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## SPONTANEOUS IGNITION CHARACTERISTICS OF

### GASEOUS HYDROCARBON-AIR MIXTURES

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Experiments are conducted to determine the spontaneous ignition delay times of gaseous propane, kerosine vapor, and n-heptane vapor in mixtures with air, and oxygen-enriched air, at atmospheric pressure. Over a range of equivalence ratios from 0.2 to 0.8 it is found that ignition delay times are sensibly independent of fuel concentration. However, the results indicate a strong dependence of delay times on oxygen concentration. The experimental data for kerosine and propane demonstrate very close agreement with the results obtained previously by Mullins and Lezberg respectively.

#### INTRODUCTION

Spontaneous ignition is a process whereby a combustible mixture undergoes chemical reaction leading to the rapid evolution of heat, in the absence of any concentrated source of ignition such as a flame or spark. In some practical combustion devices, such as the lean premix/prevaporize combustor which is now being actively developed for advanced aircraft gas turbine engines, spontaneous ignition must be avoided at all costs, since it could damage combustor components and produce unacceptably high levels of pollutant emissions (refs. 1 and 2). On the other hand spontaneous ignition is sometimes relied upon to provide the main source of ignition, as in the compression ignition-engine.

Spontaneous ignition delay may be defined as the time interval between the creation of a combustible mixture, say by injecting fuel into air at high temperature, and the onset of flame. In view of their practical importance, measurements of ignition delay times have been conducted for many fuels, over wide ranges of ambient conditions and in a variety of test vehicles, including constant volume bombs, rapid-compression machines, reciprocating engines, shock tubes, and continuous flow devices (refs. 3-14). The test methods employed and the results obtained are described in reviews by Mullins (ref. 3) and, more recently, by Spadaccini and Te Velde (ref. 5).

Although the subject of spontaneous ignition of liquid fuels has received considerable attention in the past, the role of fuel evaporation in the overall spontaneous ignition process is still unclear. It was decided, therefore, to conduct a series of experiments using only gaseous or vaporized fuels, sometimes with the injection of additional oxygen into the flowing air stream, in order to obtain more accurate data on chemical delay times under conditions where the effects of fuel evaporation are excluded. Having determined the role of chemical kinetics in the spontaneous ignition process, the second phase of the research would then comprise a number of carefully-designed experiments, using one or more liquid fuels, in which fuel evaporation time is varied systematically over a wide range while maintaining the chemical reaction time constant. This could be achieved, for



example, by conducting a series of measurements of ignition delay time, for several different values of mean fuel drop size (between 20 and 200 microns), while maintaining constant values of air flow rate, fuel flow rate, air pressure and air temperature. The results of these experiments, in conjunction with theoretical analyses, should then lead to expressions for the spontaneous ignition times of hydrocarbon fuel/air mixtures that take full account of all the physical and chemical properties of relevance to the gas turbine.

The main purpose of this paper is to present the results of some preliminary tests that have been carried out at atmospheric pressure using gaseous fuel-air mixtures.

## EXPERIMENTAL

The apparatus employed in the measurement of spontaneous ignition delay time is shown schematically in Fig. 1. Air is supplied from a high pressure blower, the air flow rate being controlled by an electrically-activated pintle valve fitted into the blower inlet duct. Air flow rates are calculated from the dynamic pressure measured in the throat of a bell-mouth orifice through which inlet air enters the blower.

Two separate heaters are employed to raise the temperature of the incoming air. A preheat section contains two heaters which consist of coiled ni-chrome resistance wire wound helically around four ceramic support tubes. Each of these preheaters operates at 3.5 kW, and can be turned on or off independently of the main heater. The main air heater consists of three hairpin-formed, incolloy-sheathed, "cal-rod" heating elements. These elements have a maximum sheath temperature of 1150 K and a maximum input power of 15 kW. Feedback proportional control is used on the main heater. Both heating sections are heavily insulated.

The fuel injector designed for the experiments on gaseous fuels and fuel vapors is illustrated in Fig. 2. For ease of manufacture and assembly, and to ensure structural integrity, a square tube matrix was constructed to provide the best distribution of holes as dictated by the round cross-section of the pipe. The location of each of the twenty-five fuel injection points was determined by dividing the cross-sectional area of the pipe into twenty-five sections of equal area and locating an injection point as close as possible to the center of each section. The objective was to achieve rapid mixing of fuel and air and to attain a uniform mixture strength in the fuel/air mixture entering the test section.

The fuel delivery system for vaporized fuels is illustrated in Fig. 3. Fuel is pumped from a reservoir to the fuel vaporizer/heater in the test cell. The liquid fuel-flow rate is monitored using a rotameter and is regulated by means of a throttle valve. A back pressure valve is installed at the vaporizer exit to eliminate the tendency of the vaporized fuel flow to surge due to small pressure fluctuations in the vaporizer. Since the vaporizer does not respond well to flow transients, the fuel cut-off valve (located just upstream of the injector) is equipped with an exhaust line to allow continuous fuel flow, as well as visual determination of complete vaporization.

