



## THERMAL IGNITION STUDY OF MULTI-GRADE FUELS

M.M.El-Kotb,<sup>\*</sup> S.L.Aly<sup>\*\*</sup> and Sh.M.El-Bahnasy<sup>\*\*\*</sup>

## ABSTRACT

The ignition behavior of blended fuels created by mixing different proportions of any of the three commercial liquid fuels, gasoline, kerosene and light diesel fuel, is investigated using the shock tube technique. The ignition delay of the blended fuels, based on the pressure rise criterion, is measured over a wide range of pressure, temperature and equivalence ratio. The results indicate that for all blends the thermal ignition delay decreases with the increase of temperature and pressure. The results also show that blending a heavy liquid fuel, containing high percentage of low boiling simple aromatics and naphthenes, results in remarkable decrease in ignition delay. The experimental results of the various blends are correlated using the following Arrhenius form

$$\tau = (A/p^n)\phi^m e^{E/RT}$$

The pressure exponent is found to be the same for all different blends; its value is calculated to be 1.05. The exponent of the equivalence ratio changes its sign from negative in the lean region to positive in the rich region. The activation energy of all different blends are also calculated.

## INTRODUCTION

There has been lately an ever increasing interest in developing fuels derived from blending different kinds of basic fuels to meet wider specifications and cope with the operational conditions of various types of engines. These fuel blends have more complex composition, wider and higher boiling points, viscosity and surface tension ranges.

In general, the study of combustion of fuel in engine comprises two parts. The first one deals with the various physical processes occurring to the fuel after its introduction to the engine cylinder such as the processes of atomization, vaporization and mixing with air. The second part deals with

\* Professor, \*\* Associate Professor, \*\*\* Graduate student, Mechanical Power Department, Faculty of Engineering, Cairo University, Giza, Egypt.

the chemical aspects of the combustion process, which are the ignition and oxidation processes. Regarding the chemical aspect of engine combustion, which may be called the combustion proper, the shock tube provides an excellent vehicle for studying high temperature combustion phenomena. It comes close to fulfilling the requirements of an ideal reaction vessel where the mixture is heated instantaneously and homogeneously to a known temperature, and the conditions can be approximated to an adiabatic constant volume model.

The shock tube technique has been used by several investigators to study ignition and combustion phenomena occurring over a reaction time of  $10^{-6}$  to  $10^{-3}$  seconds, and over a wide range of temperature and pressure. The majority of these studies have been carried out for light gaseous hydrocarbons [1-8], and to a lesser extent for heavier hydrocarbons [9-12]. Very little work has been done for liquid hydrocarbons such as benzene [13-15]. El-Kotb et al [16] employed the shock tube technique to study the ignition of gasoline, kerosene and light diesel fuels over a wide range of temperature, pressure and equivalence ratio. The above three fuels constitute the basic fuels from which the different blended fuels were composed for the present work, which is concerned with determining the ignition delay behavior of such blended fuels and the effect of pressure, temperature and equivalence ratio on it.

#### EXPERIMENTAL SET-UP

In the present section, a brief description of the experimental set-up and measuring technique used in the present study is presented. For greater details of this subject one can consult references [16] and [17]. The experimental set-up consists basically of the shock tube, liquid fuel mixture generator and gas mixing device. The gas mixing device is used to fill the driver section of the shock tube by a stoichiometric light gas - oxygen mixture up to 1.5 bar initial pressure. The rupture of the diaphragm is effected by the pressure rise caused by burning such mixture. The fuel mixture generator is used to prepare a mixture of the fuel vapor under study and the oxidant,  $O_2$ , at the required equivalence ratio, which filled the driven section of the shock tube.

The pressure time variation at the test section is monitored by a piezo-electric transducer, and displayed on the screen of a storage oscilloscope. This latter is triggered on the passage of the shock wave by another piezo-electric transducer located 20 cm ahead of the first one, i.e. nearer to the diaphragm. The shock wave velocity is obtained by measuring the time taken by the wave to pass from the first transducer to the second one.

#### RESULTS AND DISCUSSION

Several criteria exist for the definition of the ignition delay period. The one that has the greatest practical significance in engine combustion chambers is that based on the remarkable pressure rise. This criterion is

the one adopted in the present work. Accordingly, the ignition delay period is defined as the time interval from the instant the shock wave arrives at the second transducer, i.e. at the time the oscilloscope is triggered, to the moment of onset of pressure rise due to combustion with remarkable rate.

The multi-component fuels are produced by blending any two of the three basic fuels, gasoline, kerosene and light diesel fuel, at various proportions. Experiments were carried out to follow the variation of thermal ignition delay period of the various blends at different conditions. These conditions spanned pressure, temperature and equivalence ratio ranges between 3-7.5 bar, 1100-2300°K and 0.5-1.5, respectively.

