with specific gravity 0.83 was used as the fuel.

3. COMBUSTION CHARACTERISTICS

3.1 Cylinder Pressure and Rate of Pressure Rise

The mean pressure of cylinder at crank angle ϕ is given by

$$P(\phi)=\sum_{i=1}^{k}P_i(\phi)/n \tag{1}$$

where $P_i(\phi)$ is the cylinder pressure at crank angle ϕ.

The rate of pressure rise in cylinder $dP/d\phi$ can be obtained by using the numberical differentiation of pressure data from Eq.(1).

Therefore the rate of pressure rise is give by

$$dP(\phi)/d\phi=(P_{\phi-2}-8P_{\phi-1}+8P_{\phi+1}-P_{\phi+2})/(12\Delta) \tag{2}$$

where Δ is the time interval of measurement.

3.2 Rate of Heat Release and Mass Burning Fraction

The energy equation for an engine thermodynamic system may be written as

$$\frac{dQ}{d\tau}=\frac{dU}{d\tau}+\frac{dW}{d\tau}+\sum_j\frac{dH_{0j}}{d\tau} \tag{3}$$

where subscritpt j denotes the different entries to control volume and H_0 is the stagnaton enthalpy of mass entering and leaving the region of system.

From the Eq. (3), the first law of thermodynamics for the region of combustion chamber was written as

$$\frac{dQ(\phi)}{d\phi}=\frac{\chi}{\chi-1}P(\phi)\frac{dV(\phi)}{d\phi}+\frac{1}{\chi-1}V(\phi)\frac{dP(\phi)}{d\phi} \tag{4}$$

Where V is the cylinder volume, χ is the ratio of specific heat.

The mass burning fraction of fuel-air mixture is expressed as

$$BR(\phi)=(\int_c^{\phi}dQ/d\phi)/(\int_c^{d}dQ/d\phi) \tag{5}$$

where c and d are the initial and final point of burning time respectively. In this study their values are taken as 45° beofre TDC and 130° after TDC respectively.

4. RESULTS AND DISCUSSION

4.1 Cycle Variations of the Rate of Pressure Rise

Figure 3 shows the effect of changing the cooling water temperature on the maximum pressure in cylinder and crank angle at which peak pressure occurred. It can be seen that the maximum pressure of cylinder was slightly changed in accordance with the increase of cooling water temperature. However, the crank angle at peak pressure was decreased.

As the increasing the cooling water temperature, it is assumed that the injected fuel in cylinder was improved the vaporization and mixing of fuel-air of combustion chamber. Therefore, the increase in water temperature results in an

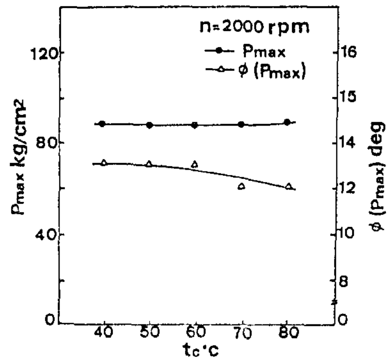

Fig. 3 Effect of cooling water temperature on the maximum pressure and crank angle at peak pressure

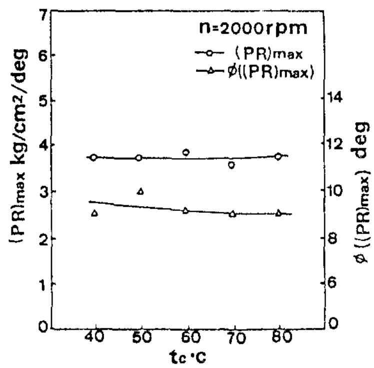

Fig. 4 Effect of cooling water temperature on the maximum rate of pressure rise and crank angle at peak value

advance of crank angle at which peak pressure occurred.

The results of influence of the cooling water temperature on the maximum rate of pressure rise and crank angle at the maximum rate of pressure rise are shown on Fig.4. The maximum rate of pressure rise in cylinder and crank angle at peak pressure shows the similar trends as shown on Fig.3. In order to investigate the influence of engine speed on the rate of pressure rise, the engine speed was varied from 1400 rpm to 2000 rpm.

