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INDUCTION PERIOD FOR IGNITION OF FUEL SPRAYS AT HIGH TEMPERATURES AND PRESSURES

T.E. Parker, M.D. Forsha, H.E. Stewart, K. Hom,
R.F. Sawyer, and A.K. Oppenheim

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ABSTRACT

An experimental study of the induction period for ignition of fuel sprays with particular consideration of its dependence upon temperature and pressure is reported. Emphasis in the study was placed upon conditions of thermodynamically supercritical state for the fuel. The tests were performed in a stainless steel cylindrical chamber located in an oven, both provided with quartz windows for optical insight in axial direction of the radially injected spray. Spray formation and ignition were observed by high-speed schlieren cinematography concomitantly with measurements of chamber pressure and the displacement of the injector needle. The induction period was evaluated as the time interval between the rise in the displacement transducer signal and the instant when pressure attained three percent of its peak value.

IGNITION of fuel sprays is at the heart of the operation of diesel engines, while its induction period occupies a significant portion of the total combustion time. Many studies of the time required for spray ignition at various pressures and temperatures were carried out in several different types of apparatus. Constant volume test cells were used for this purpose by Hurn and Hughs (1) and, more recently, by Baev et al.(2), while Ikegami et al.(3) and Tsao et al.(4) measured the induction period of diesel fuels in a rapid compression machine and in a reciprocating engine, respectively. The effect of preheating the fuel before injection was investigated also by Gerrish and Ayer(5), Spadaccini(6), Walsh and Cheng(7), and Scharnweber and Hoppie(8), demonstrating its significant influence upon the induction period.

Reported here are the results of an experimental study of the effect of preheating both the fuel as well as compressed air to supercritical temperatures for the fuel, performed with the use of pure n-dodecane. To direct as much attention as possible to the thermo-chemical phenomena, the experiment was carried out in a constant volume enclosure. Thus, unlike a rapid compression machine or an actual engine, the compressed air was at rest and uniform in temperature prior to fuel injection. The only turbulence affecting the process under study was that generated by the spray jet itself and, due to the simplicity of the apparatus, the temperature of the ignition environment was constant and precisely controlled.

APPARATUS

All our experiments were conducted in a stainless steel test cell, which was placed in a furnace, as shown in Fig. 1. Access to the cell for fuel injection, oxidant filling and purging, and measurement of temperature and pressure was provided by an array of ports. The combustion chamber was cylindrical in shape, 80mm in diameter and 25 mm long, and had windows at both ends for schlieren cinematography, Fig 2. In the course of our studies, three end-plate assemblies were used: a steel disc for tests not requiring optical access, a quartz window providing a full view of the test cell, and a steel disc accommodating a window of 1 inch aperture to furnish optical access immediately below the fuel injector. Fuel was introduced to the cell by a specially adapted Stanadyne Roosa Master

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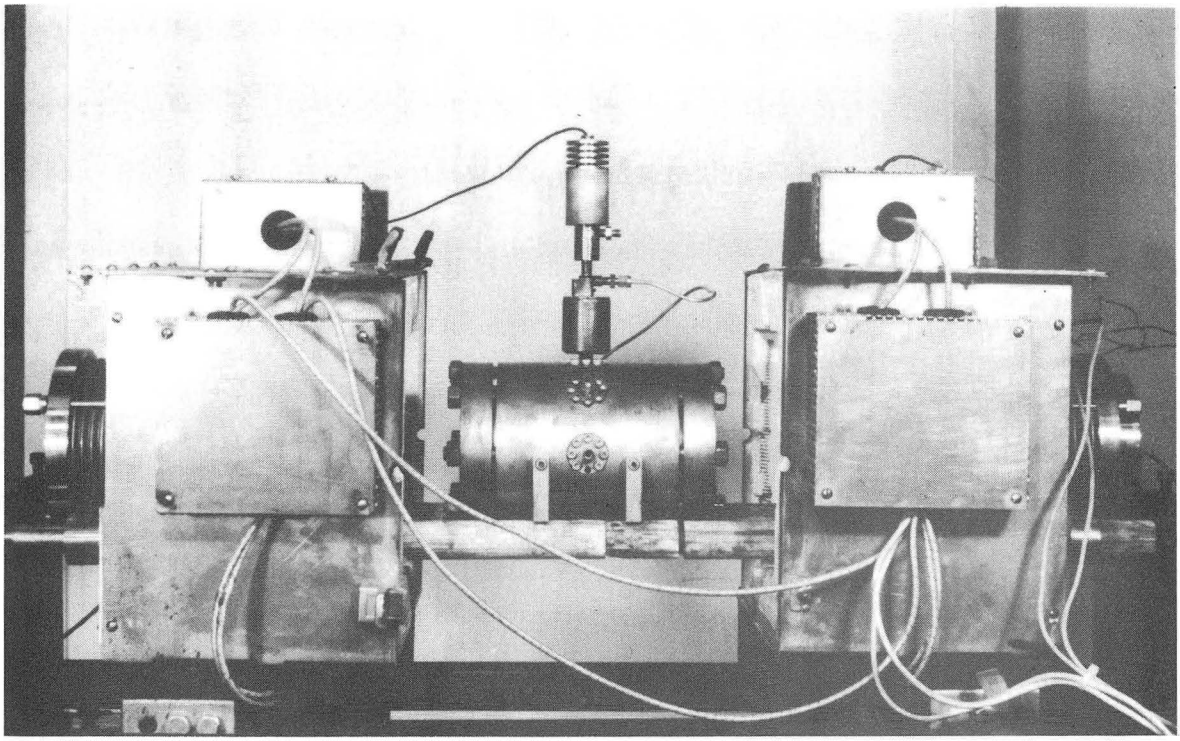

Fig. 1. Experimental apparatus: stainless test cell with injector assembly inside the expanded enclosure of a shell furnace.