The results and discussion of each blended group are exposed in the following subsections. It is to be noted that the variation of ignition delay with temperature and pressure is presented for equivalence ratio equal to 1. The results of variation of ignition delay with equivalence ratio are used to obtain the exponent of the ignition delay dependence on equivalence ratio.

#### Gasoline-Kerosene Blends

The variation of ignition delay period for these blends with pressure is depicted in Fig.1. It is noticed that the ignition delay is pronouncedly affected by the pressure at which ignition occurs, where it decreases remarkably with increasing the pressure. The variation of ignition delay with temperature for the same blends is shown in Fig.2. One more time, the ignition delay exhibits a considerable decrease with the increase of ignition temperature. It is to be noted from the above two figures that the ignition delay is more sensible to temperature variation than to pressure. The figures also indicate that the ignition delay of heavy blend (20% G + 80% K) is less than that of light blend (80% G + 20% K) over the same conditions, whereas the other two blends of gasoline and kerosene lie in between.

#### Gasoline-Light Diesel Fuel Blends

The variation of thermal ignition delay with pressure and temperature is shown in Figs.3 and 4, respectively. It is seen from both figures that the thermal ignition delay decreases with the increase in pressure and temperature individually. One can also observe that the curves of the various gasoline-light diesel fuel blends are more widely spaced than in gasoline-kerosene blends. Further, the ignition delay for any blend in this group is lower than the corresponding blend in the gasoline-kerosene group for the same conditions. Both figures also indicate that the heaviest blend (20% G + 80% LD) exhibits the lowest ignition delay period. They further indicate that the ignition delay decreases with the increase of molecular weight of the blend

#### Kerosene-Light Diesel Fuel Blends

Figs.5 and 6 show the variation of ignition delay of this group of blends

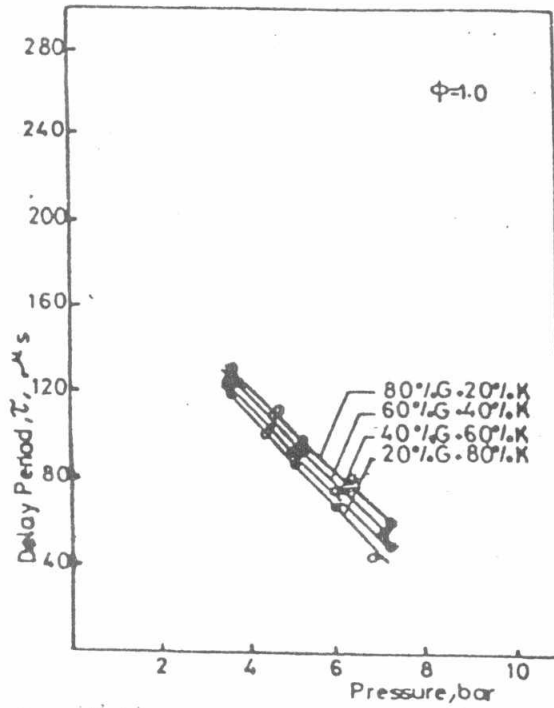


Fig.1. Variation Of Delay Period,  $\tau$ , With Pressure,  $p$ , For Gasolene-Kerosene Blends

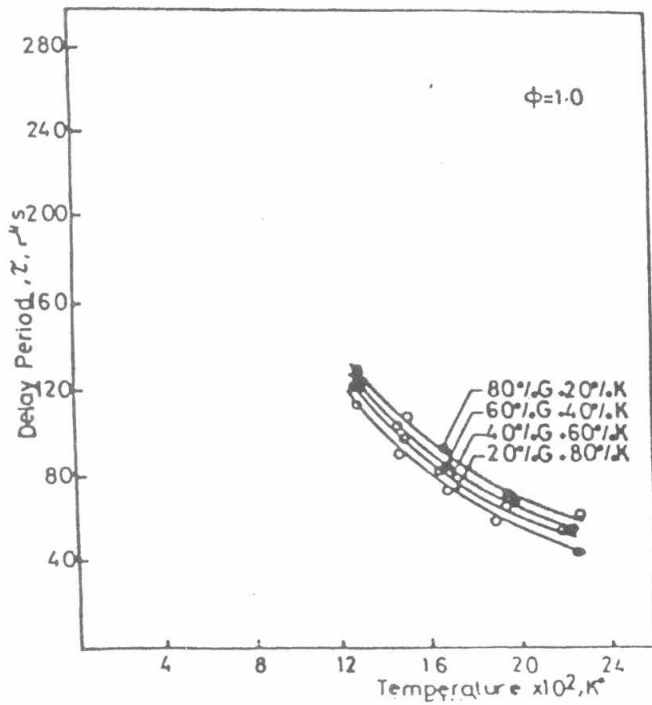


Fig.2. Variation Of Delay Period,  $\tau$ , With Temperature,  $T$ , For Gasolene-Kerosene Blends