Figure 5 shows the effect of changing the engine speed on the rate of pressure rise in cylinder. It was found that the maximum rate of pressure rise decrease with an increase in engine speed. On the other hand, the crank angle at which the

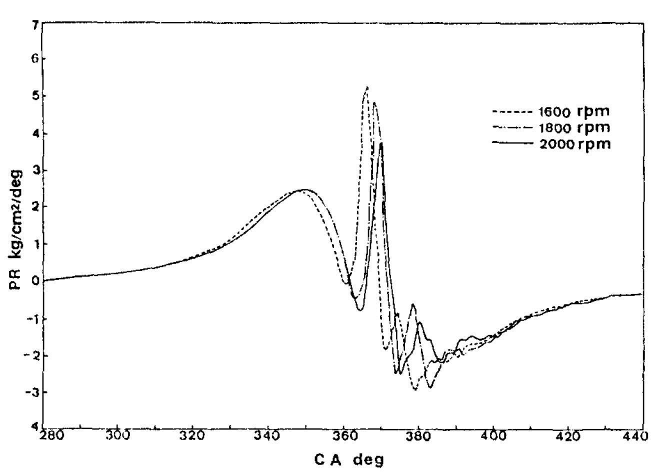

Fig. 5 Effect of engine speed on the rate of pressure rise

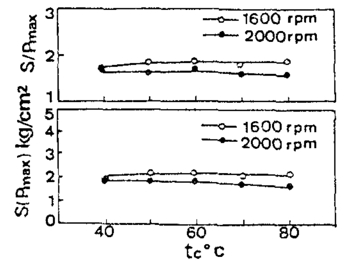

Fig. 6 Effect of engine speed on the standard deviation of peak pressure

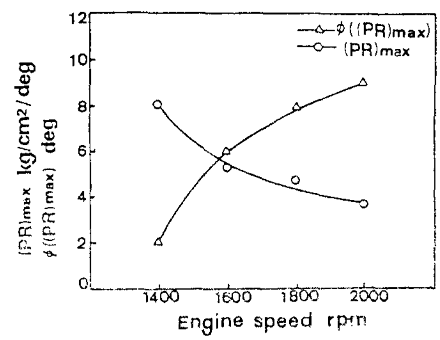

Fig. 7 Maximum rate of pressure rise and crank angle at peak value versus engine speed

rate of pressure rise occurred was retarded in accordance with the increase of engine speed. But the tendency of rate of pressure rise versus crank angle curves were essentially similar to each other in shape.

Figure 6 shows the relation between the standard deviation of peak pressure and cooling water temperature at two kinds of engine speed.

As seen from Fig.6, the standard deviation of peak pressure due to the change of engine speed decrease with the increase of engine speed. But the cooling water temperature has little influence on the standard deviation of peak pressure. It indicates that the value of standard deviation of peak pressure were varied from 1 to 2 kg/cm². As shown in Fig.5, it is considered that the decrease and delay of the rate of pressure rise due to the increase of speed results in a small effect on the standard deviation of cylinder peak pressure.

Some example of the experimental results for the rate of pressure rise and crank angle at the peak value of pressure rise, using the combustion analyzer system, illustrated in Fig. 7. The rate of pressure rise decrease with an increase in engine speed, while the crank angle at the maximum value increase in accordance with engine speed. This is the similar results of a study on the cyclic variation of combustion pressure in compression ignition engines by Sawa et al(1981).

4.2 Cyclic Variations of the Rate of Heat Release

Figure 8 shows the effect of engine speed on the rate of heat release. In this case, the engine speed varied from 1600rpm to 2000rpm.