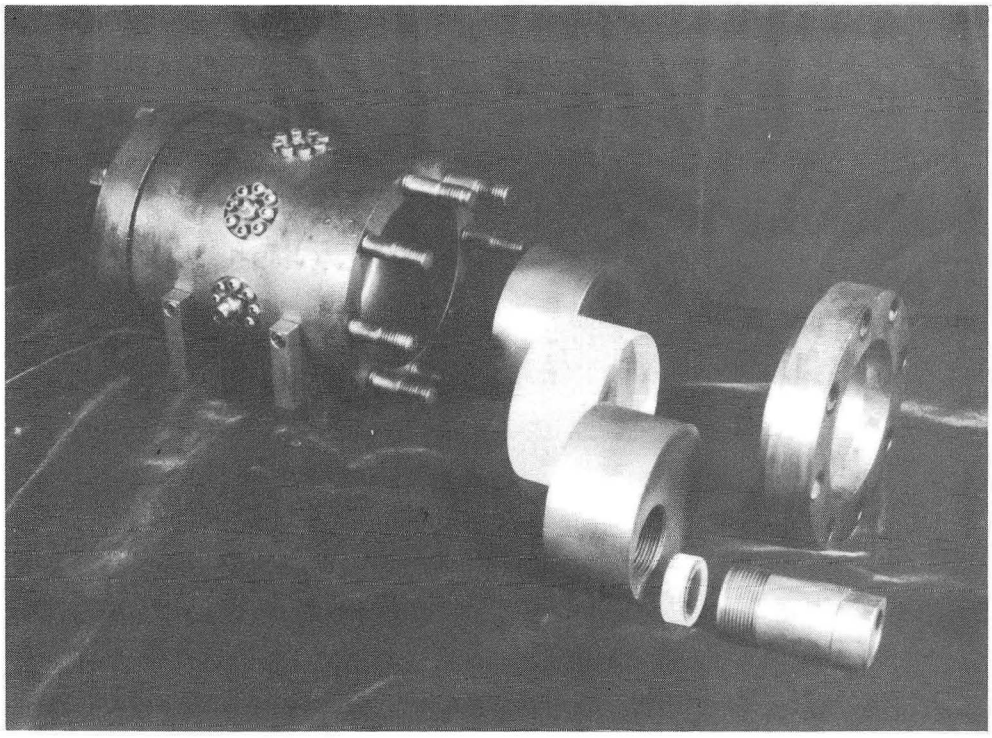

Fig. 2. Test cell and its end plate and window assemblies.

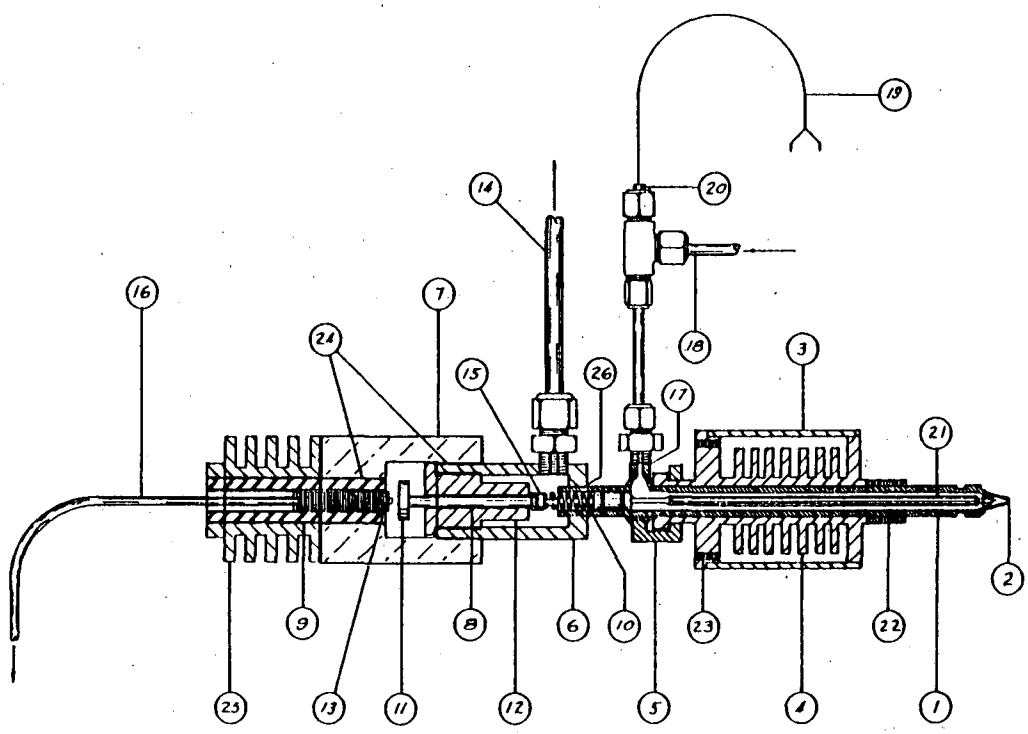

Fig. 3. Fuel injector: 1.Stanadyne Roosa Master injector - type 2d671, 2.Injector tip(sack removed), 3.Liquid flow injector cooler, 4.Cooling fins, 5.Retainer clip, 6.Adaptor, 7.Insulator(Macor), 8.Extension shaft, 9.Displacement transducer housing, 10.Injector tension spring, 11.Displacement transducer target, 12.Spring cap and extension shaft bushing, 13.Displacement transducer: Kaman KD2300 Proximity Sensor, 14.Fuel weep outlet, 15.Adjustment shims, 16.Displacement transducer output cable, 17.Fuel inlet mount, 18.Fuel inlet tube, 19.Thermocouple lead, 20.Teflon plug seal, 21. Thermocouple sensing junction, 22.Injector mount, 23.Coolant liquid inlet and outlet, 24.Threaded housing connectors, 25.Cooler for displacement transducer, 26.Press fit (class fn4) connection

injector, as displayed in Fig. 3. Included here prominently are the injector cooler, the tip thermocouple, and the needle displacement transducer. Fuel was supplied to the injector assembly by an accumulator system provided with a variable displacement pump and shunt valve as demonstrated in Fig. 4. Proper operating conditions for injection were obtained by adjusting both the pump displacement and background pressure to obtain a single high pressure pulse.

