PROGRESS REPORT NO. 7

DIESEL ENGINE IGNITION AND COMBUSTION

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I. BACKGROUND

A program to study the combustion process in supercharged diesel engines has been developed at The University of Michigan. This program is primarily concerned with the ignition delay and the effect of the different parameters on it. A special concern is given to the effect of pressure, temperature, and density on the ignition delay.

The different types of delay have been studied and an emphasis is made on the pressure rise delay and illumination delay. The instruments needed for the measurement of these two delay periods have been developed and a continous effort is being made to improve their accuracy.

This research is being made on two experimental engines. One is the ATAC high output open combustion chamber engine, and the other is a Lister-Blackstone swirl combustion chamber engine.

II. OBJECTIVES

A. To study how gas pressure at the time of injection affects ignition delay and combustion. The effects will be studied at pressures ranging from approximately 300 to 1000 psia.

B. To study how gas temperature at the time of injection affects ignition delay. The temperatures will range from approximately 900°F to 1500°F.

C. To study various combinations of pressures and temperatures to determine whether density is an independent variable affecting ignition delay.

D. To conduct all these studies with three fuels: CITE refree grade (Mil-F-45121) fuel, diesel no. 2 fuel, and Mil-G-3056 refree grade gasoline.

III. CUMULATIVE PROGRESS

Cumulative progress has been made in the following areas:

A. Review and analysis of previous work
B. Theoretical analysis
C. Experimental work on Lister-Blackstone engine

D. Comparison between the present and previous work
E. Progress work on the ATAC open chamber engine

The above items have been discussed in detail in the previous progress reports. The following is a comprehensive summary of the cumulative progress made, and the results reached.

A. Review and Analysis of Previous Work

The following is the result of the study made to analyze the previous work done on ignition delay in diesel engines:

1. Different types of ignition delay have been measured and referred to as the ignition delay period. Since these periods are unequal we found it necessary to identify each of them according to the criteria used to define its end. Thus we have the following four types of delay periods:

a. Pressure rise delay; $I.D._p$
b. Temperature rise delay; $I.D._T$
c. Illumination delay, $I.D._{Il}$
d. Hot motored technique delay;[1*] $I.D._{H.M.T}$

These delay periods are represented graphically in Fig. 1, as they can be detected in an actual engine. Note that in this case the pressure rise delay is longer than the temperature rise delay. These two delay periods would be of equal value if both end during the compression stroke.

2. The previous experimental work has been made in bombs and in engines. It is noticed that delays measured in bombs are in general longer than those measured in engines. A comparison between the conditions in bombs and engines is given under the "theoretical analysis"; item B of this part of the report.

3. Different formulae have been given for the ignition delay. These formulae are given by: Wolfer; Bauer and West; Tsoa, Myers and Uyehara; and Sitkei.

All of these formulae are for the ignition delay as a function of the gas pressure and temperature. However, these formulae express different functions. In the present study an attempt has been made to compare between these different functions by taking into consideration both the theoretical and experimental results.

The results of this study is given under item D of this part of the report.

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*Numbers refer to bibliography.

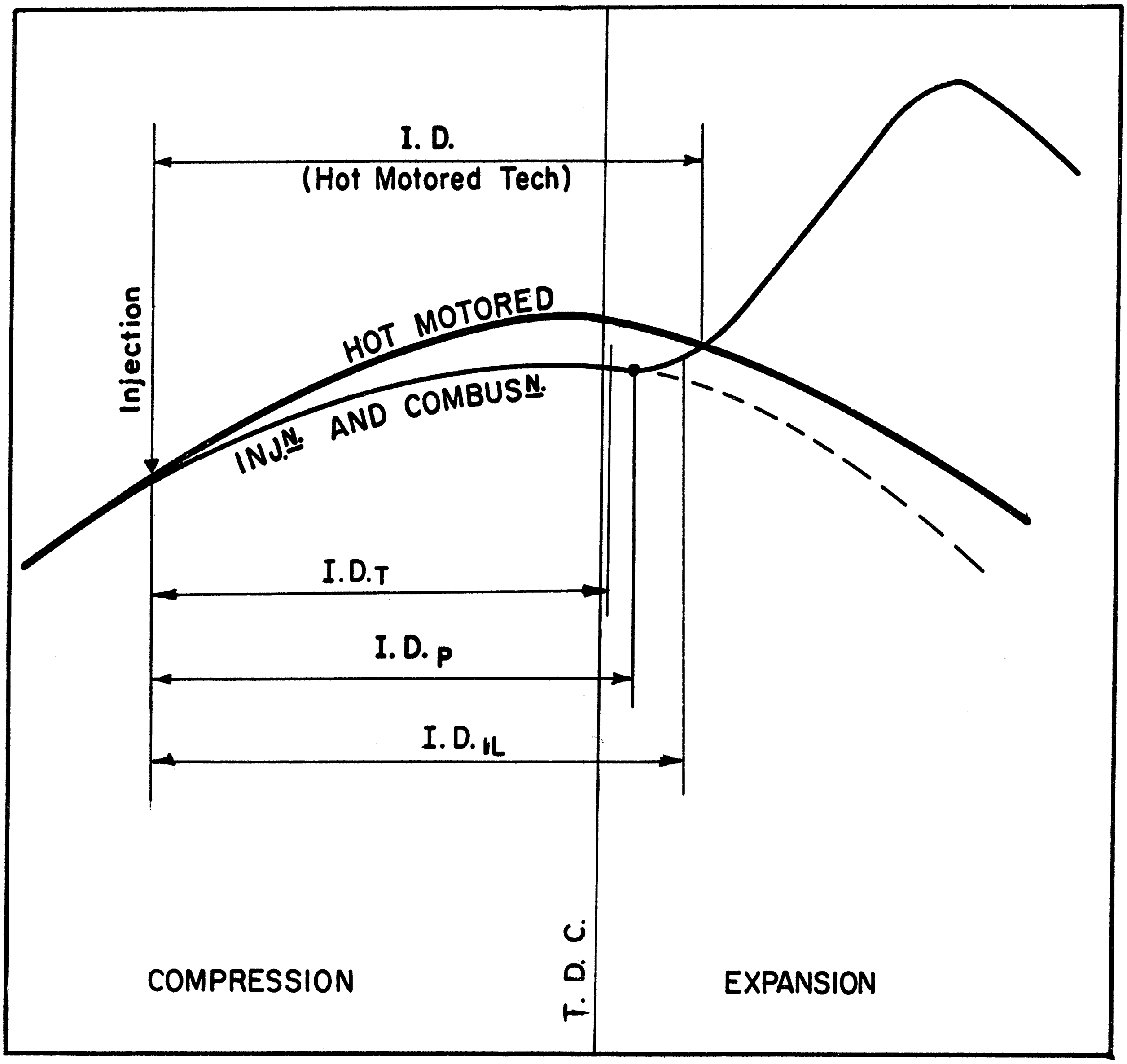

Fig. 1. Different types of delay period in diesel combustion.

4. It has been previously agreed on dividing the delay period into two parts[2-8]: the physical delay, $I.D._{Ph}$ and the chemical delay, $I.D._{Ch}$. This concept has been examined, and we found that, under some conditions in engines, another division of the delay takes place, which is called the "energy delay," $I.D._E$. This is discussed under the "Theoretical Analysis," item B of this part of the report.

B. Theoretical Analysis

In this part a study is made of the different types of energy that are involved in engines during the delay period. These types of energy are:

1. Compression work, dW.
2. Heat exchange between the gas and the combustion chamber walls, dQ_C.
3. Heat released from the fuel, dQ_{Ch}.

A graphical presentation of these types of energy for the different delay periods in engines is shown in Fig. 2. From this figure, the physical and chemical delays can be considered to have ended at point "e," after which the heat produced from the chemical reaction exceeds that absorbed in the physical changes which take place in the fuel. It is noticed that in this case the pressure rise and temperature rise delays end later. The difference between the total delay period and the sum of the physical and chemical delays is called the "energy delay." Therefore:

$$I.D._p = I.D._{(Ph+Ch)} + I.D._E \qquad (1)$$

The value of the energy delay period depends upon the rate of heat release from the chemical reaction, the heat loss to the cooling medium, and the work done by the gas.

The conditions in bombs are different from those in engines from the following points:

1. In engines the turbulence is generally much higher resulting in better mixing and higher rates of energy release by the chemical reaction. This is the main factor that cause the delay period in engines to be shorter than in bombs.

2. In engines the cylinder volume is continuously changing with time while in bombs it remains constant. The corresponding work done in engines causes an increase or a decrease in the internal energy of the gases depending on whether the work is compression or expansion, respectively. In engines most of the delay period occurs during the compression stroke, and energy is added to the gas resulting in delay periods shorter than in bombs.