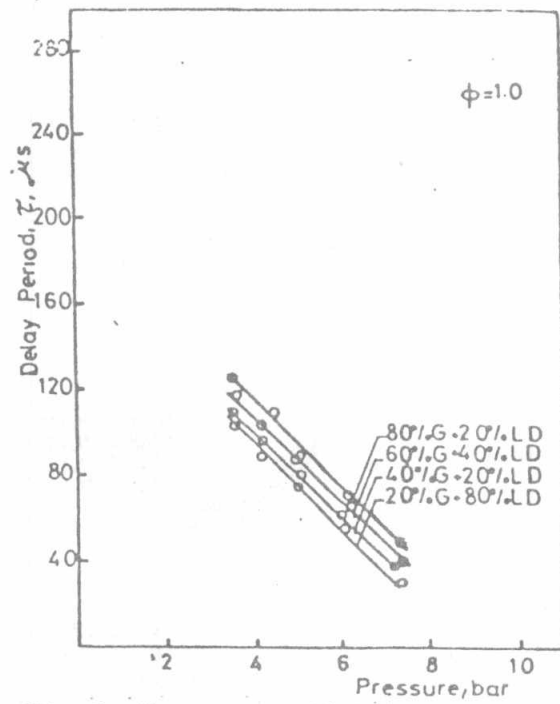


Fig.3. Variation Of Delay Period,  $\tau$ , With Pressure,  $p$ , For Gasolene-Light Diesel Blends

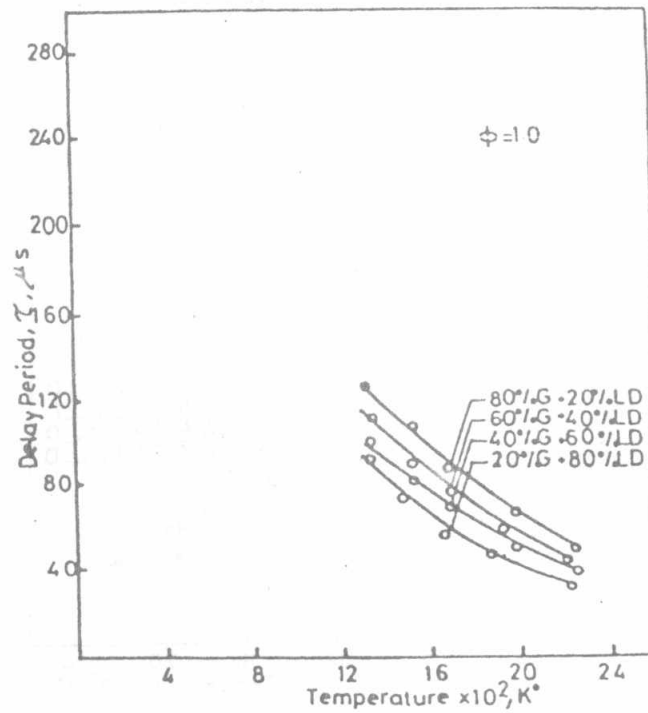


Fig.4. Variation Of Delay Period,  $\tau$ , With Temperature,  $T$ , For Gasolene-Light Diesel Blends

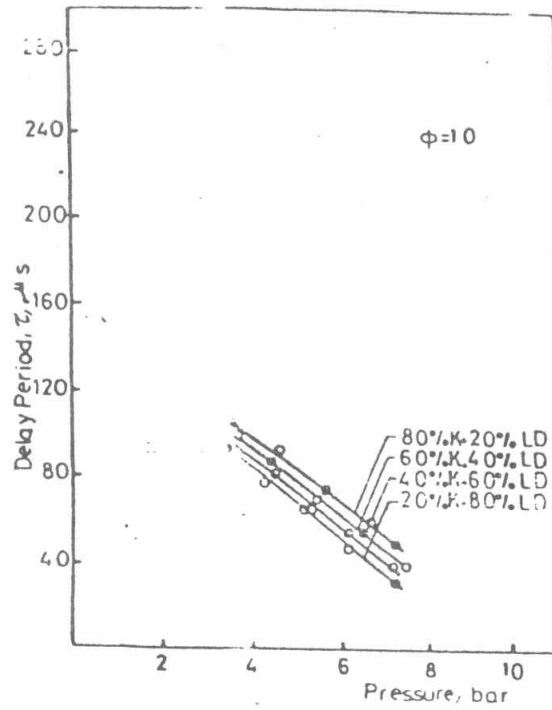


Fig.5. Variation Of Delay Period,  $\tau$ , With Pressure,  $p$ , For Kerosene-Light Diesel Blends

