621. 436. 019. 2-57

Cold Start Performance of Diesel Engines*

(1st Report, Effects of Prereaction on Cold Start)

By Shōichi FUKAZAWA**

A series of studies on combustion mechanism in cold start of diesel engines conducted by means of chemical analysis, flame observation, measurements of compression pressure and motoring torque are presented in this paper.

For the purpose of making the cold start easy, it is generally practiced to add some amount of liquid fuel, such as gasoline, into the intake air. Then such gasoline-air mixture makes a prereaction by compression heat, which increases the compression pressure and decreases the motoring torque as well.

It was clarified by the analysis of the exhaust gas that peroxide and aldehyde were produced. In the intermediate products, peroxide promotes the ignition and formaldehyde acts as an inhibitor.

Addition of methane or town gas to suction air inhibits the prereaction. In a start test with ordinary injection of fuel, addition of these gases strongly inhibits the ignition of the fuel. In starting, using only the injected fuel, the combustion is supposed to be the "low temperature mode".

1. Introduction

Since the cold start of a diesel engine is usually more difficult than that of a spark-ignition engine, various devices have been provided to improve cold starting performance of diesel engines :

1. Employment of a heater plug mainly for automotive engines
2. Addition of gasoline to the intake air
3. Employment of an ignition paper for small types of diesel engine
4. Starting of a diesel engine as a gasoline engine
5. Equipment of a small gasoline engine for the starting purpose

When the ambient temperature is extremely low, it has been recognized to be effective to burn some amount of fuel in the intake manifold or to mix ether vapor with suction air.

It is reported by D. E. Kilty⁽¹⁾ that the start of a diesel engine is still possible even at a temperature as low as -54°C by applying both diethyl ether and heater plug.

When the ambient temperature is approximately above -20°C , however, the employment of ether is sometimes dangerous because of its too early ignition.

For the purpose of clarifying the mechanism of ignition at the start of a diesel engine, the present investigation is conducted to find the effect of prereaction on the starting characteristics in the presence of gasoline, octane number secondary reference fuel, etc. by the measurements of compression pressure, temperature and flame, and by analysing the intermediate products of combustion.

2. Experimental apparatus and procedure

2.1 Experimental engines

A direct injection type diesel engine (Fig.1) and two precombustion chamber type engines (A is a K-4 type, and B is a reconstruction of the ST-95

cylinder bore $\times$ stroke : 110×140 mm,
10 IP at 1500 r.p.m.

Fig. 1 Direct injection engine

* Received 12th December, 1960.

** Professor, Department of Mechanical Engineering, Hokkaido University, Sapporo, Hokkaido.

type of Yanmer Diesel Engine Co., Fig. 2) were used in the present experiment. All these engines were four-stroke cycle, single-cylinder, water cooled ones.

In the experiments of the direct injection engine and the precombustion chamber engine (A) at the room temperature, the compression ratio of engine was decreased to make start difficult. Experiments on the precombustion chamber engine (B) were conducted at various temperature conditions in low temperature room.

The general lay-out of the apparatus is shown in Fig. 3. Each engine has another injection system in addition to the ordinary injection system by which auxiliary fuel can be injected in the intake pipe.

2.2 Instrumentation

Engine indicator : Piezo electric and strain gage indicators were used, both of which were developed

cylinder bore x stroke : 95 x 115 mm.
6 IP at 1400 r.p.m.

Fig. 2 Precombustion chamber engine (B)

Fig. 3 Experimental apparatus

in our laboratory.

Flame measurement : Flame was measured through a quartz window installed at the cylinder head by a photo-electric tube (Tōshiba PG-50) and a phototransistor (Sony T-102). Owing to the insufficient sensibility of these apparatus, only a visual observation of cool flame was made without taking any record.

2.3 Analysis of intermediate products

Injected fuel in the combustion chamber or fuel which is mixed with suction air undergoes a pre-reaction by compression heat and produces some intermediate products such as peroxide, aldehyde, keton, carbon monoxide and so on⁽²⁾⁽³⁾.

Among these intermediate products, peroxide and aldehyde might have the greatest influence on the ignition characteristics in starting period.

(a) Analysis of peroxide

The potassium iodide method was used for peroxide analysis : after dissolving 10 g of potassium iodine into 1 000 cc of water, and acetic acid to make acidic solution, 10 cc of this solution is first taken in a 100 cc injection syringe and then suck 100 cc of exhaust gas in this syringe.