The test section consists of a single length of drawn stainless steel tubing, having an internal diameter of 6.22 cm. Various lengths of tubing are available and can be joined together or interchanged to vary the length of the test section. Each segment is jacketed by a thick layer of insulating material to minimize the

axial temperature gradient in the flowing mixture. The test section is instrumented with four shielded, stagnation-type thermocouples, located along the axis of the tube. The axial locations of the four thermocouples are as follows: 1 - at the fuel injection plane, 2 - 18 cm downstream of the fuel injection plane, 3 - halfway down the test section, and 4 - at the end of the test section. Thermocouples 3 and 4 are withdrawn when ignition delay times are being measured.

### Test Procedure

The experimental procedure developed to determine ignition delay times is as follows. Initially flow conditions are set at predetermined values of velocity, temperature, and equivalence ratio, and the mixture temperature is then slowly increased. The onset of spontaneous ignition is manifested as a clearly visible cool flame, accompanied by the odor of aldehydes in the exhaust gases. (Mullins reported this same phenomenon (ref. 3)). Spontaneous ignition first appears at a distance of thirty to fifty centimeters downstream of the exit of the test section as intermittent flashes of flame. As the mixture temperature continues to increase the flame becomes stable and its location moves slowly upstream. The flame assumes the shape of a cone with its apex pointing upstream, and has an attached flame brush extending downstream. The mixture temperature is allowed to increase until the tip of the flame is located near to the exit of the test section. At this point the inlet air temperature and the mixture temperature at one or more axial locations are recorded. Fuel flow is abruptly terminated, and temperature are again recorded at various axial locations in the test section. The delay time is then obtained as the length of the test section divided by the average velocity in the test section.

The initial mixture temperature,  $T_m$  cannot be measured directly because mixing takes a small, but finite length, so some other method of determining the initial temperature must be employed. The method that was chosen is to use a temperature measured at a distance downstream of the fuel-injection plane where the results of detailed temperature surveys showed that mixing is just complete. This temperature is then extrapolated back to obtain the true initial value of  $T_m$ , using as a baseline the axial temperature profile as measured at several stations along the test section with the fuel turned off. The procedure is illustrated in figure 4, which shows that the initial value of  $T_m$  is determined by lowering the baseline temperature profile until it passes through  $T_{ref}$ .  $T_{ref}$  is then taken as the temperature where the shifted profile intersects the temperature axis. If the test section were perfectly insulated this procedure would be superfluous because  $T_m$  would be equal to  $T_{ref}$ . However, as a finite heat loss occurs, despite the thick layer of external insulation, the above procedure is necessary and is considered satisfactory.

One drawback to this method is that the temperature profile of the reacting mixture is not exactly the same as that for air only. By plotting the actual mixture temperature profile and subtracting from it the air-only profile a graph is obtained depicting the temperature rise due to reaction, as shown in figure 5. To minimize errors due to this effect it is necessary to keep  $x_{ref}$  small, although it must be large enough to ensure that the temperature measurement carried out at  $x_f$  is downstream of the mixing region. It would be desirable to measure the axial temperature profile for each data point, but this is impractical due to the problems that would arise from insertion of the thermocouple into the flowing mixture. Insertion of a thermocouple at the upstream end of the working section would affect the fuel-air mixing process, while its presence further downstream could easily induce premature autoignition of the mixture.

In order to determine whether the presence of the flame front can influence ignition delay times by supplying heat or active species to the incoming fresh mixture, a nitrogen quench system was installed. This system includes a solenoid valve which can be opened and closed very rapidly to inject a transient flow of cold nitrogen gas into the test section. Injection of nitrogen causes the auto-ignition flame to vanish, but when the nitrogen flow is abruptly terminated the flame reappears instantly at its original location. This suggests that the presence of the flame has no discernible effect on ignition delay times, which is consistent with the observations of Spadaccini (ref. 9).

Although the flame position tends to remain fairly constant it occasionally leaps forward a few centimeters and then, almost instantaneously, returns to its original position. This phenomenon was also noticed by Mullins (ref. 3) who attributed it to inadequate mixing of fuel and air, resulting in pockets of rich mixture in the flow approaching the flame. This explanation is considered unsatisfactory, at least in its application to the present investigation, partly because the results of many detailed temperature surveys have shown that mixing is complete well upstream of the autoignition flame, and also because it is generally found that ignition delay times are fairly insensitive to variations in fuel/air ratio. No attempt has been made to study this phenomenon because it only occurs during the phase when the mixture temperature is being slowly raised in order to coax the autoignition flame toward the exit of the test section. Close to the test section the flame position usually remains quite steady so that measurements of ignition delay time can be made with good accuracy.