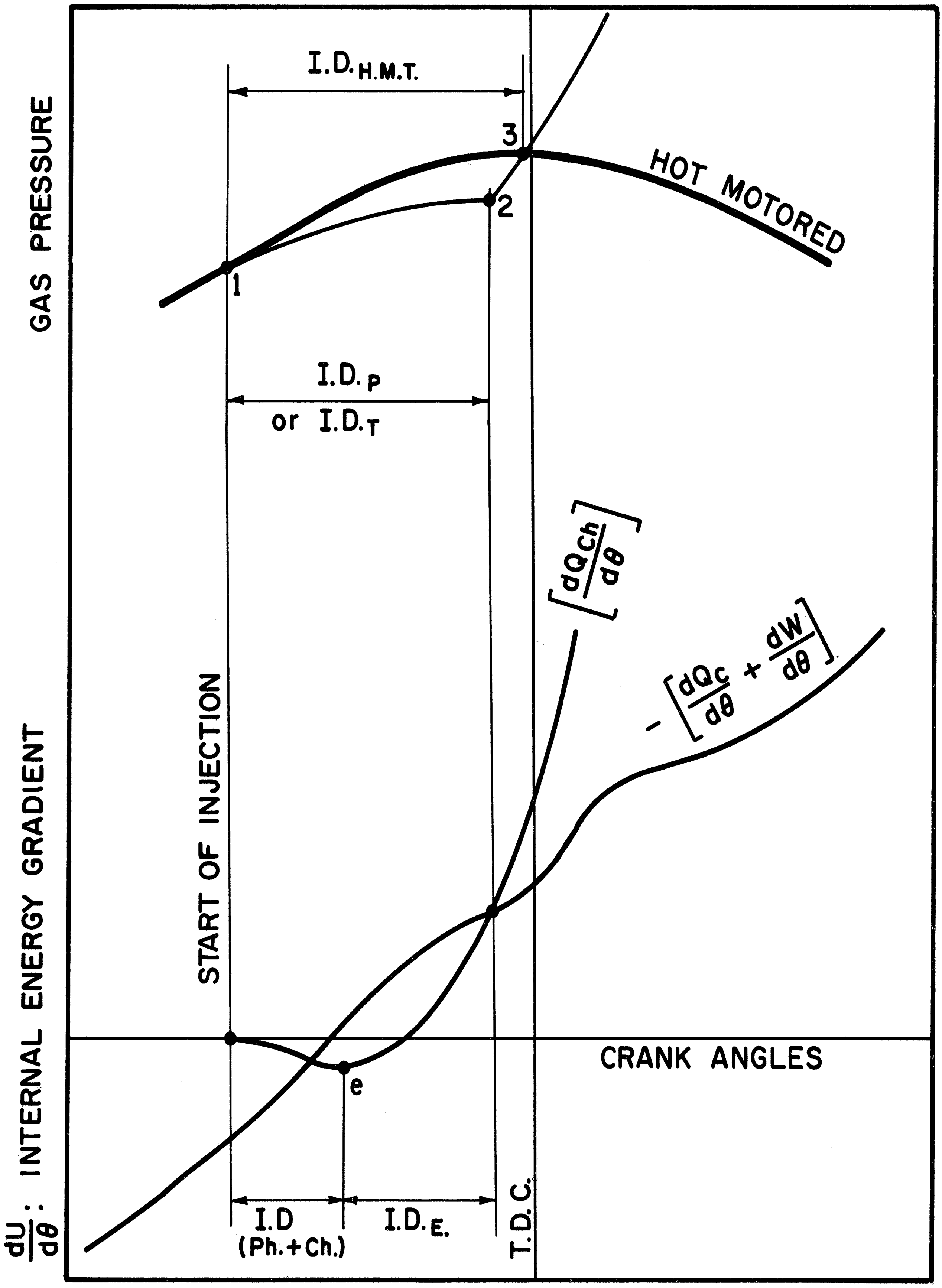

Fig. 2. Relation between the energy terms and the different delay periods.

3. In engines heat is lost from the gases to the walls, while in bombs, where the walls are used for heating, heat is generally added to the gases. The heat loss in engines does not balance the above two factors, and the final result is a shorter delay period in engines.

C. Experimental Work on Lister-Blackstone Engine

Four series of tests were carried out on the Lister engine to find the effect of the following factors on the pressure rise and illumination delay periods: the fuel-air ratio, the injector opening pressure, the cooling water temperature, the cylinder pressure, and engine speed. The results of these runs can be summarized as follows:

1. The pressure rise delay is in general longer than the illumination delay. The difference between these two types of delay periods, as well as their values, depend upon the fuel-air ratio, the injector opening pressure, and the cooling water temperature.

2. The increase in the cylinder pressure at the point of injection reduces the pressure rise delay.

3. The best correlation between the pressure rise delay and the cylinder pressure at the point of injection (at constant temperature) has been found to be:

$$I.D._p = \frac{C}{p^n} \qquad (2)$$

where:

C = a constant at a constant temperature
n = the exponent of the pressure

4. The effect of the speed on the pressure rise delay is obtained by comparing the results of two series of tests carried out at two different speeds. It has been found that an increase in speed from (600 rpm to 1000 rpm) shortens the pressure rise delay and increased the exponent "n," in Eq. (2).

D. Comparison Between the Present and Previous Results

By comparing the present results with the previous results published by West,* Tsao,* and Hurn* the following conclusions are reached.

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*References are included in Progress Report No. 6.

1. The values of the pressure rise delays measured on the Lister engine are shorter than the previously published data. This is believed to be due to the turbulence in the Lister engine which is much higher than that in previous investigations.

2. The form of Eq. (2) which has been obtained from Lister engine agrees with the theoretical formulae given by Wolfer,* Schmidt,* and Semenov.*

3. The value of the index n is higher than the value given by Wolfer for ignition delay in bombs. This is believed to be due to the higher turbulence in the Lister engine.

4. It is interesting to note that the previously published results on ignition delay in bombs and engines can be very well correlated to the corresponding gas pressures by an equation similar to Eq. (2). Thus the function expressed by Eq. (1) seems to be the most suitable for ignition delay correlations w.r.t. pressure (at a constant temperature). It is to be noted here that the value of the exponent "n" is different for each apparatus. It is greater for the runs made at higher turbulence.

The effect of temperature will be studied on the ATAC engine, in order to find a correlation between the ignition delay, and both pressure and temperature.

E. Progress Work on ATAC Open Combustion Chamber Engine

The engine has been connected to an electric dynamometer. It is supercharged with shop air that has been passed through a surge tank fitted just before the engine. Another surge tank is fitted on the exhaust side. The pressures in the two tanks can be regulated to the required values.

A Kistler pressure transducer is fitted in the hole furnished by the International Harvester Company. Two more holes were drilled in the cylinder head above the piston cavity. One hole is fitted with a quartz window, and the other is to be fitted with a surface thermocouple.

The top dead center of the engine determined by the dial gage method, was found to be 1/2 crank degree past the top dead center mark engraved on the flywheel.

The degree marks are produced by a steel disk 18 inches in diameter and 1/8 inch thick, mounted on the coupling between the crankshaft and the dynamometer. Holes 1/16 inch in diameter are drilled around the periphery at 3° intervals, and larger holes, 1/8 inch in diameter, at 45° intervals. A magnetic pickup has been used to produce corresponding pips on the oscilloscope screen every 3°, with bigger pips every 45°. One of the bigger holes is aligned at top dead center.

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*Reference are included in Progress Report No. 6.

The temperature of the inside surface of the combustion chamber is measured by a surface thermocouple placed between the inlet and exhaust valves.

The fuel-injection system is instrumented so that the start and rate of injection can be calculated from measurements of the needle lift and fuel pressure before the nozzle. The position of the plunger w.r.t. the barrel, and the injection timing are both controlled by micrometers, as shown in Fig. 3.

IV. PROGRESS DURING THIS PERIOD ON ATAC ENGINE

The progress during this period has been mainly done on the ATAC engine, with the open combustion chamber head. The progress covers the following areas:

A. Engine equipment and instrumentation
B. Calibration of instruments
C. Experimental work on the open combustion chamber ATAC engine
D. Computer programs
E. Authors' reply to discussions on SAE paper, "Ignition Delay in Diesel Engines."

A. Engine Equipment and Instrumentation

A general view of the ATAC engine equipment is shown in Figs. 4 and 5 The following equipment and instruments have been fitted to the engine.

1. Electric Heater.—An electric heater has been fitted between the critical flow meter and the inlet surge tank. All the piping between the heater, engine, and exhaust tank are insulated by 1.5-inch thick calcium silicate pipe insulation.

2. Water Spray for Exhaust Tank Cooling.—The cooling of the exhaust surge tank has been accomplished by spraying tap water into the tank. The direction of the spray is such as not to interfere with the flow of gases from the engine to the tank or with the exhaust thermocouple or smokemeter probe.

3. Electronic Instruments.--A new oscilloscope (Tektronix type 502A) and a new polaroid camera are now in use to obtain and record the different traces for the combustion process in the engine. A special projected graticule is now in use with the camera, in order to eliminate the parallex which had been noticed before using this attachment.