Refering to Fig.8, it is seen that the increase of engine speed results in a retard of heat release timing in view of crank angle. This means that effective burning time decreases with increase in engine speed. After the beginning of heat release due to fuel combustion, the rate of heat release is very rapid increase for a few degrees of crank angle as shown on first peak of curve of Fig.8. This indicates that the period from the beginning of heat release to maxi-

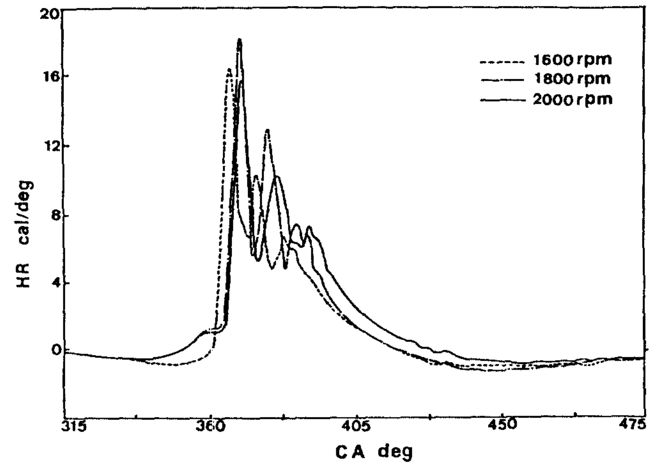

Fig. 8 Effect of engine speed on the rate of heat release

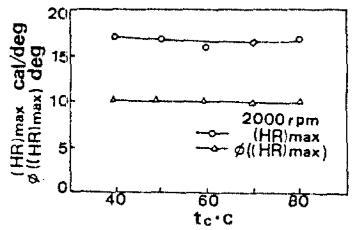

Fig. 9 Characteristics of heat release versus cooling water temperature

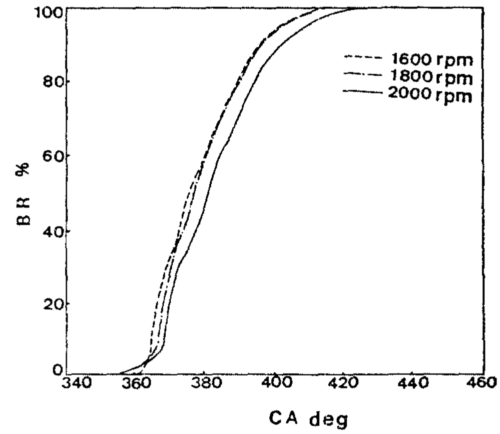

Fig. 11 The effect of engine speed on mass burning rate

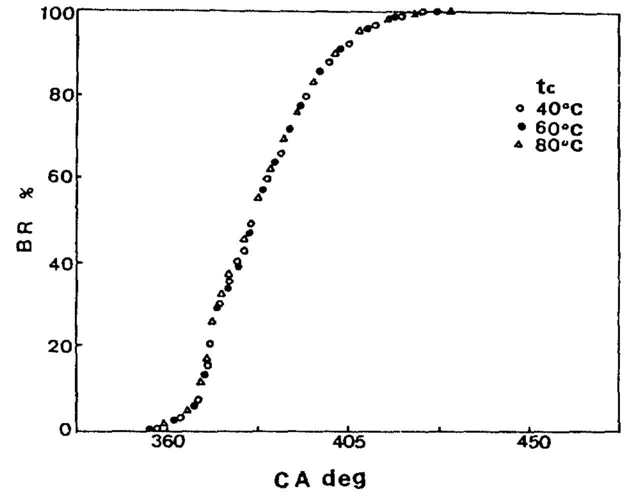

Fig. 12 The effect of cooling water temperature on the mass burning rate

mum value of heat release curve corresponds to a stage of rapid rise of cylinder pressure. The shape of curve shows that the total period of heat release for the case of $t_c = 60°C$ and 2000rpm is from 9° before TDC to 68° after TDC.

The effect of the changes of cooling water temperature on the maximum rate of heat release are shown in Fig.9. This figure shows that cooling water temperature has only a small influence on the maximum rate of heat release and crank angle at peak value of heat release.

On the other hand, Fig.10 shows an example of the rate of heat release and mass burning rate at engine speed 2000 rpm and injection timing of fuel 11° before top dead center.