After shaking the syringe sufficiently to solve the gas in the solution, remove this solution in a flask. As the solution liberate iodine by the existence of peroxide, this solution is titrated with thiosulphate by using starch as an indicator⁽⁴⁾.

(b) Analysis of aldehyde

The Schiff's reagent was employed for the analysis of aldehyde. The same procedure as the

The minimum number of revolutions for continuous ignition (main fuel only)

Fig. 4 Effect of auxiliary fuel on starting

previous analysis was conducted after taking 10 cc solution in the 100 cc injection syringe, 100 cc of sample gas was taken in this syringe, and the concentration of aldehyde was determined from a calibration curve of color depth/aldehyde concentration.

(c) Variation of intermediate product before analysis

The concentrations of peroxide and aldehyde in a sample taken at 10 sec. after the stop of engine are less than a half of the ones in a sample taken immediately after the stop. It is supposed that intermediate products continue their reaction until

the final stable substances are produced or until they are absorbed on the wall surface of the combustion chamber.

Therefore, it is necessary to take out a sample gas immediately after the stop of engine.

3. Experimental results

3.1 Influences of auxiliary (suction) fuel on starting

The results of starting test in a direct injection engine with secondary reference fuels of various cetane numbers are shown in Fig. 4. Dots in this figure indicate ignition points which do not continue

(a) Main fuel only

(b) Auxiliary fuel: Octane number 99 reference fuel

(c) Auxiliary fuel: gasoline (O.N. 75)

(d') Auxiliary fuel: normal heptane (0.06 cc/stroke)
(direct injection engine: $r=12.5$, air and cooling water temp.: 20°C , 250 r.p.m.)

Fig. 5 Effect of auxiliary fuel on start

(c') Auxiliary fuel: gasoline (0.06 cc/stroke)

(c'') Auxiliary fuel: gasoline (0.09 cc/stroke)

(d) Auxiliary fuel: normal heptane (0.03 cc/stroke)

firing. Arrow marks indicate continuous firing.

Higher cetane number fuel permits easier starting, and the starting with below 45 cetane number fuel becomes extremely hard. Injection of secondary reference fuel of octane number 99 or 65 in the suction pipe as auxiliary fuel permits starting at the revolution number of dotted line in Fig. 4. The fuel of low octane number permits easier start. Some indicator diagrams and radiation records of the same engine at 250 r.p.m., when gas oil (C. N. 55) on the market is injected as main fuel (about 0.06 cc/stroke) and gasoline (O. N. 75) or normal heptane is used as auxiliary (suction) fuel, are shown in Fig. 5.

(a) is the case when only the main fuel is used. The fuel is injected from the second cycle. When fuel is injected, slight depression of compression pressure and after that a gradual recovery of pressure are observed.

After the sixth cycle, generation of flame is observed in the radiation record, however, owing to the slight pressure change of the weak combustion, one can hear no combustion noise. It seems to be difficult to detect the start of engine by its combustion noise, because the noise of the surroundings prevents a correct judgement.

(b) is the case when O. N. 99 secondary reference fuel is used as an auxiliary fuel. The ignition becomes easy and a strong flame is observed. Short vertical lines on the pressure record obtained by piezo electric indicator denotes some positions of crank angle, such as T.D.C. and 40° , 20° before and after T.D.C.

(c) is the case when gasoline (O. N. 75) is used as an auxiliary fuel.

(c') is the results when twice as much gasoline as in the case (c) is supplied. The depression of pressure becomes greater, and the ignition becomes harder than in the case of (c)

(c'') When more gasoline (0.09 cc/stroke) compared with previous cases is supplied, ignition is impossible even after compression of twenty cycles.

The ratio of peroxide in exhaust gas in this case decreases below a half of the previous case. The fuel quantity of this engine at theoretical fuel air ratio ($\lambda=1$) is about 0.14 cc/stroke.

(d) When 0.03 cc/stroke normal heptane is sucked, greater pressure rise and easier ignition than in the case of gasoline are recognized.

(d') is the case when normal heptane of 0.06 cc/stroke is supplied. The result shows a greater pressure rise and a stronger ignition than in the case of (d).

From these results, it can be seen that lower octane number fuel permits easier ignition. There

Fig. 6 Compression pressure and flame when only auxiliary fuel is employed

are two cases when the ignition becomes easy and when it is prevented with the increase of the suction quantity. The optimum quantity depends upon octane number of fuel and ambient temperature. The discussion concerning this point will be described later.