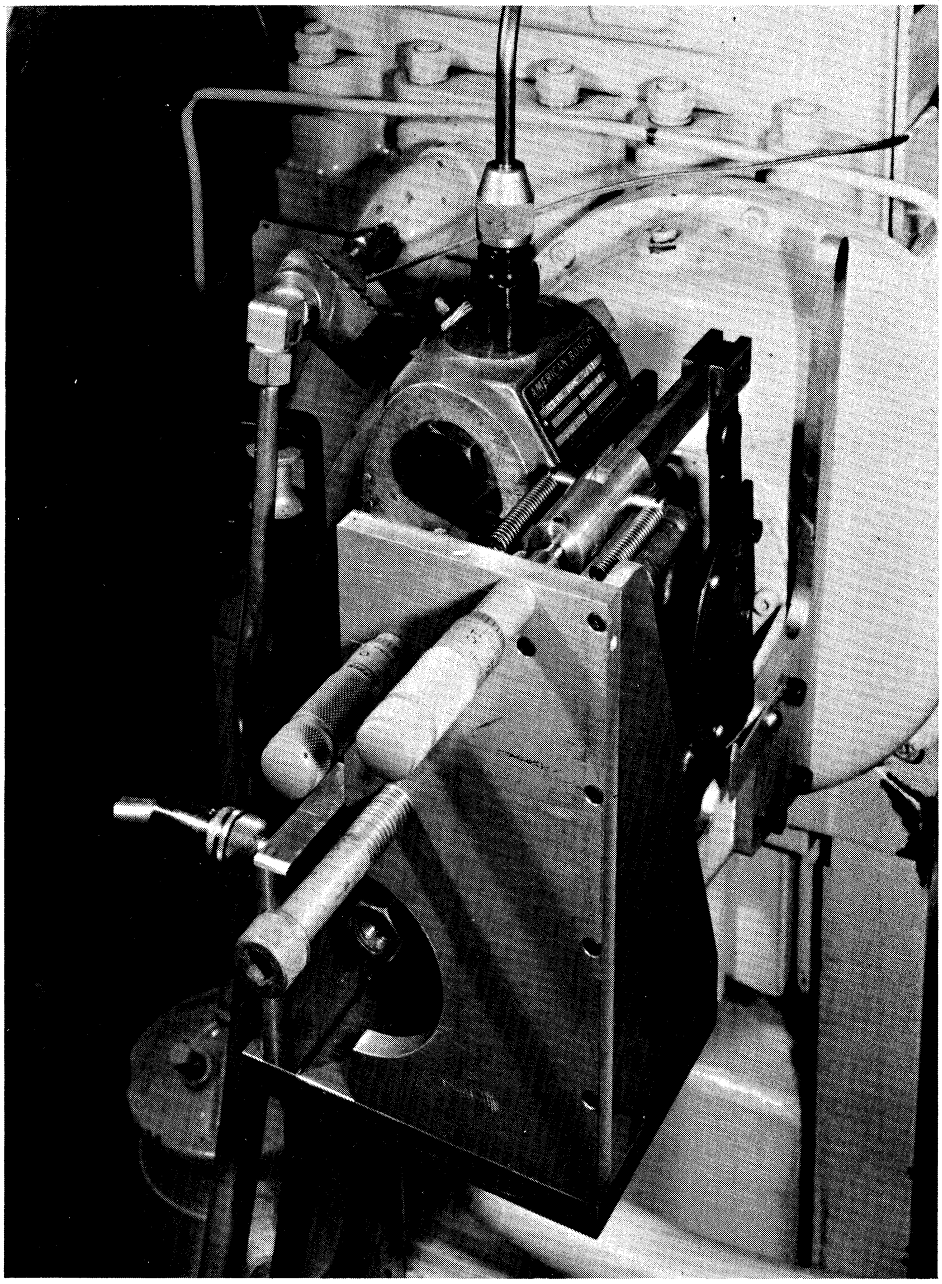

Fig. 3. Fuel injection pump fitted with micrometers to control the rack position and injection timing.

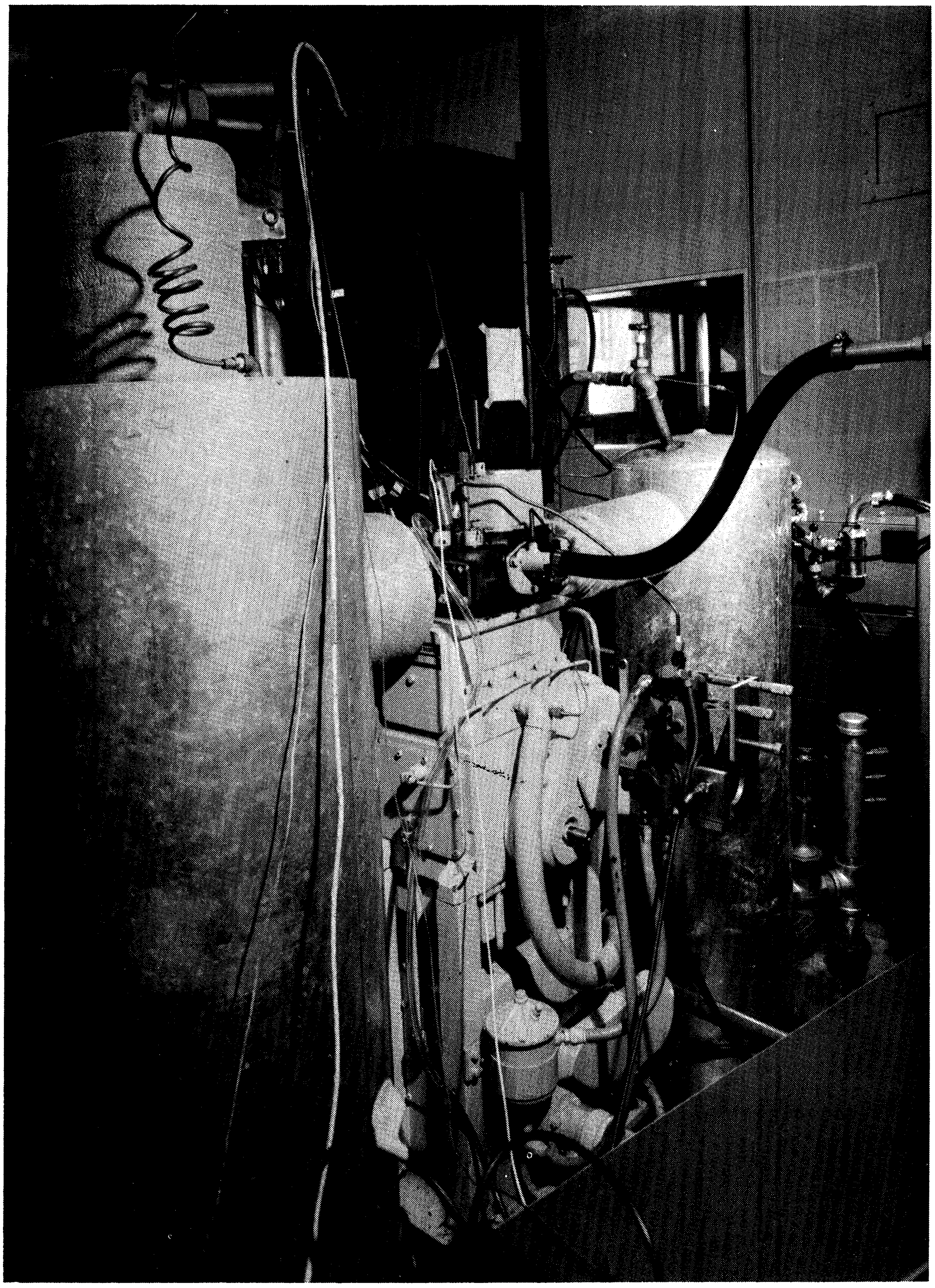

Fig. 4. View of installation of ATAC engine.

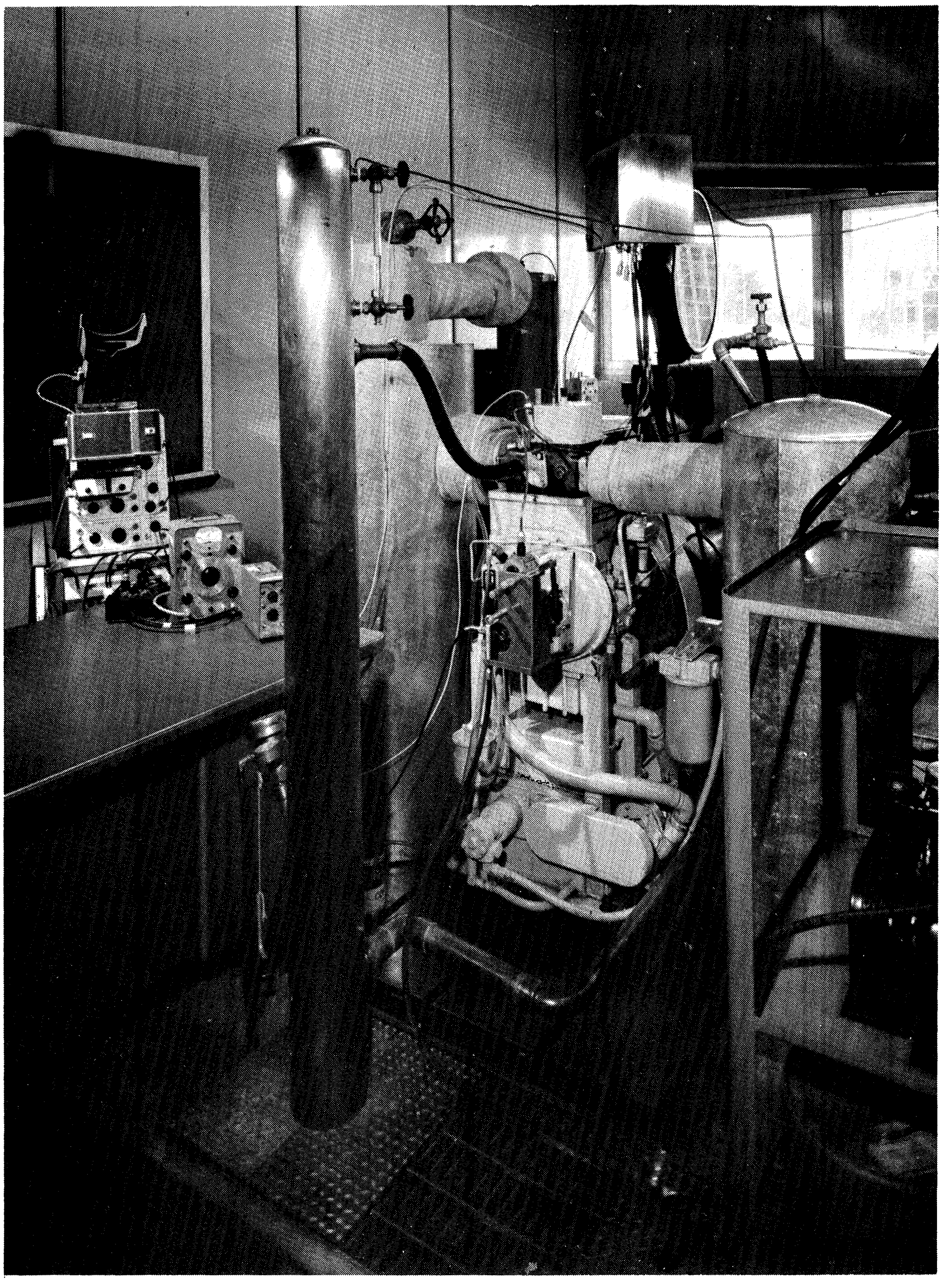

Fig. 5. View of installation of ATAC engine.