The effect of engine speed on mass burning rate of engine are shown in Fig.11. During the compression period, the burning rate is generally very high and continues for a few degrees of crank angle as shown in Fig.10. This rise or

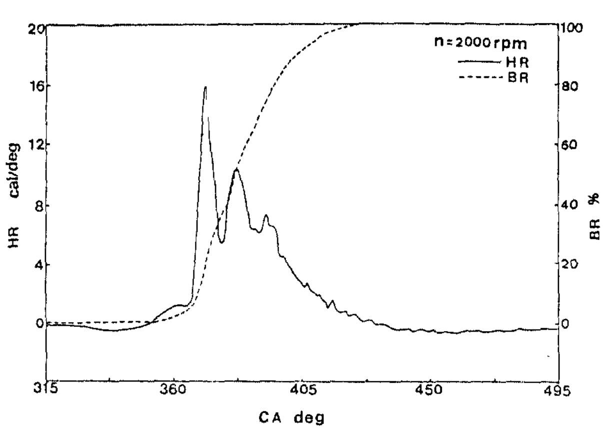

Fig. 10 Comparison betwen heat release rate and mass burned fraction

burning rate corresponds to that of a period of rapid pressure rise. Almost of total injected fuel is burned in this period but heat release of fuel is continued throught the expansion stroke of engine. Total burning time in terms of crank angle, on the other hand, was delayed but slightly with the increase in engine speed.

The some results of the effect of cooling water temperature on the mass burning rate at engine speed 2000rpm is shown in Fig.12. The results presented indicate that cooling water temperature has only a very small effect on the mass burned fraction versus crank angle plot obtained pressure-time data.

4.3 Cyclic Variations of the Frequency Distribution of Combustion Characteristics

Figure 13 shows the effect of cooling water temperature on the frequency of maximum pressure versue crank angle. It was found that the frequency distribution of peak pressure at high temperature were higher than the low temperature. With decreased cooling water temperature, the timing of peak pressure was retarded and the maximum frequency slowed down. Also, the results of frequency distribution of peak pressure indicated that the decrease of coolant temperature resulted in an increase in period of frequency distribution of peak pressure.

The effect of engine speed on the frequency distribution of maximum cylinder pressure can be seen in Fig. 14. As the

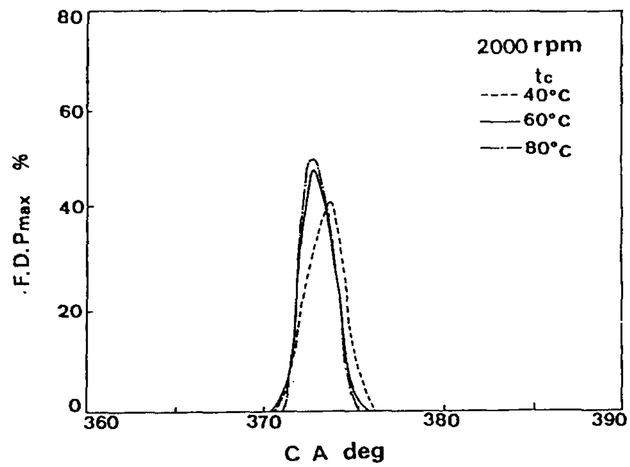

Fig. 13 Effect of cooling water temperature on the frequency of maximum cylinder pressure

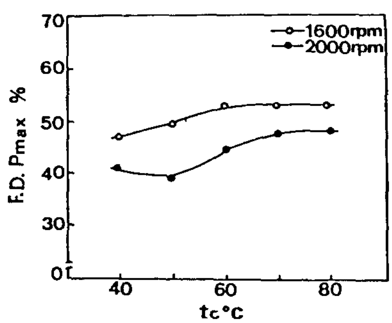

Fig. 14 Effect of engine speed on the maximum cylinder pressure

cooling water temperature was increased, the maximum frequency of peak pressure was increased.

Figure 15 is a test result which investigates the effect of engine speed on the frequency of maximum pressure for 60℃ of cooling water temperature. As shown in figure, the curve has a sharp and high peak for three kinds of engine speed result in the retard of peak frequency of maximum gas pressure. Figure 16 shows the frequency plot of average value of maximum pressure obtained combustion data at various engine speed and the range between 20°before TDC and 19°after TDC.