For an experimental test run the cell was heated to the desired temperature and filled with air to an appropriate pressure. The fuel was then injected. Cell pressure and injector needle position were recorded at 0.1 msec intervals using a PDP 11/34 computer. The induction period was specified as the time interval between the start of needle lift and the initial pressure rise (see Plates 1-4). At the same time the process was recorded by high speed schlieren cinematography.

RESULTS

Induction times for ignition of a fuel spray in air were measured in the combustion cell over a range of high temperatures and pressures. Pure n-dodecane was used as fuel. Its thermodynamic properties were evaluated using the principle of corresponding states extended by Pitzer et al.(9) and implemented by Lee and Kesler(10). The extension is based on the concept that the compressibility of a nonpolar substance is a function of not only the reduced pressure and temperature, but also of the so-called acentric factor expressing the effects of non-ideality of molecular structure, a correction of particular importance in the evaluation of specific volumes. In computations it appears as a linear coefficient, ω, in the expression for the compressibility factor, Z, as follows:

$$Z = Z^{(0)} + \omega \quad Z^{(1)} \qquad (1)$$

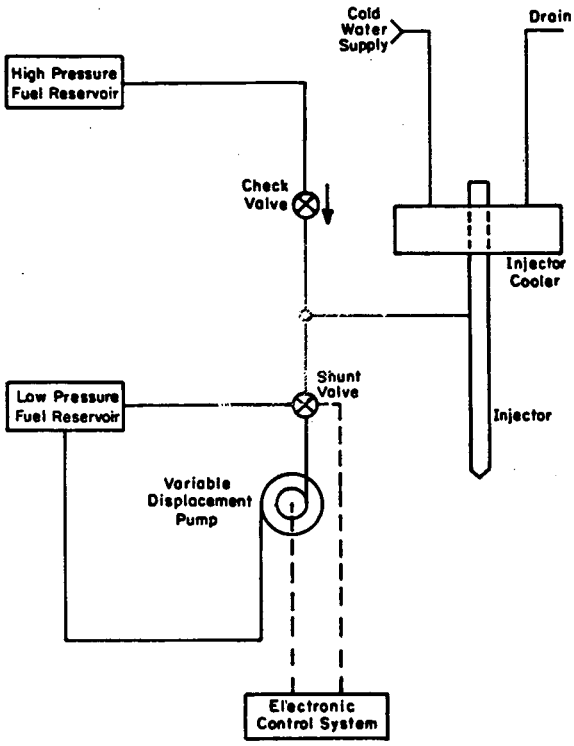

Fig. 4. Schematic diagram of the injection system.

where, according to Pitzer et al.(9),

$$\omega = -\ln(P_{rs}) - 1 \qquad (2)$$

P_{rs} being the reduced saturation pressure at $T_r = 0.7$. In the above, superscript (0) denotes an "ideal" fluid while (1) refers to the deviation from an ideal substance adopted as a reference. Among the former are noble gases and methane. For the latter Lee and Kesler(10) used primarily n-octane for which the acentric factor is equal to 0.3978.

On this basis a set of corresponding pressures, temperatures, and specific volumes was evaluated and the results applied to determine the coefficients in a virial equation of state. Information on the thermodynamic properties was then complemented with perfect gas specific heat data obtained from the compendium on Selected Values of Physical and Thermodynamic Properties of Hydrocarbons(11). In this connection our calculations were carried out following the procedure developed by Reynolds for the evaluation of Thermodynamic Properties in SI(12). The enthalpy-pressure diagram thus deduced is presented in Fig. 5, where the conditions for air within the cell for our experiments are marked by circles. Points denoted by numbers in circles refer to initial conditions of tests whose results are presented in Plates 1-4.

It should be noted that fuel temperature could not be measured in the course of an actual test run because the thermocouple could not be accommodated inside the injector without rendering it inoperative. The temperature of the fuel, T_f, was measured with a thermocouple located at the tip of the injector while its exit nozzle was blocked. For an air temperature within the cell, T_a, whose range was 400K to 875K, the fuel temperature was thus found to be

$$T_f = .55(T_a) + 177 \qquad (3)$$

Extracts of cinematographic schlieren records are presented in Plates 1-4 along with the corresponding injector needle lift and cell pressure traces. Plates 1 and 2 depict the entire cross section of the cell, so that the interaction of the fuel jet with the walls is visible. They were obtained respectively for P_i=7.8 atm., T_i=699K and P_i=21.4 atm., T_i=684K. At the relatively low initial temperatures of these tests three distinct stages of ignition can be discerned: formation of the spray, mixing with air, and ignition. After ignition a turbulent flame develops which engulfs the bulk of the gas in the cell and subsequently spreads through its entire volume. These events are associated with a relatively fast pressure rise. The induction process under these conditions is dominated by chemical kinetics, allowing the initially heterogeneous system to become relatively homogeneous before the exothermic stage of combustion takes place.

Ignition events displayed in Plates 1 and 2 are quite similar in spite of the large difference in initial pressures. Frames A and B display the formation of the jet, with a relatively small amount of vaporization at its periphery; frame C portrays the convection and diffusion of the jet through the cell, while frames D and E depict the process of combustion. The similarity between the schlieren records and pressure traces, associated with comparable induction times of 12.3 and 14.3 msec, indicates that under such circumstances spray ignition is not a sensitive function of initial pressure.