3.2 On the prereaction of auxiliary (suction) fuel

Reaction of only the auxiliary fuel heated during the compression stroke was tested. Fig. 6 shows the compression pressure and radiation in a cylinder of the direct injection engine, which is driven by an electric motor at 200 r.p.m. with an injection of an auxiliary fuel in its intake pipe. The flame was measured by photo electric-tube PG-50.

(a) Auxiliary fuel: normal heptane: 0.07

cc/stroke, cooling water temperature: 15°C. Compression pressure rise is seen, but ignition does not occur. However, ignition occurs at the fuel quantity of 0.105 cc/stroke.

(b) When both the temperatures of engine and cooling water are raised, injection of an auxiliary fuel gives a larger pressure rise and the ignition occurs even at the fuel quantity of 0.07 cc/stroke.

(c) Auxiliary fuel: benzol

When benzol is applied, the compression pressure lowers and the depression becomes larger with the increase of its amount. The depression of pressure must be caused by the temperature drop of mixture on account of the evaporation of the additive fuel.

Such a pressure drop appears to be caused by the suction of normal heptane, but in this case, a pressure rise caused by chemical reaction overcomes such a depression, which results in the ultimate pressure rise. Fig. 7 shows the influence of inlet air temperature when only an auxiliary fuel is supplied.

Fig. 7 Effect of air temp. on prereaction

Fig. 7 (a) Fuel: gasoline. Inlet air temperature: 20°C. A small pressure rise occurs stepwise near the T.D.C., but no flame can be observed.

(b) Air temperature: 40°C. The pressure rise becomes large, and the cool flame is visible but cannot be recorded.

(c) Air temperature: 57°C. There are two steps in the process of pressure rise, and the radiation of flame corresponding to the pressure rise of the second stage is recorded on the oscillogram. When this oscillogram is compared with a~b period of the pressure diagram shown in Fig. 7 (c), it seems that the cool flame is produced in this period. But the cool flame is not visible on account of the outbreak of very strong normal flame which appeared after the cool flame.

By the experiment with only auxiliary fuel in precombustion chamber engine (A), compression pressure, motoring torque, peroxide and aldehyde are measured as illustrated in Fig. 8. Compression ratio: $r=15.4$, motoring speed: 200 r.p.m., air temp.: 20°C.

The readings of compression pressure, motoring torque were taken at the fifth cycle after the fuel was introduced.

In the case of normal heptane, the compression pressure becomes high and the productions of peroxide and aldehyde are both increased with the increase

Fig. 8 Effect of fuel quantity on prereaction

in fuel. But the aldehyde concentration decreases at the fuel quantity of 0.045 cc/stroke, and the rate of increase of peroxide concentration is also decreased. These decreases of intermediate products result from a complete combustion of a part of the fuel. When the engine begins to run once on account of further increase in the fuel, such intermediate products are completely extinguished. In the case of secondary reference fuel of O. N. 30, O. N. 50 or isooctane, the lower the octane number of fuel is, the greater the production of intermediate products becomes and the higher the pressure rise is. When ordinary gasoline (O. N. 75) is used, the prereaction increases with the increase of the quantity of fuel. On the other hand, benzol is comparatively stable for heat and produces no intermediate product by the prereaction. The use of benzol, however, shows a decrease of motoring torque with the increase of its quantity. This fact may be based on the dilution of lubricating oil on the cylinder wall by the benzol introduced. It can be certified by motoring test without compression that the motoring torque decreases with the increase of benzol supply.

The decrease of motoring torque by reducing the friction should occur almost equally on the other fuels. Since it can easily be understood that the fuels show a certain pressure rise at the end of compression stroke and the expansion work becomes large as shown in Fig. 9, a decrease of the motoring torque appears to result not only from the dilution of lubricating oil, but also from the advancement of prereaction of fuels.

When an auxiliary fuel was supplied, the tendencies of the rising in the cylinder pressure and the lowering of the motoring torque in precombustion chamber engine appear in the direct injection engine as well.

The work of Townend⁽⁵⁾ established that the pressure-temperature ignition diagrams for paraffinic fuels show two main regions, so called "high temperature region" and "low temperature ignition peninsula." Ignition process in the latter region is further divided into the following two stages, the first stage corresponding to the interval from the beginning of prereaction to the appearance of the "cool flame" and the second stage being defined as a period between the appearance of "cool flame" and a normal flame. Ignition process in the "high temperature region" is, however, found as a continuous single stage.