4. Blowby Flowmeter (shown in Fig. 8).—A flowmeter has been connected to the crankcase ventilation tube to measure the rate of flow of the blowby gases. An oil separater has been installed between the ventilating tube and the flowmeter to collect the oil droplets discharged with the blowby gases before reaching the flowmeter. The value of the blowby rate will be recorded together with all other data while running the engine.

5. Smoke Measurements.--In order to measure the intensity of the smoke produced in the exhaust of the ATAC engine a "Hartridge Smokemeter" is connected to the exhaust, as shown in Figs. 6 and 7.

B. Calibration of Instruments

During this period a great effort has been made to calibrate and improve the accuracy of the different instruments. These include the following:

1. Calibration of the critical flowmeter used to measure the rate of air flow into the engine. This calibration has been done by using an inverted bell positive displacement unit in the Fluids Laboratory, The University of Michigan. The inverted bell has an inside diameter of 104.0 inches, and a net displacement of 226.1 cubic feet used for the calibration.

2. Calibration of the Kistler pressure transducer (type 401A) together with the charge amplifier (type 655, S/N 1194), by using a dead weight tester. This transducer is used for measuring the gas pressure in the cylinder.

3. Calibration of Kistler pressure transducer (type 601H) together with the charge amplifier (type 503, S/N 359), by using a dead weight tester. This transducer is used for measuring the fuel pressure before the nozzle.

4. Calibration of the distance detector used to measure the needle lift.

5. Calibration of the surface thermocouple used to measure the inside wall surface temperature. The thermocouple output is found to agree with the standard thermocouple tables.

6. Calibration and zero adjustment of the Honeywell thermocouple (rotating disk type) used to measure the air, water, oil, and exhaust gas temperature.

C. Experimental Work on the Open Combustion Chamber ATAC Engine

Tests are now being carried out to study the ignition delay and other combustion phenomena of the following fuels:

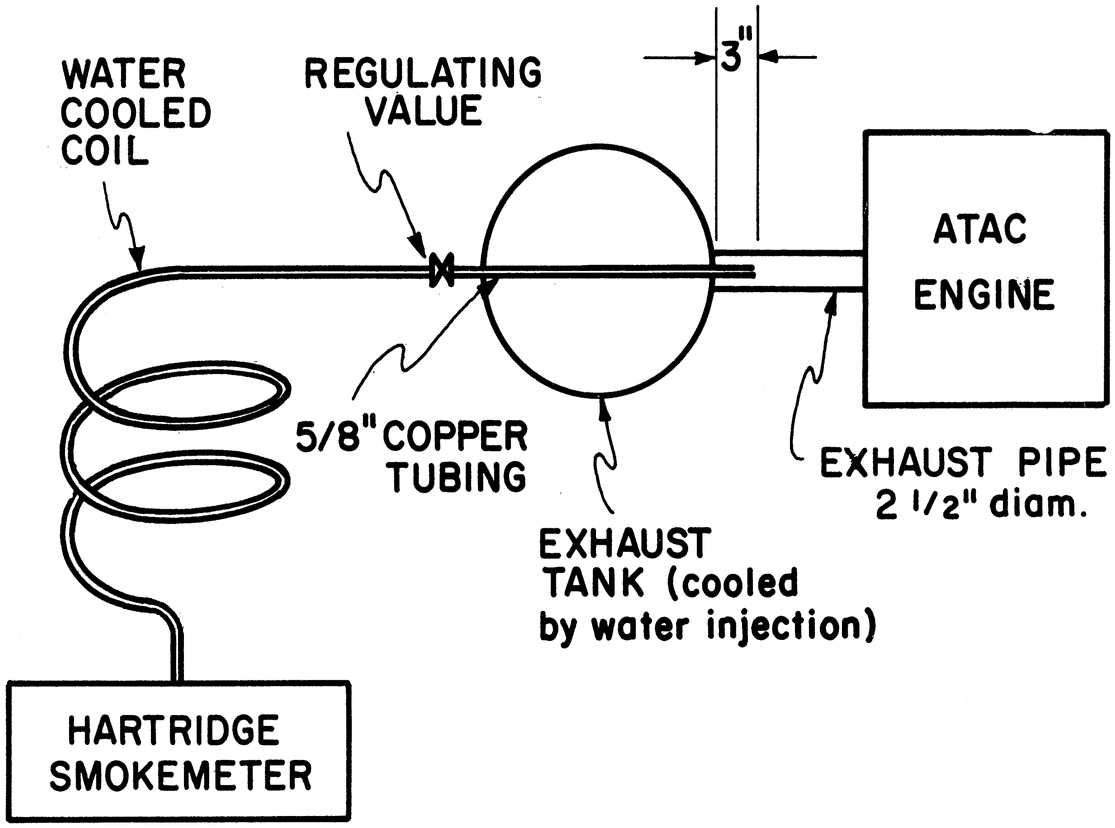

Fig. 6. Smokemeter con

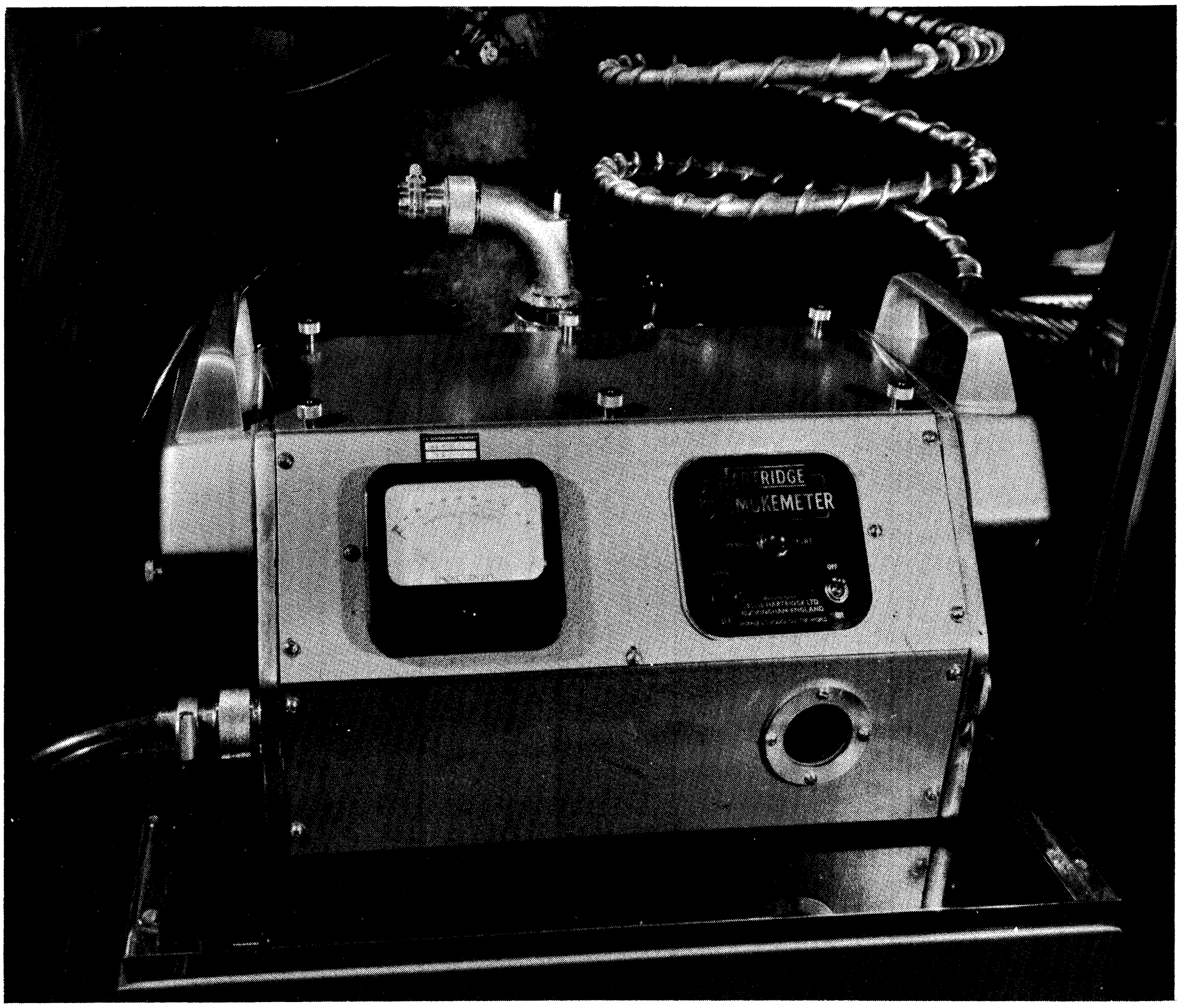

Fig. 7. Hartridge Smokemeter connected to the ATAC exhaust pipe.