#### RESULTS

From global reaction rate considerations the chemical ignition delay time can be expressed as

$$\tau \propto \exp(E/RT_m) [\text{Fuel}]^m [\text{Oxygen}]^n \quad (1)$$

where  $\tau$  = ignition delay time, ms  
 $T_m$  = initial mixture temperature, K  
 $E$  = global activation energy, kcal/kg. mol.  
 $R$  = universal gas constant, kcal/kg. mol -K  
 $[\text{Fuel}]$  = fuel concentration  
 $[\text{Oxygen}]$  = oxygen concentration

The form of equation (1) suggests that a plot of  $\ln \tau$  versus  $1/T_m$  should yield a straight line with a positive slope, and this is borne out by the results shown plotted in figure 6 for propane-air mixtures at a constant equivalence ratio of 0.5. The line displayed in this figure is drawn through three sets of data points corresponding to three different lengths of test section. The value of activation energy,  $E$ , calculated from the slope of this line is 38,200 kcal/kg. mol.

It is of interest to observe that all the data points lie in close proximity to the line drawn in figure 6. This is in marked contrast to the results of a previous investigation where it was found that ignition delay time was very dependent on the

length of the test section employed (ref. 15). This problem was attributed to excessive heat loss from the duct walls and was overcome effectively by increasing the internal diameter from 2.54 to 6.22 cm, and by applying a thick layer of insulating material to the outer pipe wall.

The results obtained using mixtures of vaporized kerosine with air are shown in Fig. 7. The straight line drawn through the data points in this figure corresponds to a value for E of 40,900 kcal/kg. mol.

Equivalence ratio was varied over a range from 0.2 to 0.8. For propane the results showed that equivalence ratio has an almost negligible effect on  $\tau$ , although an increase in equivalence ratio tends to produce a 'stronger' tail flame. Equivalence ratios higher than 0.8 could not be used due to problems of flashback. It was found that as the auto-ignition flame located downstream of the test section was brought slowly upstream by gradually increasing the mixture temperature, it would suddenly flash upstream and stabilize on the fuel injector, thereby obscuring any results and incurring risk of damage to the injector.

Mixtures of vaporized n-heptane and air also exhibited only a slight dependence of ignition delay time on equivalence ratio. Analysis of the results showed that  $\tau \propto [\text{fuel}]^{-0.23}$ .

The results obtained for mixtures in air of propane, vaporized n-heptane, and vaporized Jet A, are shown in Fig. 8. The equivalence ratio is 0.5 in all cases. From inspection of this figure it is apparent that all three lines run roughly parallel to each other, thereby indicating that all three fuels have about the same value of activation energy. Moreover, it is also clear that ignition delay times for propane are appreciably longer than those for Jet A.

Figures 9 and 10 show for propane and vaporized kerosine respectively the effect of replacing some of the nitrogen in the air by oxygen, while maintaining the fuel concentration constant. Analysis of the results shows that for propane  $\tau \propto [\text{oxygen}]^{-0.59}$ , while for kerosine  $\tau \propto [\text{oxygen}]^{-0.65}$ .

In figure 11 the experimental data obtained in the present investigation for propane-air and Jet A-air mixtures are plotted, for the purpose of comparison, alongside the results of previous workers as compiled by Chiappetta and McVey (ref. 6). It is of interest to note that the results for Jet A (kerosine) show striking agreement with those of Mullins (ref. 3), who also conducted his experiments at normal atmospheric pressure. Equally noteworthy is the close consistency between the propane data obtained by Lezberg (ref. 14) and the results of the present experiments.

## CONCLUSIONS

From the results of experiments conducted at atmospheric pressure on the influence of mixture temperature on the spontaneous ignition delay times of mixtures with air of propane, n-heptane vapor and kerosine vapor, the following conclusions are drawn.

1. Ignition delay times can be expressed in terms of mixture temperature, fuel concentration, and oxygen concentration, by the equation

$$\tau \propto \exp [E/RT_m] [\text{Fuel}]^m [\text{Oxygen}]^n$$

2. For the fuels employed in this study the value of  $E$  is fairly close to 40,000 kcal/kg mol. For example, for propane  $E = 38,200$  kcal/kg mol., while for kerosine  $E = 40,900$  kcal/kg mol.
3. The dependence of ignition delay time on fuel concentration is quite small, i.e.  $m \approx 0$ . Of the fuels examined the strongest dependence on fuel concentration is exhibited by n-heptane, for which  $m = -0.23$ .
4. Ignition delay times are strongly dependent on oxygen concentration. For propane  $n = -0.59$ , while for kerosine  $n = -0.65$ .
5. The experimental data obtained in the present investigation for propane-air and kerosine-air mixtures are remarkably consistent with the results of previous studies by Lezberg and Mullins respectively.