More details of the structure of the fuel jet and the subsequent process of ignition are provided by Plates 3 and 4, presenting excerpts of high speed schlieren movies taken through the one inch aperture immediately below the injector tip, with concomitant records of injector needle lift and cell pressure. They correspond respectively to P_i=14.6 atm., T_i=655K and P_i=28.2 atm, T_i=873K. These records show the significant effects of initial temperature upon the ignition event. The induction time associated with the low temperature record of Plate 3 is 21.2 msec, which is significantly longer than the period

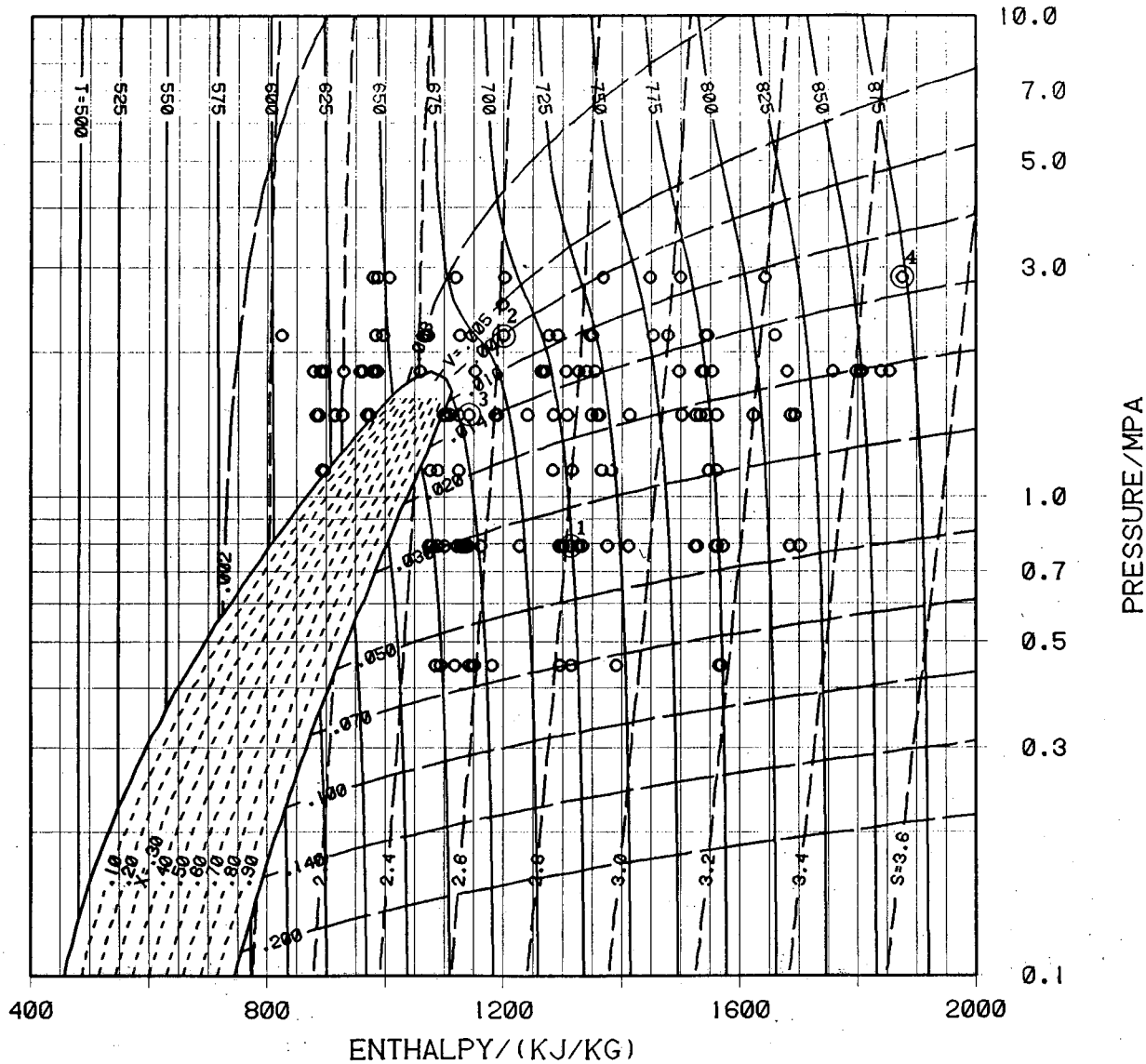

Fig. 5. Thermodynamic properties of n-dodecane. Conditions of all the tests we performed are expressed by circles; large circles with numbers refer to conditions of movie excerpts presented in Plates 1,2,3, and 4.

of 2.9 msec measured at the high temperature level of Plate 4. Three stages are discernible in Plate 3: jet formation in frame A, mixing in frames B and C associated with a relatively weak exothermic reaction proceeding outward from the injector tip, and the onset of a turbulent flame in frames D and E. Here the induction process is dominated by chemical kinetics while combustion is quite homogeneous in nature, as evidenced by the fast pressure rise and the turbulent flame traversing the cell.

High temperature ignition events, as displayed in Plate 4, exhibit a different type of behavior. Here the relatively short induction period evidently precludes the formation of a well mixed region and results in a diffusive burning of the fuel jet. Frame A displays the initial fuel jet, frame B shows that ignition has occurred, frames C, D, and E illustrate the diffusion controlled burning of the fuel jet. The relatively slow pressure rise indicates also that under such conditions, in contrast to the events illustrated in Plates 1-