1. CITE refree grade (MIL-F-45121) fuel
2. Diesel no. 2 fuel
3. MIL-G-3056 refree grade gasoline fuel

It has been noticed that the engine runs properly on the first two fuels. But with the gasoline it is noticed that the engine runs irregularly with frequent misfirings. The details of this series of tests will be given in the future progress reports.

D. Computer Programs

Most of the computations needed for this project are now carried out on an IBM 7090, in The University of Michigan Computing Center. Statistical and curve fitting procedures are made to assist in the following programs:

1. Data synthesis programs; to combine related data into an orderly sequence.

2. Combustion analysis programs; to calculate the thermodynamic conditions of the gases in the cylinder at any point in the cycle.

3. Delay analysis programs; to process ignition delay data and seek correlations between the experimental results and other operating parameters.

E. Authors' Reply to Discussions on SAE Paper "Ignition Delay in Diesel Engines"

The discussions on the SAE paper indicated the great interest in ignition delay investigations, and the great need for combustion research in supercharged engines.

A copy of these discussions and authors' reply is given in the Addendum.

V. PROBLEM AREAS AND CORRECTIVE ACTIONS

1. The faulty Kistler transducer mentioned in Progress Report No. 6 has been replaced.

2. It was difficult to detect the oil level in the lower sump of the ATAC engine. This was corrected by constructing a sealed dip stick device that can be reached easily. This device is shown together with a blowby flowmeter in Fig. 8.

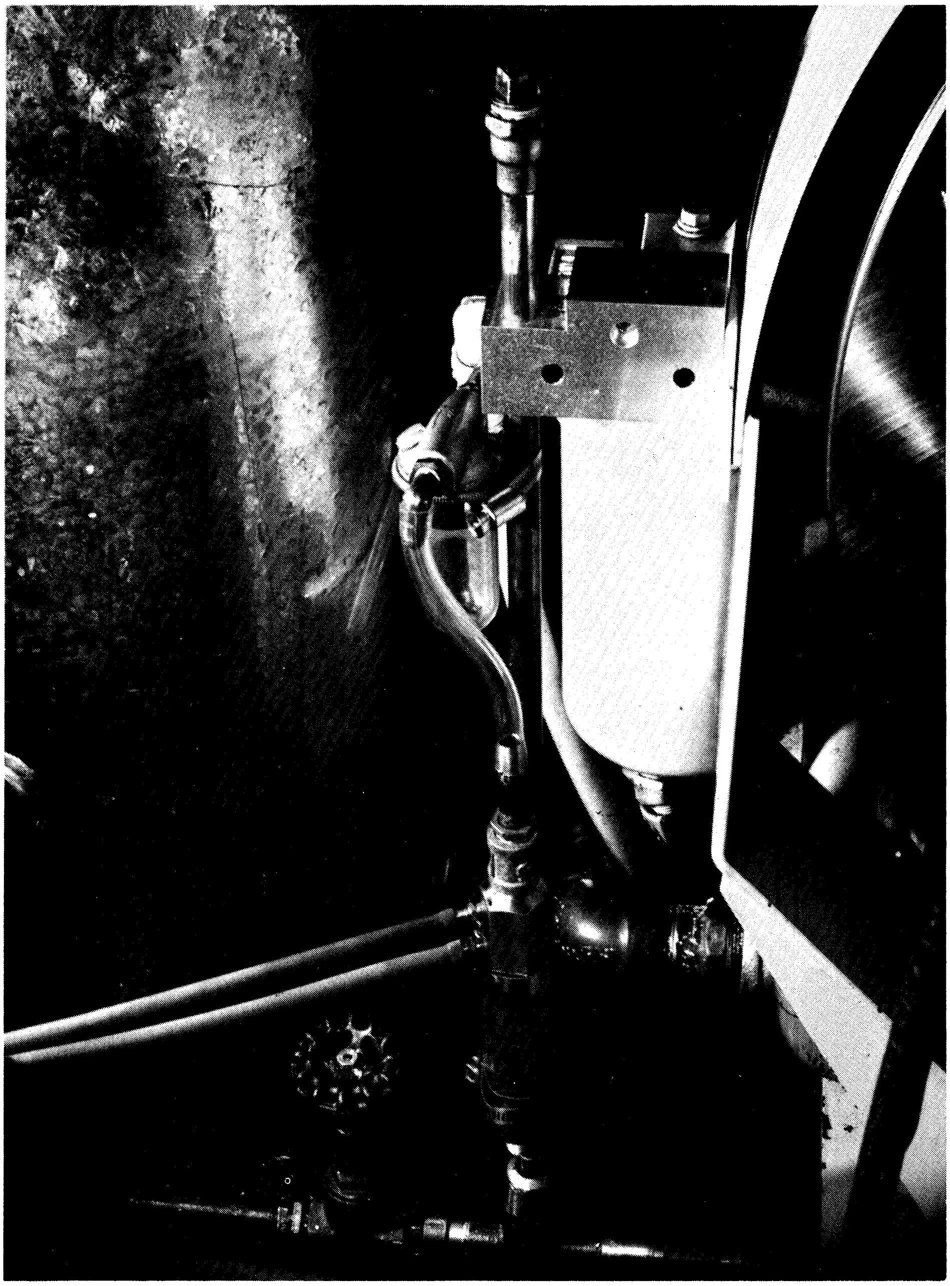

Fig. 8. Blowby flowmeter mounted on newly installed dip stick type oil level indicator.

3. The vacuum in the crankcase was noticed to be less than 4 inches of water, specified by the manufacturer. This caused flow of lubricating oil out with the blowby gases. This was corrected by cleaning and adjusting the relief valve.

4. The engine has been noticed to operate erratically when gasoline is used as fuel. In order to avoid running the engine for long periods of time on gasoline without combustion, an injection test rig will be constructed to make gasoline injection studies away from the engine.

VI. FUTURE PLANS

A. Next Period

To run tests on the ATAC engine to compare between the ignition delays and combustion phenomena of the three fuels mentioned before.

B. Overall

1. To investigate the effect of pressure, temperature, and density on ignition delay with the different fuels.

2. To process the experimental data on a digital computer.

3. Report the results.

C. Change From Original

Since turbulence has been found to affect ignition delay significantly, it will be studied along with temperature, pressure, and density.

VII. SIGNIFICANT ACCOMPLISHMENTS

1. Newly identified defintions of the ignition delay have been made.

2. The theoretical work indicated that the ignition delay in engines can be divided into a physical, a chemical, and an energy delay.

3. Correlations of experimental results of ignition delay, with gas pressure, gave a formula that is found to correlate very well all previous ignition delay results in bombs and engines, with the corresponding gas pressure.

4. Completion of the equipment and instrumentation of the ATAC engine.

VIII. PROJECT STATUS

Funds and Expiration Date of Contract

Original contract July 1, 1964, to January 1, 1965	$ 23,020
Modification No. 7 Extension of contract to February 28, 1966; addition of $18,000 to contract funds for a total of	$ 41,020
Modification No. 8 Extension of contract to February 27, 1967; addition of $37,000 to contract funds for a total of (funds will be exhausted about January 1, 1967)	$ 78,020
Modification No. 10 Extension of contract to December 1, 1967; addition of $45,000 to contract funds for a total of	$123,020

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ADDENDUM

A. DISCUSSIONS ON SAE PAPER "IGNITION DELAY IN DIESEL ENGINES," BY N. A. HENEIN AND JAY A. BOLT, SAE ANNUAL MEETING, JANUARY 9-13, 1967

1. K. C. Tsao
Associate Professor, South Dakota School of Mines and Technology

Professors Henein and Bolt are to be congratulated for their contributions in adding another piece of work to the literature regarding diesel combustion. In particular, the authors have (i) successfully correlated the ignition delay* among the three published data by a simple expression, (ii) explored the effect of air turbulence on ignition delay, and (iii) obtained additional experimental information on the effect of cooling water temperature on ignition delay. The following comments are presented for the sole purpose of strengthening the authors' findings and do not detract, in any form, the merit of their paper.

Authors' Eq. (21) indicates that at a given temperature and probably at given engine speed, the ignition delay is a hyperbolic type function of pressure. The constant C and the exponent n would differ for different sets of operating conditions. For the engine designer, having only the information of the intake air temperature, the intake air pressure and the engine speed, an estimate of ignition delay would require knowledge including the selection of C and n values. Hence, it seems that Eq. (21) may present itself as a limited application, but it does validate that the cylinder pressure at the start of injection process is of primary importance in delay correlations among various engines. It would be useful and rewarding in the engine design if the authors would give some details on selecting the values of the constant C and the exponent n as some functions of engine operating variables.

In the course of their presentation, the authors raise one important, yet unresolved question: the effect of engine turbulence in ignition delay. The engine turbulence, as most of the engine researchers realize, is an extremely difficult and perplexing subject, but with the pressing need of understanding the diesel combustion phenomenon. It was thought that the engine speed is the principal cause of air turbulence, which includes the air flow pattern, inside the combustion chamber. It seems unlikely that the air turbulence would have the same flow pattern inside the cylinder when the engine rpm increases from 607 rpm to 1000 rpm. By comparing the authors' data of Fig. 17 and Fig. 19, the ignition delays are nearly equal at cylinder air pressure of

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*The ignition delay is defined here in its most general sense whether it be the temperature rise delay or pressure rise delay.