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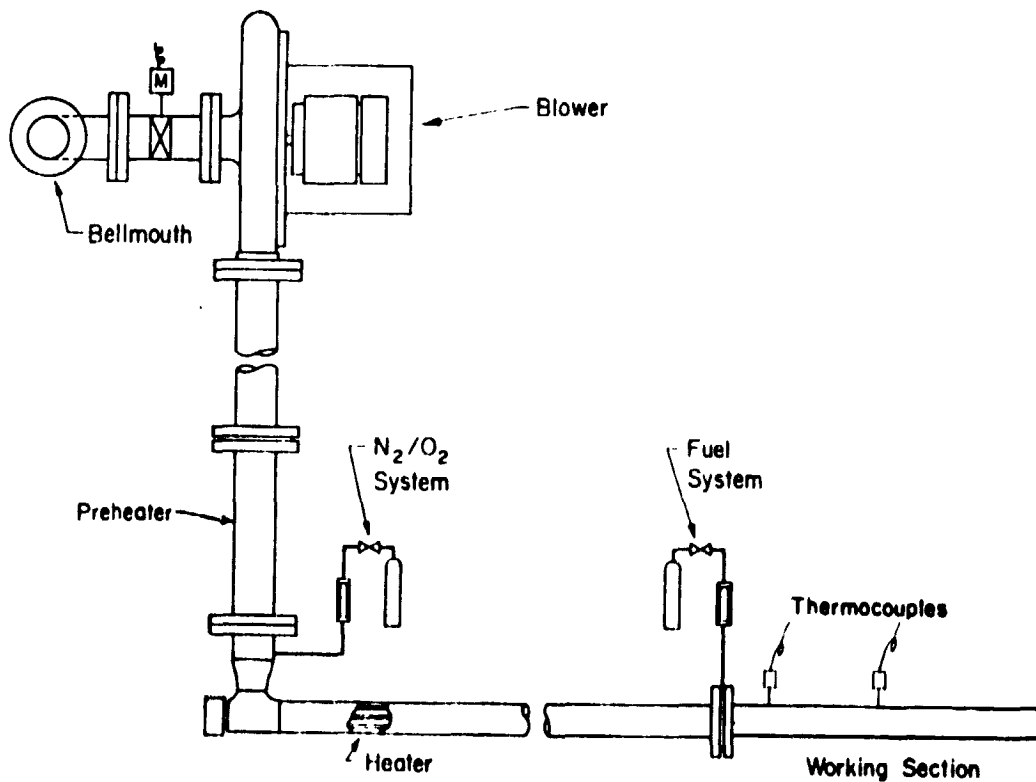
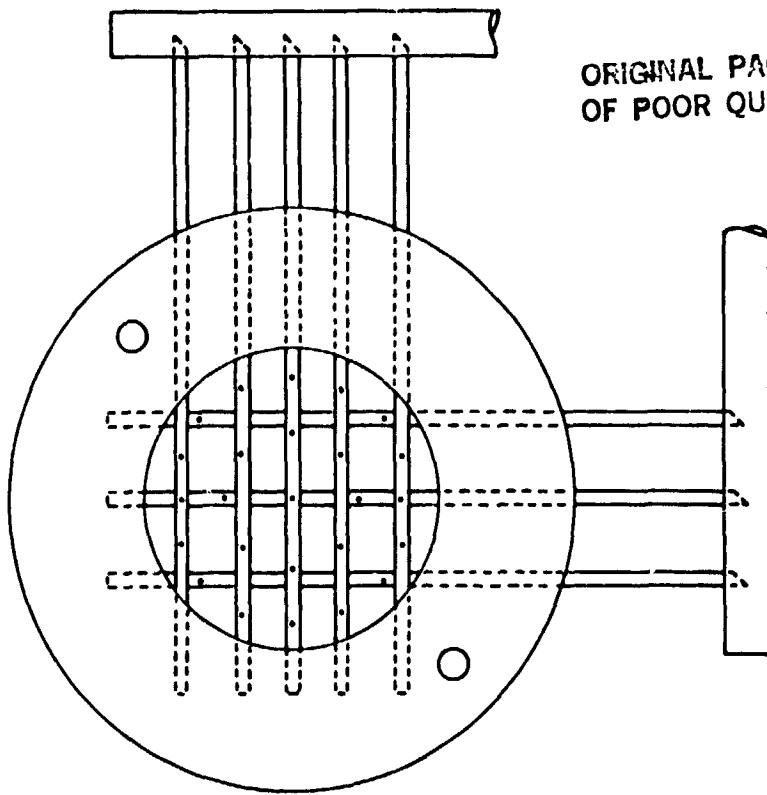


Fig. 1. Schematic diagram of test rig.