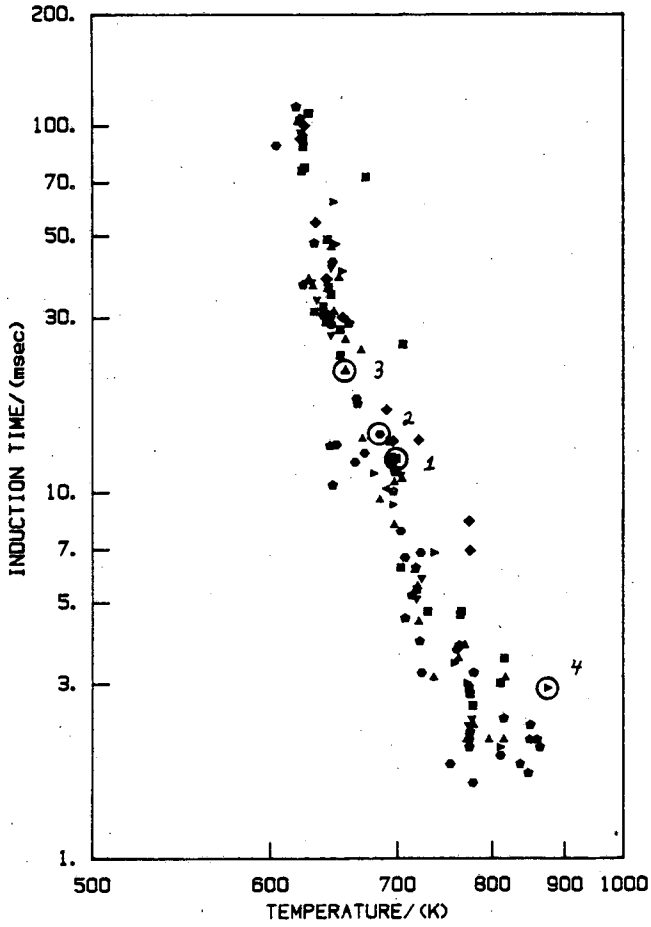

Fig. 6. Arrhenius plot of induction periods. Points denoted by large circles with numbers indicate induction periods for Plates 1, 2, 3, and 4. ◆ - 4.4 atm., ■ - 7.8 atm., ▼ - 11.2atm., ▲ - 14.6 atm., ⬟ - 18.0 atm. ⬢ - 21.4 atm., ◀ - 24.8 atm., ▶ - 28.2 atm.

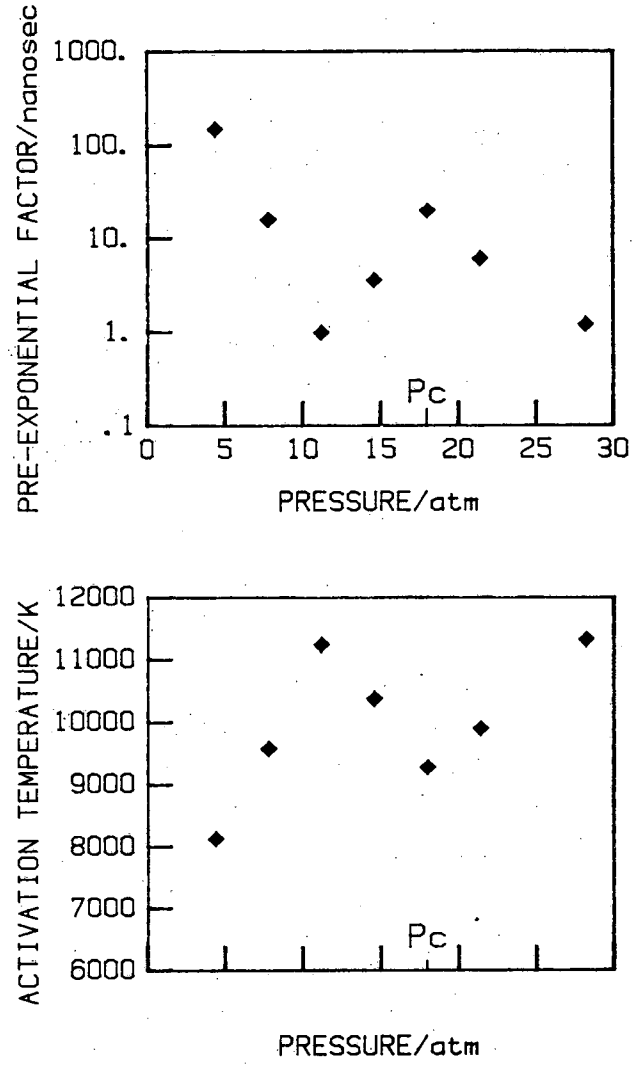

Fig. 7. Arrhenius parameters as a function of pressure.

3, a diffusion flame is established. Thus, high initial temperature, in addition to affecting the duration of the induction period, also modifies the nature of the physical mechanism of combustion. Instead of being dominated by chemical kinetics, the induction process is then controlled by evaporation and mixing.

Figure 6 presents induction times in the form of an Arrhenius plot. The scale for the time is logarithmic while that for temperature is linear with respect to its reciprocal. All the ignition periods were derived from the cell pressure and needle lift records as shown in Plates 1-4. The correlation presented by the straight line can be expressed in terms of

$$\tau = A \exp(T_a/T) \qquad (4)$$

where $A = 2.69 \times 10^{-8}$ sec and $T_a = 9032$K. The data were obtained for cell temperatures and pressures between 600K and 875K and 4.4 atm and 28.5 atm.

Activation temperatures, T_a, and pre-exponential factors, A, in Eq. (4), are shown plotted as a function of cell pressure, in Fig 7. At first glance this plot appears to demonstrate a significant influence of pressure. However, on closer inspection it becomes evident that the two parameters plot as mirror images of each other, indicating that the effects of pressure cancel out. Moreover, as demonstrated by the data of Baev et al.(2), presented in Fig. 8, Eq. (4) becomes insufficient over a large range of temperatures. This is because at lower temperatures the induction process is controlled by chemical kinetics, while at higher temperatures it becomes strongly influenced by transport phenomena. This suggests that the correlation should be expressed more appropriately in terms of a sum of two Arrhenius terms, as done by DeZubey(12), namely:

$$\tau = A \exp(T_a/T) + B \exp(T_b/T) \qquad (5)$$

The data of Baev et al.(2) were obtained using a constant volume cell like ours. Their fuel, unlike ours, was maintained at room temperature. The significant difference between their data and ours shows that preheating the fuel has a significant influence in shortening the induction period.