250 psia, while the rest of the operating variables were held nearly the same. Would it be correct to assume that the engine speed (or air turbulence) has no effect on ignition delay in a Lister engine at the listed operating conditions? Or would it be correct to assume that the engine speed (or air turbulence) does have effect, to some degree, on ignition delay, but this effect has been compensated by an undetermined variable or variables? If so, then what are the other undetermined variables?

The effect of engine cooling water temperature on ignition delay as shown in authors' paper, Fig. 15, is very interesting. In a previous publication,* the peak motored compression temperature was correlated and modeled with the engine operating variables, the intake air temperature, the engine speed, the engine compression ratio and the cooling water temperature. It was also shown that the ignition delay** is affected by the air temperature at the point of injection, the air pressure at the point of injection and the engine speed. Hence, it seems reasonable to assume that the temperature at the point of injection in a fired diesel engine must also be affected by the jacket cooling water temperature, which in turn, will affect, to a certain degree, the ignition delay.

Since there is no semi-empirical relationship available in the literature for computing the air temperature at the point of injection, it was then decided to apply the motored compression temperature model to calculate the air temperature at the point of injection. In the process of computation, the intake air temperature was chosen as 530°R; the engine speed as 1200 rpm, the engine compression ratio as 12.5 and the jacket cooling water temperature varies from 530°F to 660°R. It must be noted that the actual compression ratio at the point of injection (injection at 27° BTDC)** was about 6.5 instead of 12.5. The choice of compression ratio of 12.5 is simply to eliminate the engine compression ratio effect which appears as an exponent in Eq. (2),* and to compensate the difference of air temperature between a motored and a fired diesel engine.

By so doing, the computed peak temperatures change from 1445.3°R to 1493.4°R when the cooling water temperature increases from 530°R to 660°R. These computed temperatures agree fairly well as the temperatures at the start of injection in a fired diesel engine.** In turn, they are employed to calculate the ignition delay.

The pressure at the point of injection and the engine speed were chosen as 300 and 600 psia, and 1200 rpm, respectively. The following figure presents the computed and the experimental ignition delay vs. the cooling water temperature. The authors' experimental data agrees very well with the calculated values. However, it must be noted that the reduction in ignition de-

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*K. C. Tsao and S. M. Wu, "On the Mathematical Model of Motored Compression Temperature," SAE Paper 650453 or SAE Trans., 1966, p. 594.

**Authors' reference (36).

lays by increasing the cooling water temperature from 70 to 200°F are different. It is 14.8% in a Lister engine and 42 8% in the computed delays.

Finally, I have noted the maximum pressure and temperature advances in a motored Lister engine as given in authors' Fig. 22. These same phenomena were also observed in a modified C.F.R. engine motored cycle.*

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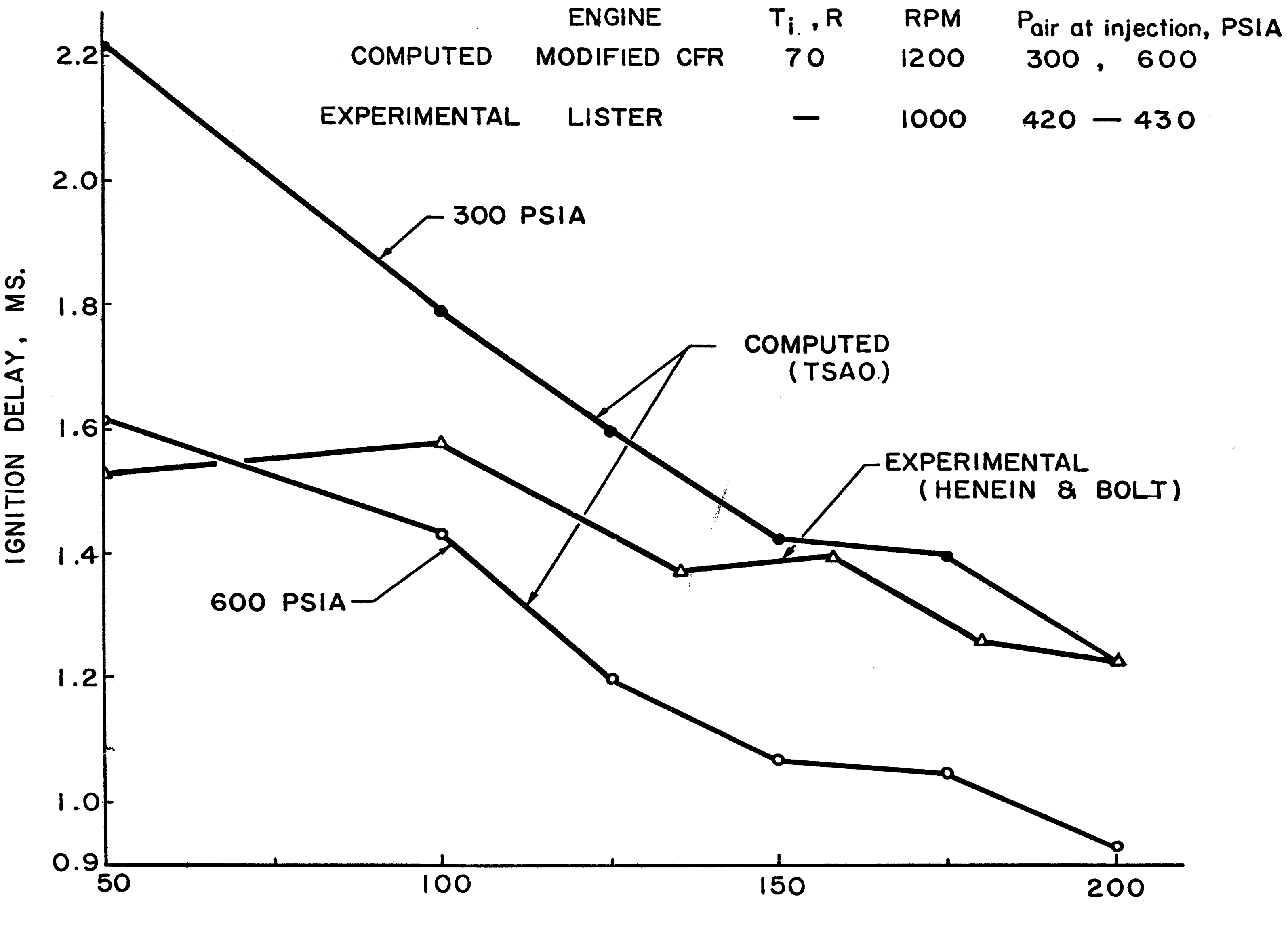
*K. C. Tsao, "The Effect of Operating Variables on Compression Temperature in a Compression Ignition Engine," Ph.D. Thesis, University of Wisconsin, 1961, Figs. 13, 15, 19, 21, and 26.



Effect of cooling water temperature on ignition delay.

2. C. W. Chiang

Associate Professor, University of Denver

The authors should be complimented on their fine research work on ignition delays which are still not very well known.

A few comments in regard to the thermodynamic considerations of the paper are as follows:

1. Equation (26) of Appendix II does not seem to be for a closed system. dm in Eq. (26), means that there exists a change of mass due to the injection of fuel crossing the boundary of the system and thus implies an open system. It is then obvious, if the system is considered as a closed system, there should not exist any term of dm.

2. During the period of ignition delays, the fuel is injected into the combustion chamber and an amount of fuel dm_f or dm is crossing the boundary of the system. According to the first law of thermodynamics written for an open system

$$\delta Q + dm(u_f + P_f V_f) = \delta W + dU \tag{1}$$

or

$$\frac{\delta Q}{d\theta} + \frac{dm}{d\theta} h_f = \frac{PdV}{d\theta} + mc_v \frac{dT}{d\theta} \tag{2}$$

where h_f is the enthalpy of the injected fuel at injected pressure

$m = m_f + m_a$, the mass of air, m_a, remains constant.

Other notations remain the same as those in the paper.

Now applying the ideal gas law

$$d(PV) = d(mRT) \tag{3}$$

or

$$PdV + VdP = mRdT + RTdm \tag{4}$$

Combining Eqs. (2) and (4) gives

$$\frac{dP}{d\theta} = \frac{R}{c_v}\frac{1}{V}\left[\frac{\delta Q}{d\theta} - P\frac{dV}{d\theta}\left(\frac{c_v}{R} + 1\right) + (h_f + c_v T)\frac{dm}{d\theta}\right] \tag{5}$$

Basically, Eq. (5) is similar to Eqs. (26) or (15) of the paper except that the sign of the last term of Eqs. (26) or (15) is supposed to be (+). The only difference is the enthalpy of the fuel h_f which may be neglected. However, the last term in Eq. (5) is of considerable importance and may not be neglected.

3. To demonstrate the importance of the last term in Eq. (5) a numerical estimate is given. Although the estimate is crude, it only serves as qualitative analysis. Since the ignition delay is usually in the order of 10 crank angle degrees, the total pressure change after the ignition delay may be obtained by integrating Eq. (5) as follows:

$$\Delta P = \frac{R}{c_v}\frac{1}{V}\Delta Q - P\Delta V\left(\frac{c_v}{R} + 1\right) + (h_f + c_v T)\Delta m \tag{6}$$

(a) Comparison of the last two terms.