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Fig. 2. Fuel Injector

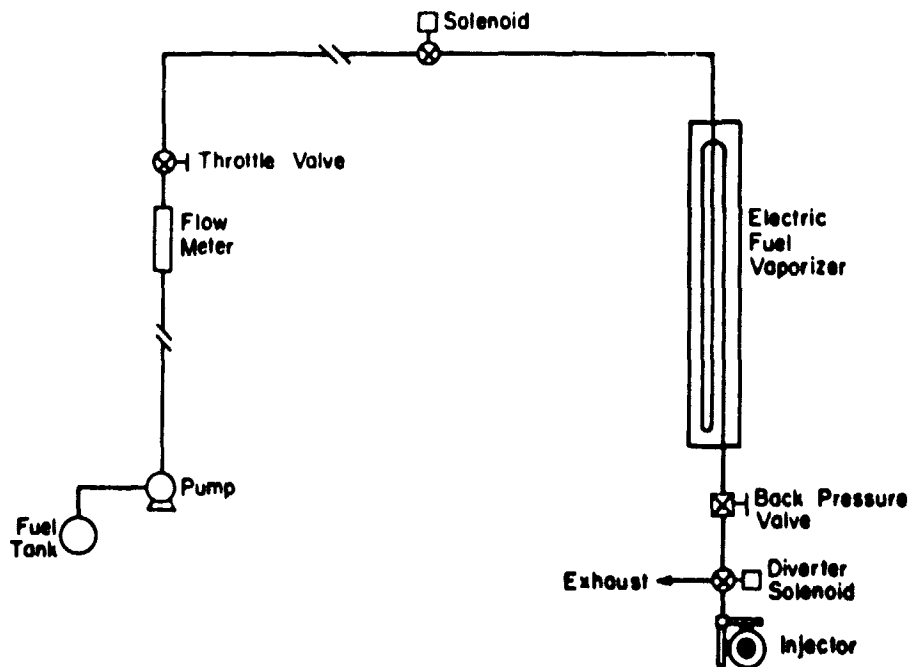


Fig. 3. Fuel delivery system for liquid fuels.



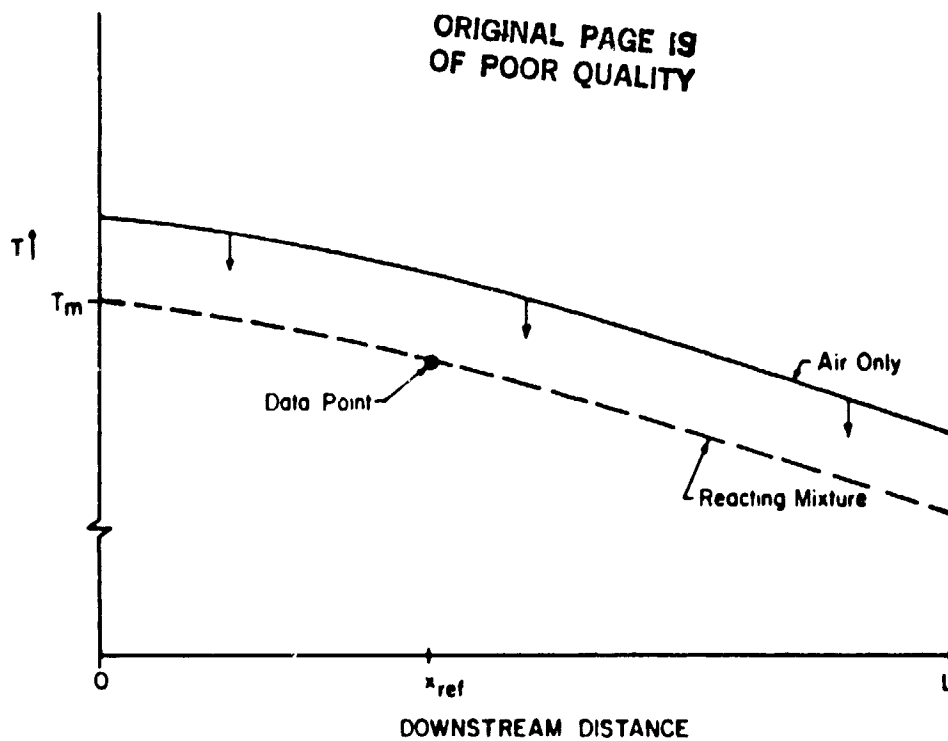


Fig. 4. Graphs illustrating method of determining initial mixture temperature.