An added comparison of interest is provided by the results of Spadaccini and Tevelde(14), obtained using a steady flow system. In their experiment, the fuel and air were rapidly mixed and the resultant induction periods were shorter than those reported by Baev et al.(2). One can attribute this difference to the effects of heterogeneity and conclude that mixing and evaporation play a significant role in the ignition process when fuel is injected into a stagnant gas in a constant volume cell. In a turbulent flow field mixing proceeds much more rapidly and its effect upon the ignition period is reduced.

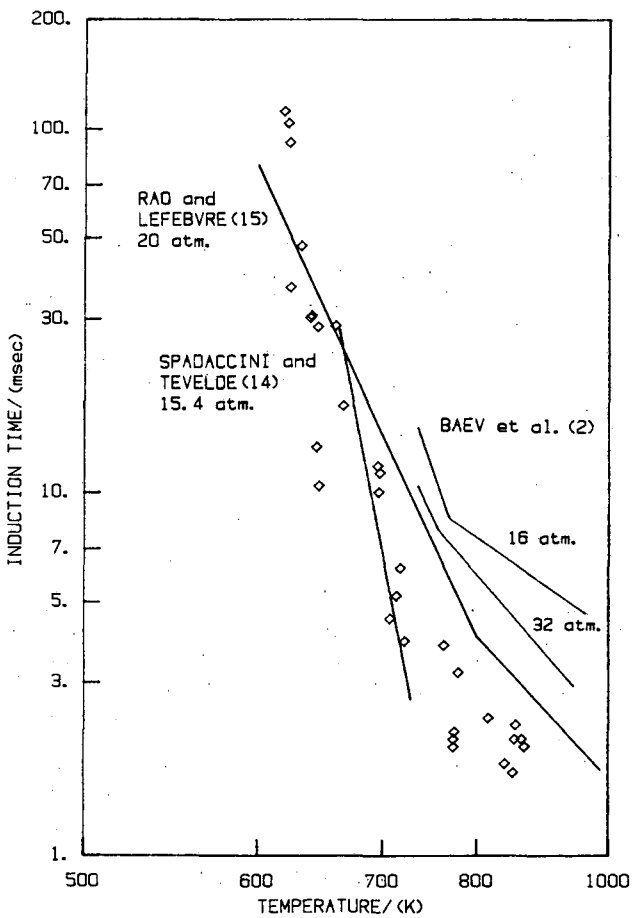

Fig. 8. Comparison of results obtained at 18.2 atm.(◊) with the data of Baev et al.(2) and Spadaccini and Tevelde(14).

At high temperatures the difference between the data of Spadaccini and Tevelde(14) and those of Baev et al.(2) becomes more pronounced, suggesting the increased importance of mixing and evaporation under these conditions. This inference is supported by high speed schlieren movies where the process was observed to change at higher temperatures from ignition of a premixed charge to diffusion controlled burning of the fuel jet. The well mixed flow data of Spadaccini and Tevelde(14) are in good agreement with ours. Thus, in addition to our earlier conclusion that in a constant volume cell the induction period is reduced significantly by preheating the fuel, this implies that the mechanisms most affected by initial fuel temperatures are, indeed, vaporization and mixing. A further justification for this conclusion is provided by comparison of our results with the correlation of Rao and Lefebvre(15) applicable to unheated fuels. At lower temperatures, where chemical kinetics dominates, the agreement is good. However, at higher temperatures, where the role of mixing and evaporation is more significant, the induction period becomes gradually overpredicted.

Further correlations are provided by Fig. 9, where the data of Ikegami et al.(3) and Walsh and Cheng(7) obtained in rapid compression machines are compared to those of Tsao et al.(4) taken in a reciprocating engine. In our case, a well specified and relatively gradient-free temperature field is established in contrast to the comparatively unspecified and spatially distorted temperature field in the rapid compression machine or in an engine.

The existence of large temperature gradients in a rapid compression machine was documented by Livengood and Leary(16) with the use of high speed schlieren films. The influence of these gradients, together with a time varying field, makes the temperature in an engine or in a rapid compression machine quite difficult to measure. Thus, typically, instead of being measured, the temperatures are evaluated as was done by Ikegami et al.(3) and Walsh and Cheng(7). In contrast to this, the mass average temperatures reported by Tsao et al.(4), measured using an infrared pyrometer, indicate that the temperature increased with engine speed. This implies that transport phenomena play a significant role in establishing the temperature within the cylinder.

It is not surprising, therefore, that there is relatively little agreement between the data of Ikegami et al.(3), Walsh and Cheng(7), Tsao et al.(4), and ours. One should note, nonetheless, that the results of Walsh and Cheng(7) obtained in a rapid compression machine with preheated and room temperature