Taking data from the paper listed as follows:

Piston displacement, V	approx. 278 in.^{3}
Compression ratio	14:1
T (Fig. 22, 9° B.T.D.C.)	1200°R
P (Fig. 22, 9° B.T.D.C.)	440 psia
m_a $(\frac{278}{1728} \times .076)$	approx. 1.22×10^{-2} lb
m_f (Take fuel air ratio of .03)	approx. 3.66×10^{-4} lb
c_v (air)	.17 Btu lb^{-1} F^{-1}
R (air)	approx. .07 Btu lb^{-1} F^{-1}
ΔV (for 10 crank angle degree B.T.D.C.)	approx. 4.2 in.^{3}

neglecting h_f, and heat of vaporization of the fuel

$$c_v T\Delta m = .17 \times 1200 \times 3.66 \times 10^{-4} = 7.5 \times 10^{-2} \text{ Btu}$$

$$\left(1 + \frac{c_v}{R}\right) P\Delta V = \frac{440 \times 4.2}{778 \times 12} \left(1 + \frac{.17}{.07}\right) = 6.8 \times 10^{-1} \text{ Btu}$$

$$\frac{c_V T \, \Delta m}{\left(1 + \frac{c_V}{R}\right) P\Delta V} \cong 11\%$$

With higher fuel-air ratio, this percentage is proportionally higher. Thus, the last term amounts to a good percentage of the term before it.

(b) Total pressure drop after 10° ignition delay in the absence of of combustion due to the contribution of the last term.

Assuming 1200 rpm and T wall ≈ 300°F or 760°R, the film coefficient of heat transfer due to convection at this speed is estimated at 2 Btu hr^{-1} ft^{-2} F^{-1}. ΔQ is found negligibly small.

$$\begin{aligned} \Delta P &= \frac{R}{c_V V} \left[c_V T \, \Delta m\right] \\ &= \frac{53.4}{\frac{278}{12}} \times 1200 \times 3.66 \times 10^{-4} \\ &= 1 \text{ psi} \end{aligned}$$

Although, in this case, the contribution to pressure rise is rather small, nevertheless, for higher compression rates or higher T, lower V, the pressure rise may amount to 7 or 8 psi, as experienced in Yu's paper.

In conclusion, the authors had good intentions of having thermodynamic considerations; however, this approach should be pursued further.

4. Although the authors did mention briefly the importance of different fuels, unfortunately they did not consider them in their experiments. In the literature survey the cetane number is known to be a vital influential parameter to ignition delays. A further study is deemed necessary.

3. C. W. Bouchillon
Professor, Mississippi State University

INTRODUCTION

The period of time which lapses between fuel injection and some physical manifestation of auto-ignition has been classically referred to as the ignition delay period. Professors Henein and Bolt have presented an excellent discussion of the concepts and findings of previous investigations of this phenomena as presented in the literature. Their literature review was comprehensive and the basic contributions to gaining an understanding of the ignition delay phenomena were succinctly presented. Both the theoretical and the empirical findings were discussed in sufficient detail that the reader is brought through the historical developments up to the report of the present investigation being conducted by Professors Henein and Bolt.

The equipment is described in sufficient detail to give the reader a very clear picture of the nature of the experimental techniques.

The instrumentation utilized was verified through motoring techniques, etc., in order to establish reliability of the results obtained.

It is interesting to note the following trends in the variation of the pressure rise delay with the several physical variables involved in the experimental investigation. The pressure rise delay is seen to decrease with an increasing fuel to air ratio as presented in Fig. 13. The injector opening pressure did not have a significant effect on the pressure rise delay times for the study presented in Fig. 14. An increase in cooling water temperature at the outlet resulted in a reduction in the pressure rise delay times for the runs reported in Fig. 15. And finally, the variation in pressure rise delay with gas pressure at the start of injection was represented approximately by a constant divided by the pressure raised to some power as reflected in Figs. 17 and 19. The authors present a simplified thermodynamic analysis of the cylinder and combustion chamber, however, it appears that the vaporization of the fuel was assumed to be instantaneous upon injection into the cylinder and no energy exchange was entered into the thermodynamic analysis to account for the latent heat of vaporization of the fuel.

The simplified thermodynamic approach to the analysis of a system can often yield surprisingly good cause-effect relationships and it is at this point that the following analysis is presented as a possible means to extend the theoretical portion of the paper, and as a consequence, some slightly different conclusions might be drawn from the experimental findings than those presented by Professors Henein and Bolt.

THERMODYNAMIC ANALYSIS

In that the fuel injection process represents an unsteady flow phenomena, it may be more appropriate to employ the unsteady energy equation for an open system by

$$\left.\frac{\Delta E}{\Delta t}\right|_{c.v.} = \dot{m}_f h_f - \frac{\delta W}{\Delta t} + \frac{\delta Q}{\Delta t} \tag{1D}$$

where the subscript f refers to the fuel. Equation (1D) may then be divided by the angular velocity $\Delta\theta/\Delta t$ to yield

$$\left.\frac{\Delta E}{\Delta \theta}\right|_{c.v.} = \frac{\delta m_f}{\Delta\theta} h_f - \frac{\delta W}{\Delta \theta} + \frac{\delta Q}{\Delta \theta} \tag{2D}$$

where δm_f is the increment of fuel introduced during the crank angle $\Delta\theta$.

Now solving for the heat transfer and introducing the internal energies in the control volume at crank angles θ and $\theta+\Delta\theta$, there results

$$\frac{\delta Q}{\Delta\theta} = \frac{M_A C_{V_A}(T_{\theta+\Delta\theta} - T_\theta) + \delta m_f U_{f_{\theta+\Delta\theta}}}{\Delta\theta} - \frac{\delta m_f}{\Delta\theta} h_{f_\theta} + \frac{PdV}{\Delta\theta}$$

which reduces to

$$\frac{\delta Q}{\Delta\theta} = M_A C_{V_A}\left(\frac{\Delta T}{\Delta\theta}\right) + \frac{\delta m_f}{\Delta\theta}(U_{f_{\theta+\Delta\theta}} - U_f) - \frac{\delta m_f}{\Delta\theta}\left(\frac{Pv}{J}\right)_{f_\theta} + \frac{PdV}{\Delta\theta} \tag{3D}$$

Assuming that at least some of the fuel vaporizes on injection during the period $\Delta\theta$, then $U_{f_{\theta+\Delta\theta}}$ represents the internal energy of the vaporized fuel with a temperature approximately equal to the chamber air temperature and at a relatively low partial pressure in comparison with the cylinder pressure. This may be assumed because of the small values of fuel/air ratio being used.

Introducing

$$h_{fg} = U_{f_{\theta+\Delta\theta}} - U_{f_\theta} + \left(\left.\frac{Pv}{J}\right|_{\theta+\Delta\theta} - \left.\frac{Pv}{J}\right|_{\theta}\right)$$

and assuming that the latter terms may be considered negligible at the relatively low partial pressures of the fuel in the chamber, then

$$U_{f_{\Theta+\Delta\Theta}} - U_{f_\Theta} \simeq h_{fg_f} \tag{4D}$$

Then assuming that during the crank angle position relative to TDC-15° < Θ < 15°, the total volume is approximately constant, then Eq. (3D) in combination with Eq. (4D) yields

$$\frac{\delta Q}{\Delta\Theta} \simeq M_A C_{v_A} \frac{\Delta T}{\Delta\Theta} + \frac{\delta m_f}{\Delta\Theta} h_{fg_f} \tag{5D}$$

Then assuming that the temperature may be approximately represented by

$$T = \frac{PV}{mR}$$

and neglecting any volume or mass changes,

$$\frac{\Delta T}{\Delta\Theta} = \frac{V}{mR} \frac{\Delta P}{\Delta\Theta} \tag{6D}$$

In combining Eqs. (5D) and (6D), there results

$$\frac{\Delta P}{\Delta\Theta} \simeq \frac{mR}{M_A C_{v_A} V} \left[\frac{\delta Q}{\Delta\Theta} - \frac{\delta m_f}{\Delta\Theta} h_{fg}\right]$$

Now if the heat transfer is assumed to consist of the chemical energy supplied from the combustion process and of the convection losses to the cylinder walls as did the authors, along with the assumption that $M_A \simeq m = M_A + M_f$ there results

$$\frac{\Delta P}{\Delta\Theta} \simeq \frac{R}{C_{v_A} V} \left[\frac{\delta Q_{Ch}}{\Delta\Theta} - \frac{\delta Q_c}{\Delta\Theta} - \frac{\delta m_f}{\Delta\Theta} h_{fg}\right] \tag{7D}$$

Consider that the latent heat of vaporization for the fuel at relatively low pressures may be given approximately by

$$h_{fg} \simeq K_1 - K_2 \ln \frac{P_f}{T_f} \tag{8D}$$

as suggested by and presented in for other hydrocarbons. Also, the heat transfer to the walls may be approximated by

$$\frac{\delta Q_c}{\Delta\theta} \simeq A \cdot \alpha \cdot \frac{\Delta(T_g - T_w)}{\Delta\theta} \cdot \Delta t \qquad (9D)$$

Then a prediction equation may be developed for the ignition delay time by solving for $\Delta\theta$. This yields

$$\Delta\theta \simeq \frac{C_{v_A} V(\Delta P)}{R\left\{\frac{\delta Q_{Ch}}{\Delta\theta} - A\cdot\alpha\cdot\frac{\Delta(T_g - T_w)}{\Delta\theta}\cdot\Delta t - \frac{\delta m_f}{\Delta\theta}\left(K_1 - K_2 \ln \frac{P_f}{T_f}\right)\right\}} \qquad (10D)$$

Now for a constant fuel/air ratio, with higher initial chamber pressures at the start of injection, there will result higher partial pressures of the fuel in the chamber, because of the reduced volume, and as a consequence, Eq. (10D) may be modified to yield

$$\Delta\theta \simeq \frac{C_v V(\Delta P)}{R\left\{\frac{\delta Q_{Ch}}{\Delta\theta} - A\cdot\alpha\cdot\frac{\Delta(T_g - T_w)}{\Delta\theta}\cdot\Delta t - \frac{\delta m_f}{\Delta\theta}\left(K_4 - K_3 \ln \frac{P_c}{T_f}\right)\right\}} \qquad (11D)$$

Let us now consider the results obtained by experiment in relation to the approximate predictions of Eq. (11D).