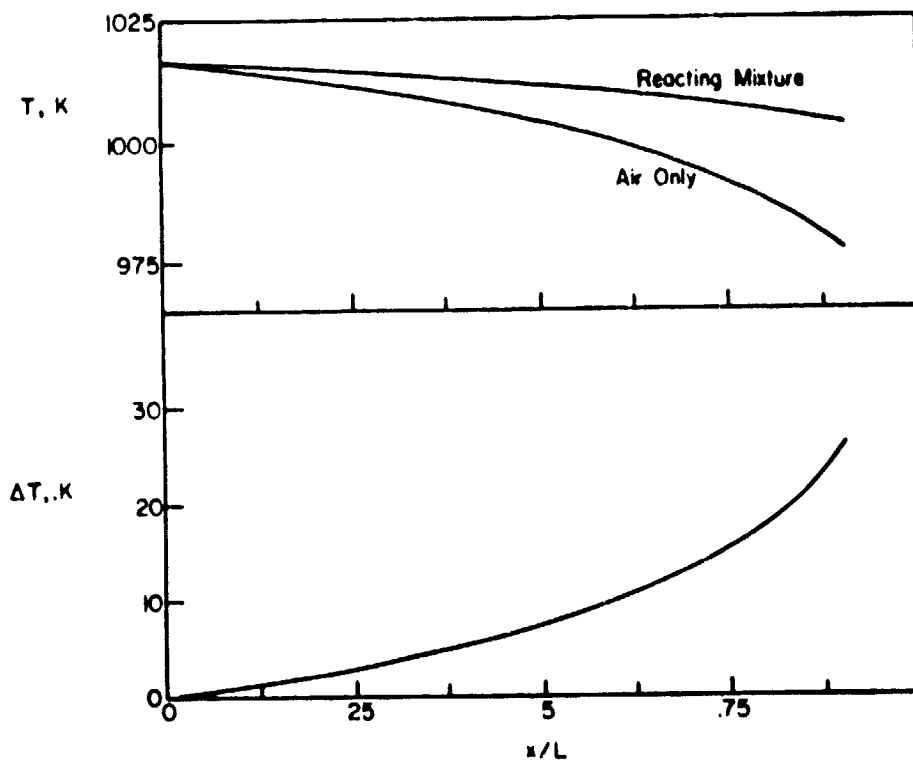


Fig. 5. Graphs illustrating preflame temperature rise as a function of axial distance.

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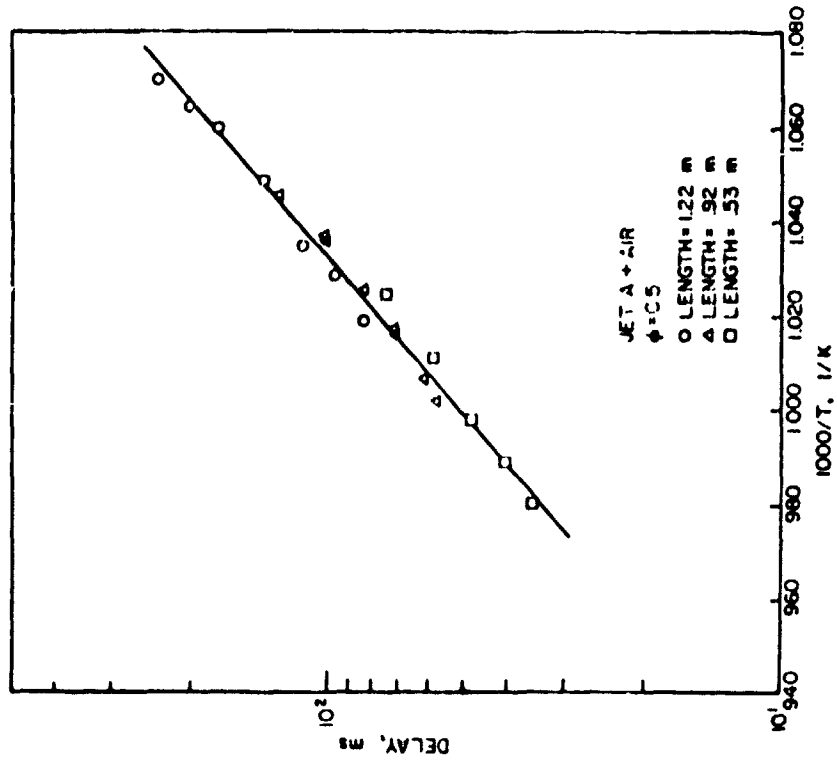


Fig. 7. Spontaneous ignition delay times for kerosene air mixtures.