Alkyl hydroperoxides are produced only in the "low temperature region," and the ignition of methane and benzen are of the "high temperature mode." Furthermore, he said that formaldehyde has

Fig. 9 Effect of prereaction on motoring torque

an accelerating effect on the ignition in the "high temperature region," however, it prolongs the first intervals involved in the "low temperature type" ignition.

Therefore, the auxiliary fuel premixed with the intake air, such as normal heptane, secondary reference fuel or gasoline is presumed to be subject to such a reaction of "low temperature type" and its reaction is a type of chain branching.

3.3 Effect of ambient temperature and auxiliary fuel quantity on the prereaction

Auxiliary fuel of lower octane number produces more of intermediate product, and the addition of a large quantity of fuel makes the start of engine easy in general. But if addition of fuel is too much, it gives a reverse effect in some special cases as mentioned already.

Figs. 10 (a) and (b) show the effect of ambient temperature and fuel quantity on starting. Fig. 10 (a) is the case when gasoline is mixed with intake air in precombustion chamber engine (B) (no main fuel). When the ambient temperature is 10°C, prereaction in the mixture increases with the increase in auxiliary fuel. Ignition occurs at the fuel quantity of 0.06 cc/stroke, and therefore, the engine begins to run only on the auxiliary fuel without any main fuel. At low ambient temperature, prereaction decreases and the rising of peak pressure disappears at -10°C.

Fig. 10 (b) shows the result when normal heptane is used. When the ambient temperature is 0°C, ignition occurs at the fuel quantity of 0.06 cc/stroke. Compression pressure increases even at -15°C with the increase of fuel quantity, and a considerable amount of intermediate products are produced. In

Fig. 10

fact, the addition of normal heptane seems to be remarkably effective for easy starting of diesel engine at a cold state of -15°C .

In view of above considerations, it is seen that the optimum quantity of auxiliary fuel depends upon its chemical stability and the ambient temperature.

3.4 Effect of formaldehyde, acetaldehyde, etc. on easy starting of engine

When an auxiliary fuel such as gasoline is introduced, peroxide and formaldehyde are produced. However, the effect of each component on the engine starting remains unknown. A series of experiments were carried out to clarify the effect of gas on the starting of a diesel engine by introducing formaldehyde, acetaldehyde, methane and town gas respectively.

(a) Addition of formaldehyde

Precombustion chamber engine (A, $r=14.15$) was employed, and a secondary reference fuel of cetane number 30 or 50 was used as the main fuel. It was found that if formaldehyde was added to the intake air, ignition did not occur even under the condition that the engine would fire immediately by injection of main fuel.

By the addition of formaldehyde, its amount in the exhaust gas increases, but the amount of peroxide decreases.

Fig. 11 shows the effect of formaldehyde addition on the prereaction, which is caused by the suction

Fig. 11 Effect of formaldehyde on prereaction

of secondary reference fuel of octane number 36, instead of injecting main fuel.

The addition of formaldehyde decreases the compression peak pressure rise, the depression of motoring torque, and the quantity of peroxide. From the above result, it may be said that the addition of formaldehyde inhibits the pr reaction and hinders the starting of a diesel engine.

(b) Addition of acetaldehyde

Acetaldehyde is produced by heating the liquid acetaldehyde by adding a small quantity of concentrated sulphuric acid. Addition of acetaldehyde decreases the production of peroxide and inhibits starting, but the effect is much smaller than formaldehyde.

Concerning the effect of acetaldehyde on the oxidation of hydrocarbon, there are various reports of different opinions: one insists that acetaldehyde inhibits the oxidation and the other supports that it promotes the reaction⁽⁶⁾. In the present test, it seems that acetaldehyde inhibits the reaction at comparatively low temperature range.

(c) Addition of methane

Experiment of the addition of methane in intake air was conducted with the precombustion chamber engine (A, $r=14.15$). The main fuel is secondary reference fuel of C.N. 70, and its quantity is twice as much as the fuel for the rated load.

The result is shown in Fig. 12. Increase in the amount of methane reduces the generation of peroxide and makes starting very difficult. The concentration

Fig. 12 Effect of methane on the ignition of C.N. 70 secondary reference fuel

of aldehyde increases with the increase of methane at its first period, but it decreases beyond a certain amount of methane.