Case I. Pressure Variations

Increasing chamber pressures result in an increase in the denominator and therefore a decrease in the ignition delay time (see Figs. 17 and 19).

Case II. Fuel/Air Ratio Variations

Because of the very short time involved in the ignition delay period, the heat transfer to the walls should be small in comparison with the chemical and vaporization energies, therefore the ignition delay time should be inversely proportional to the fuel/air ratio (see Fig. 13).

Case III. Cooling Water Temperature

A reduction in the cooling water temperature should result in an increase in the heat transferred to the walls, thereby reducing the denominator of Eq. (11D) and as a consequence, the delay time would be increased (see Fig. 15).

Case IV. Injection Pressure

The injection pressure effects do not appear in Eq. (11D) and as a consequence may not affect the ignition delay time (see Fig. 14).

Case V. Engine Speed

An engine speed increase of the order of 2 would reduce the time for heat transfer to the walls by 1/2 and unless there is a significant increase in the heat transfer coefficient, the net effect would be to reduce the heat transfer to the walls.

In order to draw a comparison with the data presented in Fig. 20, the different chamber temperature effects must also be considered.

$$\frac{\delta Q_c}{\Delta\theta} \simeq A \cdot \alpha \cdot \frac{\Delta(T_g - T_W)}{\Delta\theta} \cdot \Delta t$$

Assuming that the heat transfer coefficient increases as $\sqrt{V}$, then the net effect will be a reduction in the heat transfer with an increase in speed for this case.

$$\frac{\left.\frac{\delta Q_c}{\Delta\theta}\right|_{1000}}{\left.\frac{\Delta Q_c}{\Delta\theta}\right|_{500}} \simeq \frac{A\sqrt{1000}\left[\frac{\Delta(1520-500)}{\Delta\theta}\right]\Delta t_{1000}}{A\sqrt{500}\left[\frac{\Delta(1457-500)}{\Delta\theta}\right]\Delta t_{600}} < 1$$

This results in an increase in the denominator and consequently a reduction in the ignition delay time with increase in engine speed.

Case VI. Increase in Chamber Temperature

Increase in chamber temperature appears to be significant as evidenced by the ignition delays reported by West in comparison to the present investigation (Fig. 20).

This may be due to the fact that the heat of vaporization of the fuel term is probably significantly larger than the heat transfer to the walls. As a consequence, this evaporative process could be effected more rapidly in the higher temperature conditions, thereby reducing the ignition delay time for the higher temperature runs.

The above arguments are admittedly qualitative and are presented only to indicate that careful theoretical analysis may yield useful quantitative results if the qualitative trends are correct.

CONCLUSIONS

Professors Henein and Bolt have presented an excellent literature review and have obtained and reported some significant experimental observations of ignition delay.

In order to obtain a clearer understanding of the physical phenomena involved, it is necessary to make theoretical attacks on the problem yielding results which are in agreement with the experimental findings. It appears that the fuel vaporization phenomena may be one of the major controlling influences on the ignition delay as defined by the time lapse from the beginning of injection to the onset of pressure rise in the chamber. Further attention to thermodynamic and heat transfer analyses of the injected fuel stream may prove beneficial and further efforts in this direction are required in order to evaluate this hypothesis.

In order to establish a theoretical approach to predicting the delay time as described by the time from the start of injection to onset of illumination, it appears that the combustion energy release rate is significantly involved. Further analytical attack may reveal that through thermodynamic analysis of the fuel vaporization phenomena and the application of the theory of combustion kinetics, explanations of the illumination delay time may be obtained.

Many facets of this phenomena remain to be explained and the authors are to be commended for their contribution by bringing additional information on the subject of ignition delay in diesel engines.

B. AUTHORS' REPLY ON DISCUSSIONS

(February, 1967)

The authors wish to thank the discussors for their interest in the paper, and for the valuable points brought up in the discussions.

IN REPLY TO PROFESSOR K. C. TSAO

1. For fundamental studies, we believe it is better to correlate the pressure rise delay with the pressure and temperature in the cylinder at the beginning of injection, rather than in the intake manifold of the engine. If the correlations are made in terms of the intake air pressure and temperature, as suggested by Professor Tsao, the resulting formula would have included two additional factors which vary among engines. The first is the compression ratio at start of injection, which depends on the injection timing. The second is the average index of compression which depends mainly on the cooling losses and engine speed. Equation (21) can be used for any engine if the pressure and temperature at the beginning of injection are calculated. It is expected that the engine designer would be familiar with such calculations as applied to his engine.

2. The effect of increased turbulence is to decrease the ignition delay in the range of pressures and temperatures occurring in the actual diesel engine at the start of injection. Below 250 psia, we cannot draw any conclusions based on experimental data. Our tests did not cover these low pressures because they are outside the range of present use.

3. The results of computations made by Professor Tsao indicate that an increase in cooling water temperature from 70°F to 200°F causes an increase in the air temperature at the end of compression from 1445.3°R to 1493.4°R or an increase of 48.1°F. According to his calculations, this increase causes a drop of 42.8% in the pressure rise delay. Our experimental results show a drop of only 14.8%.

At this time we cannot give a conclusive answer, based on experimental work, for the effect of temperature on ignition delay because this work is still in progress at The University of Michigan. However, we believe that the decrease in delay, as computed by Professor Tsao, is very large. This can be shown by comparing the computed change with the results of several formulae available for the ignition delay. Wolfer's formula (Eq. (2)) gives a value of 17.8%, and Elliott's formula (Eq. (8)) gives a value of 4.45%. Sitkei's formula (Eq. (14)), gives a value of 13%. These values are much lower than the 42.8% given by Professor Tsao, and close to our reported experimental results.

4. We agree with Professor Tsao that a correlation is needed between the gas pressure, temperature, and engine speed, and the constant "C" and exponent "n" in Eq. (21). This, and the effect of gas temperature on ignition delay, are among the main goals of the work now in progress under sponsorship of the U.S. Army Tank Automotive Command.

IN REPLY TO PROFESSOR C. W. CHIANG

The authors wish to thank Professor Chiang for calling their attention to a printing error in Eqs. (15), (20), and (26). The sign of the last term in these equations should be positive.

However, we do not agree with Prof. Chiang about the importance of this last term for the graphical presentation made in Figs. 2 and 3 of the text. This term represents the effect of the change in the mass of the system on the slope of the pressure-time trace. In the demonstration made by Professor Chiang he assumed that all the fuel is injected before the end of the delay period. We do not believe this assumption is justified. Under the conditions quoted by Professor Chiang, the amount of fuel actually injected during the ignition delay is about 20% of the total amount injected. The ratio of 11.1% given in his demonstration therefore is 2.2%, which can be neglected in the graphical representation.

This conclusion is also supported by Part b of item 3 of the discussion. This indicates that the error in the pressure caused by neglecting this last term is 1 psi in 440 psi. This corresponds to an error of 0.2% only.

The authors appreciate the effect of the fuel cetane number on ignition delay. This, however, was not the subject of the present paper. For our program now in progress three fuels of different cetane numbers are being tested for ignition delay.

IN REPLY TO PROFESSOR C. W. BOUCHILLON

The discussion of Professor Bouchillon is based on the assumption that the physical delay is the dominating factor in the total ignition delay. This assumption cannot be justified in view of the previous theoretical and experimental work done.

Wentzel (16)* computed the physical delay and found it much shorter than the pressure rise delay.

Boerlage and Broeze (11) proved experimentally that the chemical portion of the delay period is the controlling factor in the total delay. They com-

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*Numbers refer to Bibliography of the original paper.

pared cetane ($C_{16}H_{32}$) and Tetraisobutylene ($C_{16}H_{32}$) and found that the latter has a longer ignition delay due to its molecular structure. This occurred inspite of the fact that the two fuels have the same number of carbon and hydrogen atoms.

Another interesting experiment was made by Starkman (26) to prove the small effect of the physical delay on the total delay. He measured the total delay of a mixture of a diesel fuel and Tetra-ethyl lead. He found that the ignition delay increased with addition of T.E.L. Since T.E.L. has no known effect on the physical delay, and since the ignition delay increases with T.E.L., Starkman concluded that the chemical delay is the major part of the ignition delay.

Another experiment that supports our point of view was made by Hurn, R. W., et al. (31). They studied the effects of the physical and chemical properties of the fuels on the ignition delay in bombs. They concluded that the greatest difference between the autoignition behavior of fuels is in those factors that affect chemical reaction, rather than in those that affect the physical processes.

From the above discussion it can be concluded that the assumption made regarding the importance of the physical part of the delay period is not justified.