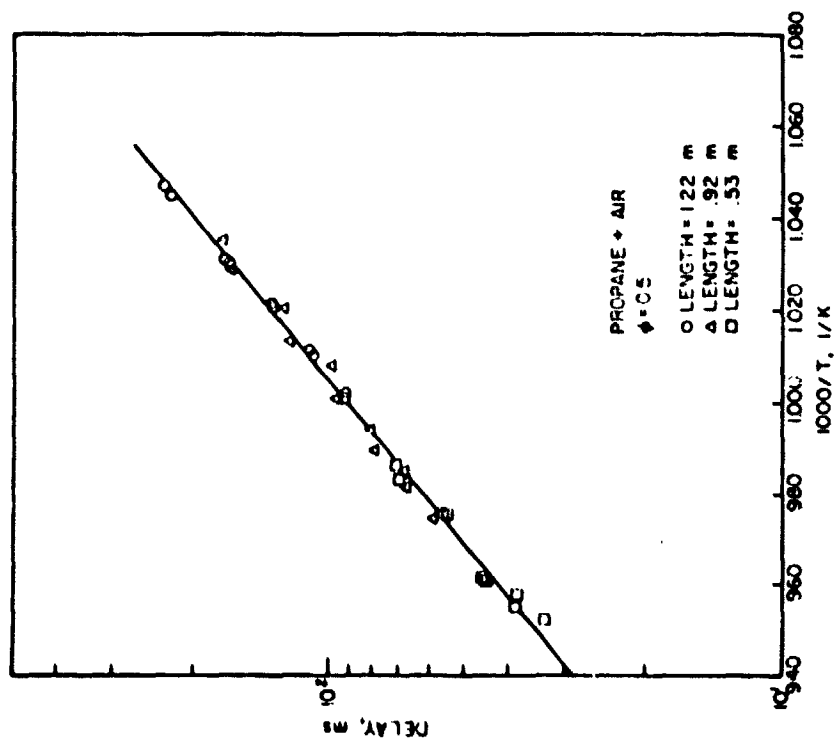


Fig. 6. Spontaneous ignition delay times for propane-air mixtures.

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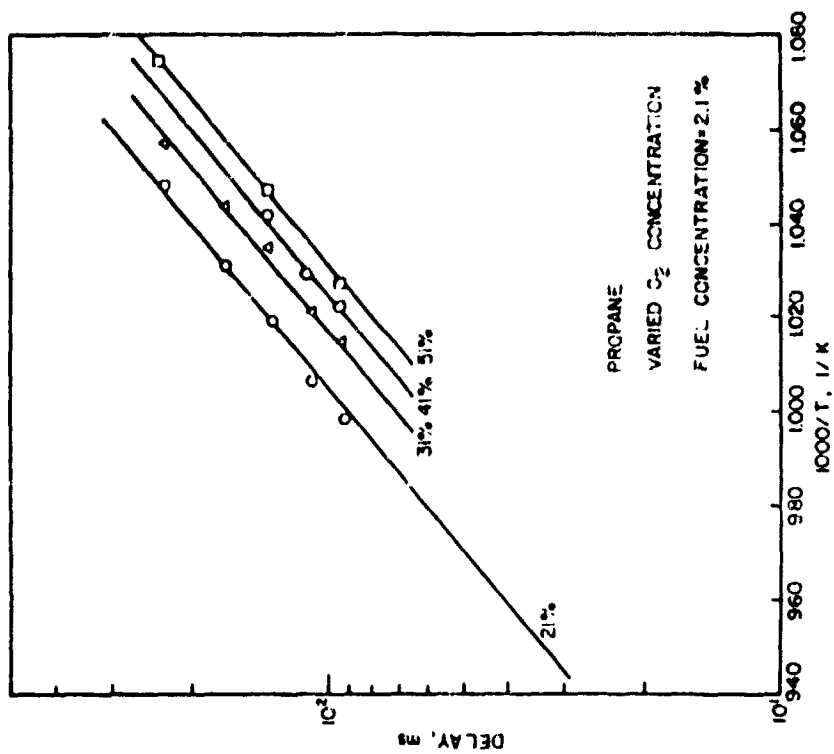


Fig. 9. Graphs illustrating influence of oxygen concentration on ignition delay times.