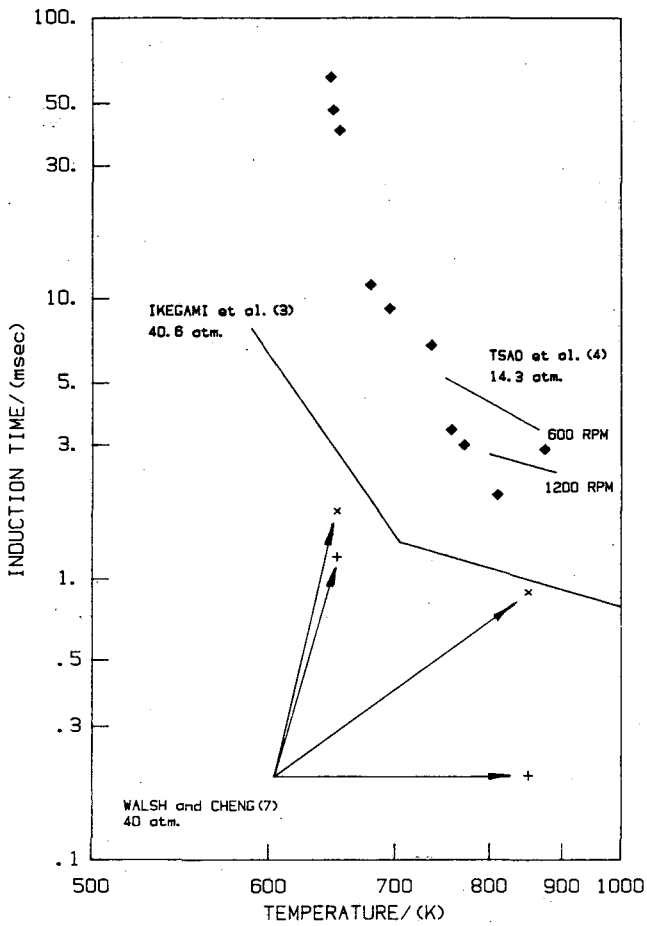

Fig. 9. Comparison of our results obtained at 28.0 atm. with the data of Ikegami et al.(3), Tsao et al(4), and Walsh and Cheng(7).
♦ - our results, ✕ - Walsh and Cheng(7) with room temperature fuel, + - Walsh and Cheng(7) with fuel preheated to the temperature of the air.

fuel display the same trend as exhibited by our data in comparison to those of Baev et al.(2). In all cases, preheating the fuel leads to a significant decrease in induction period. In addition, the results of Ikegami have a distinct knee in the curve, similar to that exhibited by the data of Baev et al.(2), confirming our conclusion that mixing and vaporization acquire a dominant role at high temperatures.

Finally, we wish to comment on the dependence on engine speed reported by Tsao et al.(4), as displayed in Fig. 9. This, in our opinion, is partially due to the fact that the temperature was measured for this purpose at the start of injection. Engine speed, on the other hand, influences the rate of additional temperature increase due to compression. Consequently at higher speeds the induction period corresponds de facto to a higher temperature, bringing the data of Tsao et al.(4) into a reasonable agreement with those of Baev et al.(2).

CONCLUSIONS

1. The induction period, τ, for ignition of preheated n-dodecane injected into air in a constant volume cell measured at a pressure level of 4.4 to 28.0 atm. and over the temperature range of 600 to 875K displays an Arrhenius type behavior, so that

$$\tau = A \exp(T_a/T)$$

where $A = 2.69 \times 10^{-8}$ sec. and $T_a = 9032$ K.

2. The induction period under such conditions is relatively insensitive to pressure in the combustion chamber.

3. Preheating the fuel before injection has a significant influence in shortening the induction period by diminishing the vaporization and mixing times.

4. At higher temperatures, the heterogeneous effects due to transport phenomena become increasingly dominant.

ACKNOWLEDGMENT

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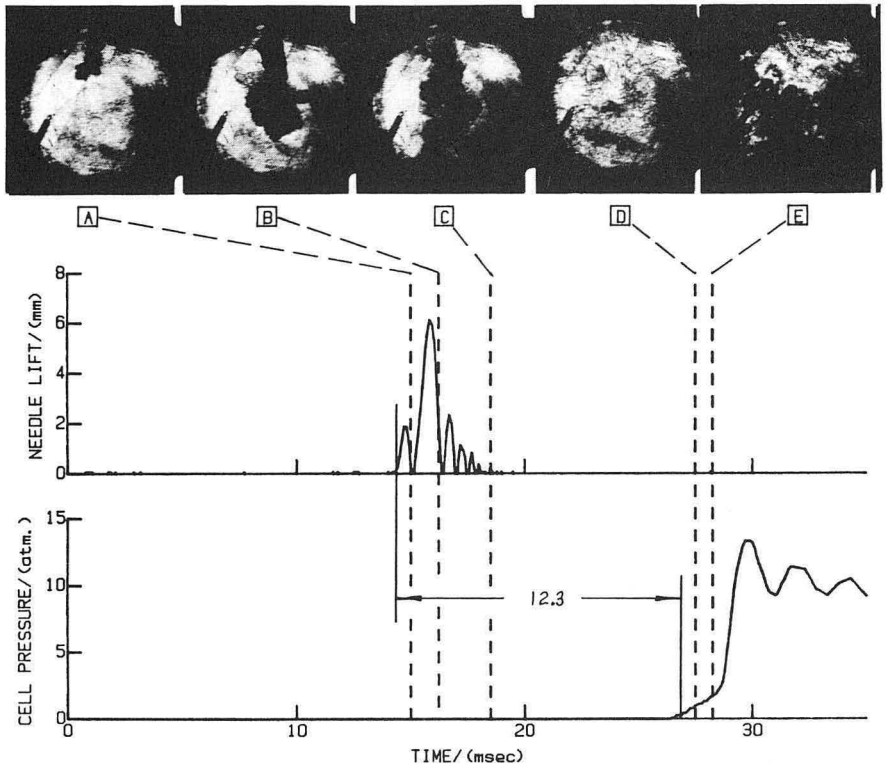

Plate 1. Excerpts of cinematographic schlieren movies for P_i= 7.8 atm. and T_i=699K, with concomitant needle lift and cell pressure records yielding the value of induction period.