The period between 20° before TDC and 19° after TDC was selected to be in the region of largest cyclic pressure

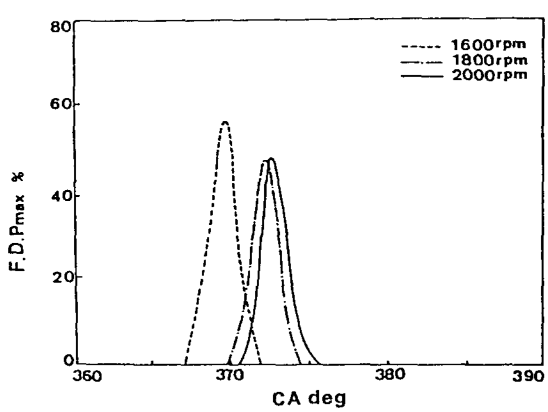

Fig. 15 The effect of engine speed on the frequency of maximum cylinder pressure

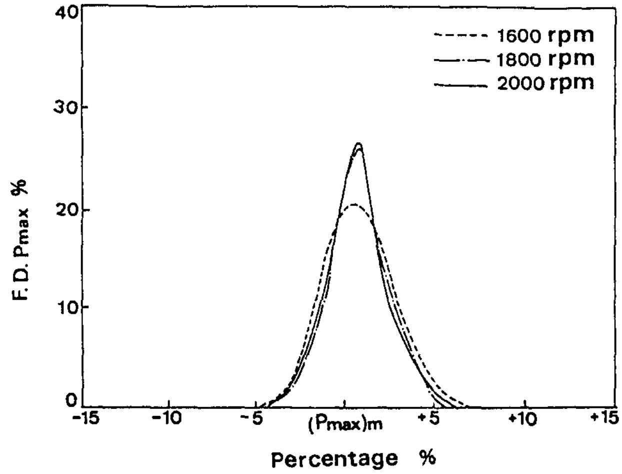

Fig. 16 The frequency distribution versus mean value of maximum cylinder pressure

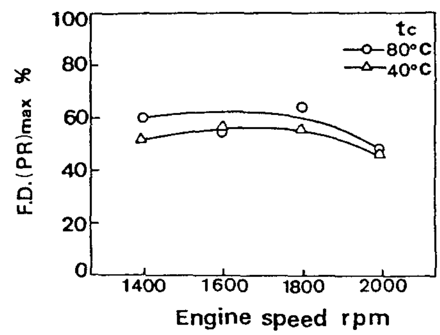

Fig. 17 Effect of cooling water temperature on the frequency of maximum rate of pressure rise

variations. In this diagram, $(P_{max})_m$ on the horizontal axes means the average value of peak pressure for stored one thousand cycles. As shown previously, the cyclic variations in maximum frequency of cylinder peak pressure showed that the increase of engine speed results in the increase of maximum point of peak frequency.

The effect of cooling water temperature on the rate of pressure rise can be seen on Fig.17. This figure shows that the increase of cooling water temperature results in an increase of frequency of maximum rate of pressure rise. In general, the rate of pressure rise should increase with the amount of fuel evaporated and mixing during the dealy period of ignition. With decreasing the cooling water temperature, the evaporation and mixing of fuel during the ignition delay period is promoted and therefore the frequency of maximum rate of pressure rise is increased.

5. CONCLUSIONS

In order to obtain the effect of engine opperating conditions on the variations of combustion in a diesel engine, the cyclic variations of combustion characteristics were investigated using the pressure time data of combustion analyzer system. The results of this study show that the variations of combustion characteristics does change as engine operation conditions are altered. Summarizing these results, the following conclusions may be drawn:

(1) The maximum rate of pressure rise decrease with the increase of engine speed, but crank angle of peak value of pressure rise retards with the increase of engine speed.

(2) The beginning time of heat release and mass burning rate of fuel is retarded by increasing the engine speed. The influence of coolant temperature on the crank angle at maximum rate of heat release is very small compare with the effect of engine speed.
(3) The frequency distribution of maximum cylinder pressure increase with increasing cooling water temperature, with a decrease in engine speed.
(4) The increase of coolant temperature results in a increase in the frequency of maximum rate of pressure rise.

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