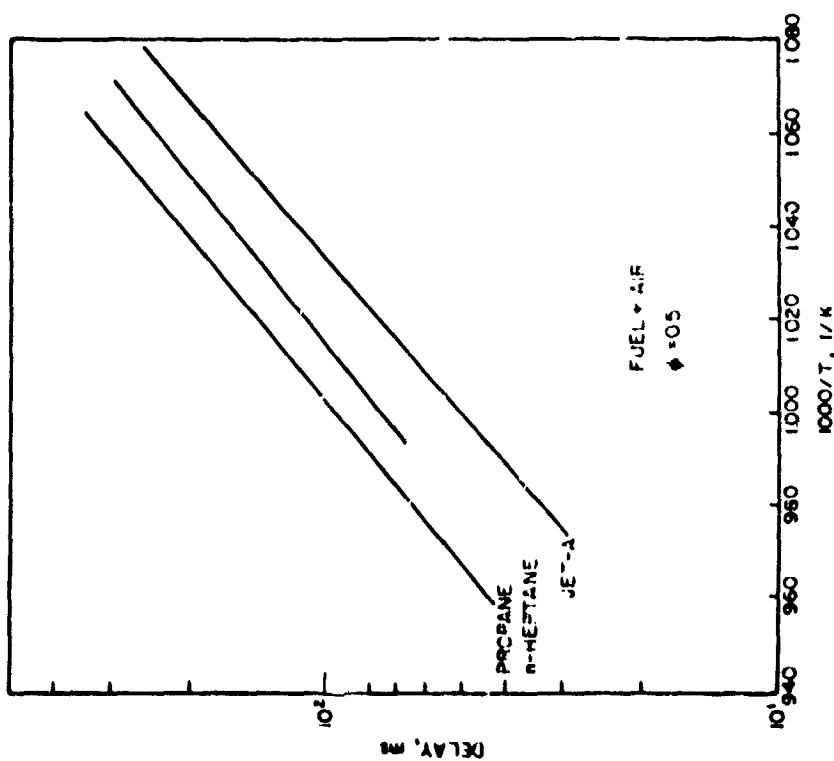


Fig. 8. Comparison of ignition delay times for various fuel-air mixtures.

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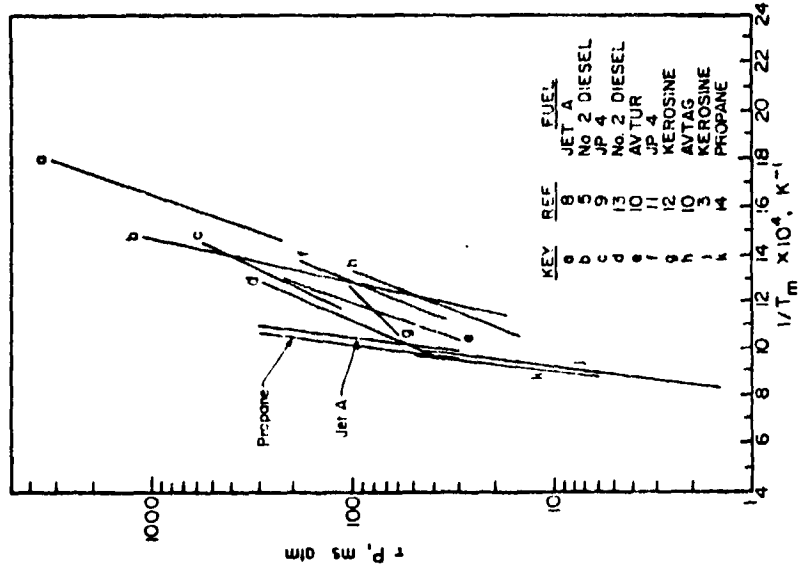


Fig. 11. Comparison of present data with results of previous workers as compiled by Chiappetta and McVey [6].

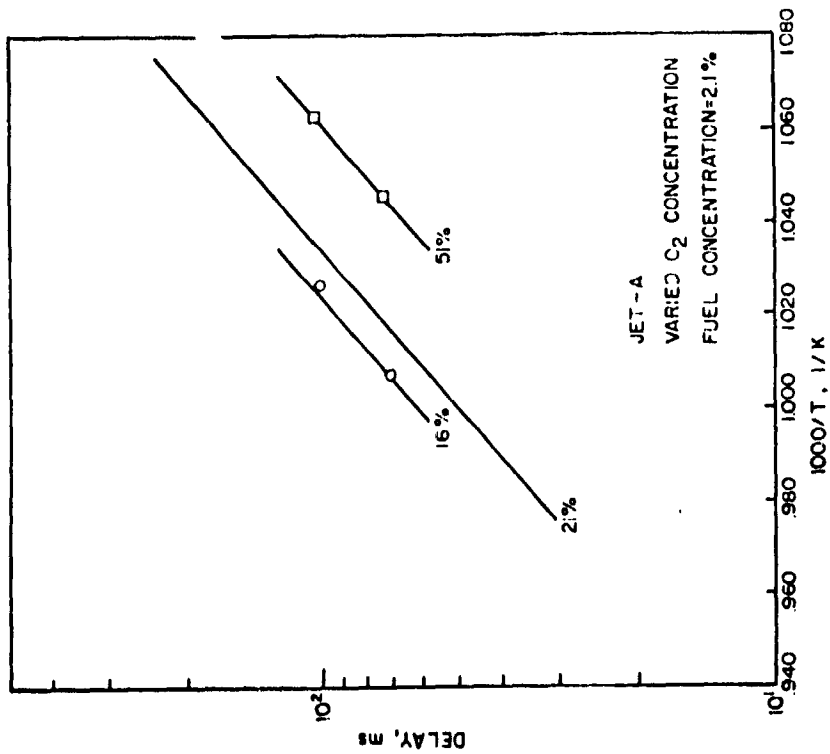


Fig. 10. Graphs illustrating influence of oxygen concentration on ignition delay times.