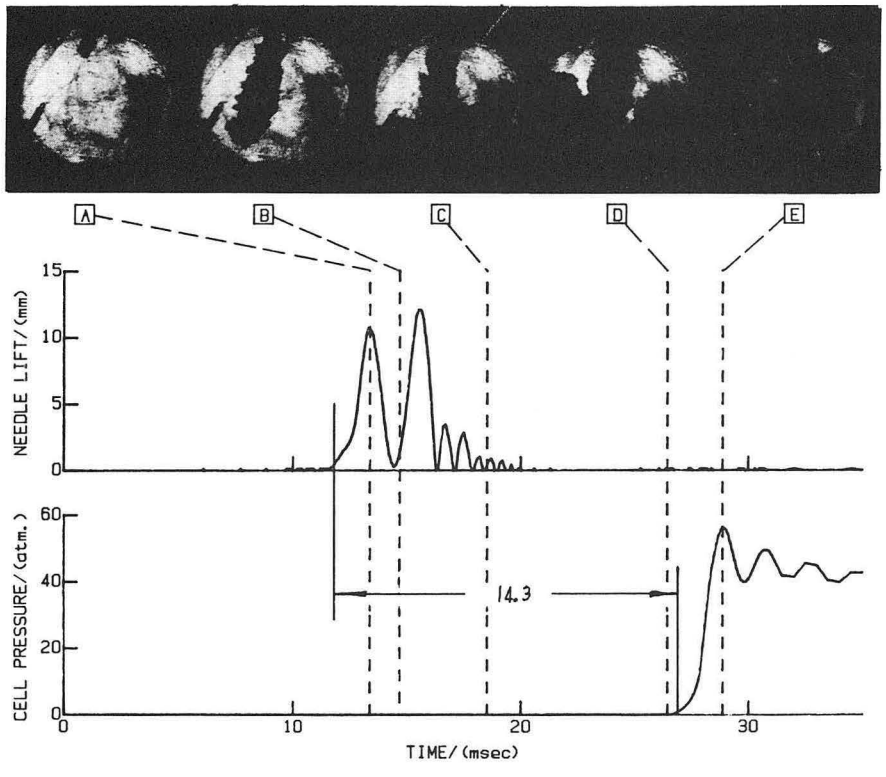

Plate 2. Experimental records for P_i= 21.4 atm. and T_i=684K.

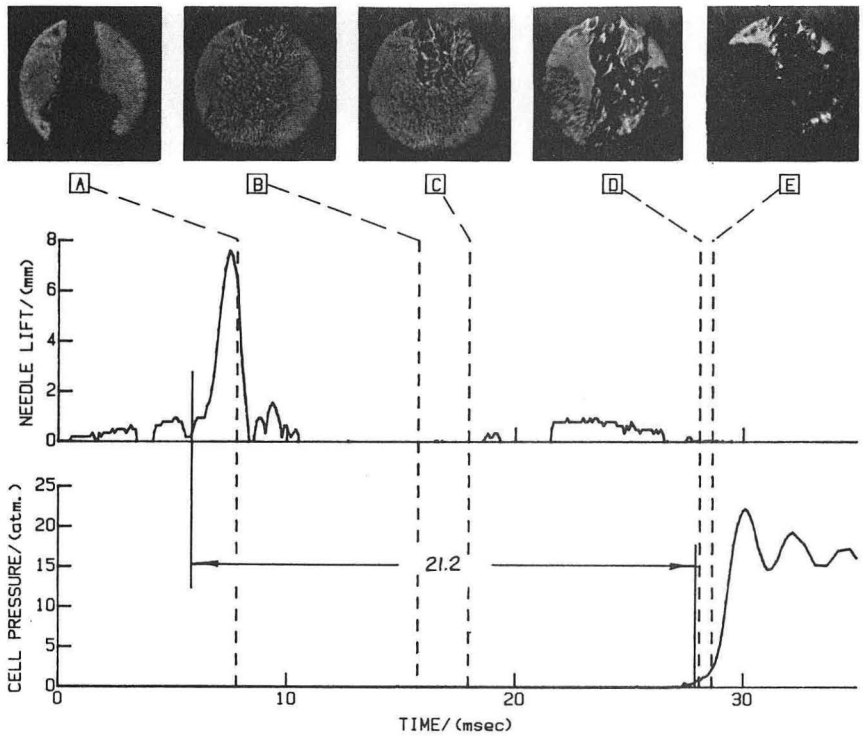

Plate 3. Experimental records for P_i=14.6 atm. and T_i=655K.

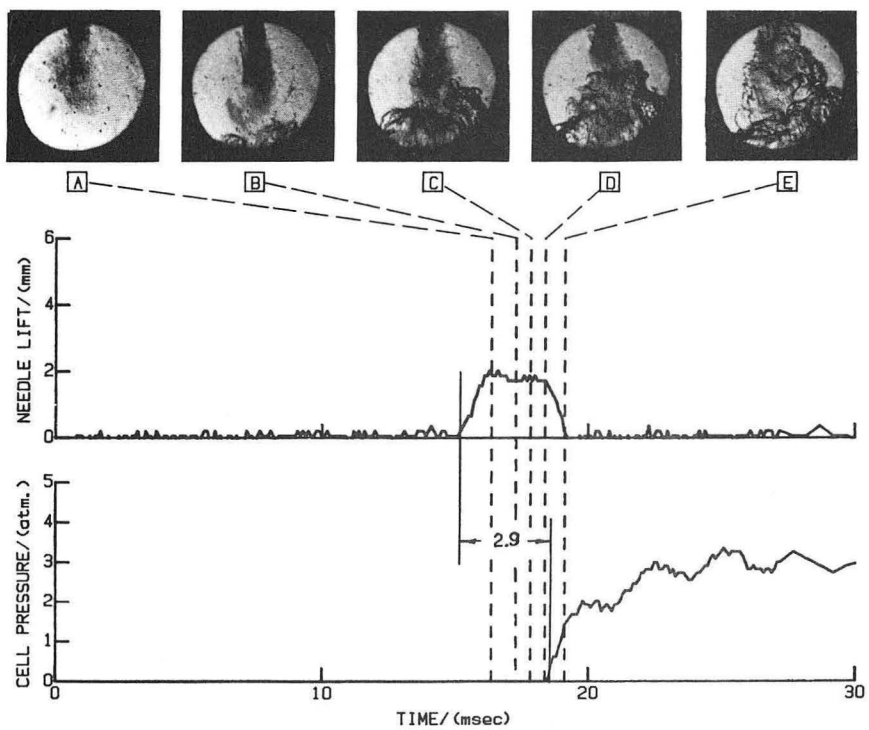

Plate 4. Experimental records for P_i=28.2 atm. and T_i=873K.

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