(d) Addition of town gas

The introduction of town gas as an auxiliary fuel contrary to the expectation did not help starting. It was found that the town gas inhibits the ignition of injected main fuel.

When a prereaction occurs by using an auxiliary fuel such as gasoline, the prereaction is halted to advance by adding a very small quantity of town gas. The components of the town gas are methane 22.5%, hydrogen 22.3%, nitrogen 39.1%, and others. The theoretical air of the gas is 2.75 Nm³/Nm³. The effect of town gas on the ignition of a diesel engine is shown in Fig. 13. Fig. 13 (a) is the case when only the main fuel is injected: ignition occurs after the first injection.

Fig. 13 (b) is the case when town gas is added: the ignition lag increases by 20°. It can be understood that town gas inhibits the production of peroxide by methane involved in the town gas.

4. Conclusion

(1) In direct injection and precombustion chamber diesel engines, addition of auxiliary fuel such as gasoline in the intake air makes starting easy. The lower the octane number of auxiliary fuel is, the more effective the starting aid is.

(2) When auxiliary fuel prereacts by the compression heat, the fuel of low octane number

(b) Town gas is added to the intake air
Direct injection engine: $r=12.5$, 200 r.p.m.

Fig. 13 Effect of town gas on the ignition of main fuel

prereacts considerably and increases the production of such intermediate products as peroxide and aldehyde.

(3) Among the intermediate products of prereaction, peroxide promotes the ignition of main fuel, but aldehyde inhibits the reaction.

(4) The liquid auxiliary fuel of comparatively high octane number promotes the ignition when it is supplied moderately. However, it prevents the engine from its ignition, because such a liquid fuel has rather a cooling effect on the ignition when added too much.

(5) Methane and town gas act as the ignition inhibitor. Addition of these gases strongly prevents starting, because the existence of methane reduces the formation of peroxide.

(6) The addition of a very small quantity of methane or formaldehyde in the intake air strongly inhibits the ignition of the main fuel in starting test.

From these results, the ignition in cold start can be understood to be promoted by the prereaction, which is a mechanism of chain branching.

References

- (1) D.E. Kilty, N.K. Lammers, and K.J. Fleck : *SAE Jour.*, Vol. 61, No. 2 (1953), p. 36.
- (2) B. Lewis and G. von Elbe : *Combustion, Flame and Explosion of Gases*, (1951), p. 117, p. 135, Academic Press.
- (3) B.M. Sturgis : *SAE Trans.*, Vol. 63 (1955), p. 253.
- (4) F.H. Garner, G.H. Grigg, Frank Morton, and W. D. Reid : *Jour. Inst. Petr.*, Vol. 38 (1952), p. 312.
- (5) D.T.A. Townend : *Chem. Rev.*, Vol. 21 (1937), p. 253.
- (6) Reference (2) p. 155.

621.436.019.2-57

Cold Start Performance of Diesel Engines*

(2nd Report, Some Factors Affecting the Ignition in Cold Start)

By Shōichi FUKAZAWA**

In 2nd Report, discussions on the ignition for the case of supplying both the main and the auxiliary fuel are presented. In general, auxiliary (suction) fuel undergoes prereaction and produces intermediate products which promote the ignition of main fuel.

To investigate the effects of ignition quality, volatility and amount of injected fuel, injection timing, and motoring speed on the ignition in cold start, some experiments were carried out. From these results, it was found that the prereaction was closely related to the cold start performance of a diesel engine.

The result of experiments on a new method of improving the cold starting performance by throttling the suction air moderately is explained. If the proposed method will be employed, the temperature of cold start could be lowered by more than 10°C.

1. Introduction

In the previous paper, it is reported that the auxiliary fuel such as gasoline added in the intake air undergoes prereaction and improves the startability of a diesel engine. In this report, discussions on the ignitions of both the main (ordinary injection fuel) and the auxiliary fuel and on some factors which affect those ignitions in cold start are presented.

Moreover, a new method of improving the starting of a diesel engine is proposed.

2. Experimental apparatus and method

Experimental engines : A 4-cycle direct injection engine and two 4-cycle precombustion chamber engines (A), (B) are employed as well as in the experiments reported in the previous paper. For the purpose of measuring compression temperature, the engine (B) is reconstructed to equip a rapid response resistance thermometer as shown in Fig. 1. The

* Received 12th December, 1960.

** Professor, Department of Mechanical Engineering, Hokkaido University, Sapporo, Hokkaido.