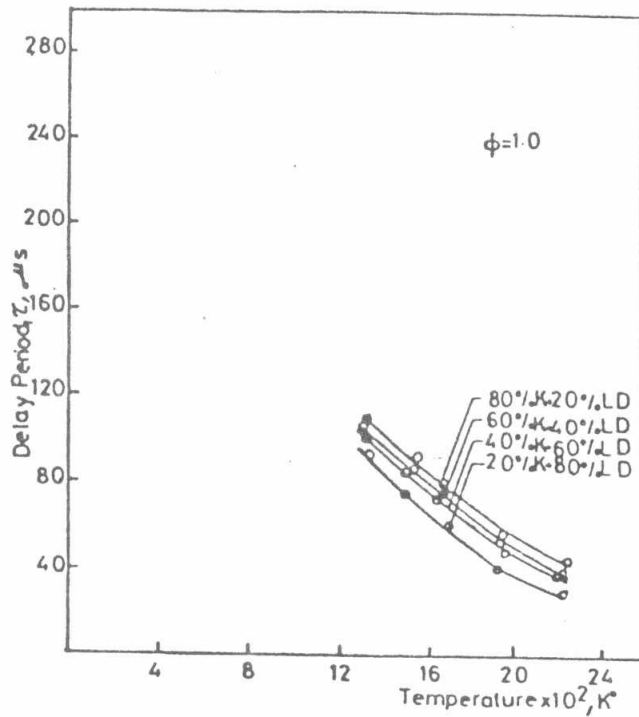


Fig.6. Variation Of Delay Period,  $\tau$ , With Temperature,  $T$ , For Kerosene-Light Diesel Blends

with pressure and temperature, respectively. From these graphs, one can easily note that the ignition delay period for all blends decreases sensibly with pressure or temperature increase. The steepest variation and lowest ignition delay are exhibited by the heaviest blend (20% K + 80% LD).

Comparing the behavior of the three previous groups one can conclude that the minimum thermal ignition delay is observed for the blends containing the largest proportion of light diesel fuel while the maximum delay is exhibited by the blends containing a large proportion of gasolene. The blends with high proportion of kerosene show an intermediate behavior. The aforescribed behavior of the various blends may be attributed to the chemical structure of each group. High proportion diesel fuel blends consist mainly of higher paraffinic hydrocarbons which can crack rather easily due to heating, forming lower hydrocarbons and high radical concentration. On the other hand, the blends containing high proportion of gasolene consist mainly of such low boiling simple aromatics and high percentage of naphthenes which crack so slowly. High percentage blends of kerosene contain proportional amounts of the previous types of hydrocarbons, and consequently show an intermediate ignition delay behavior between the gasolene and light diesel blends.

#### ANALYSIS OF RESULTS

The results of the ignition study of the various gasolene-kerosene-light diesel blends can be meaningfully presented in terms of what is known as the Arrhenius plot, in which the logarithm of the ignition delay is plotted against the reciprocal of the temperature. This is based on the celebrated Arrhenius form for the variation of ignition delay time with temperature, namely that  $\tau \propto \exp(E/RT)$ . E represents the activation energy of the fuel under test, which is an important parameter in the field of chemical kinetics. Physically, it reflects the energy required to destruct the intermolecular bonds of the fuel. It changes from a fuel to another, and for the same fuel it is highly dependent of temperature.

The results of the present work are fitted, in the least square sense, to an Arrhenius equation of the following form

$$\tau = (A/p^n)\phi^m e^{E/RT} \quad (1)$$

Thus, the results of the ignition delay data for the blended fuels appear as a straight line on the  $\ln(\tau p^n / \phi^m)$  versus  $(1/T)$  plane. The slope of such line yields the value of  $(E/R)$ .

Fig.7 depicts the plotting of  $\ln(\tau p^n / \phi^m)$  against the reciprocal of temperature for the gasolene-kerosene blends. It is clear from these graphs that the heaviest blend (20% G + 80% K) shows the lowest slope relative to the other blends in the group, indicating that the heaviest blend has the lowest activation energy.

The Arrhenius plots for the various gasolene-light diesel fuel blends are given in Fig.8. One more time, the slope of the Arrhenius plot, and consequently the activation energy, is lowest for the heaviest blend (20% G +

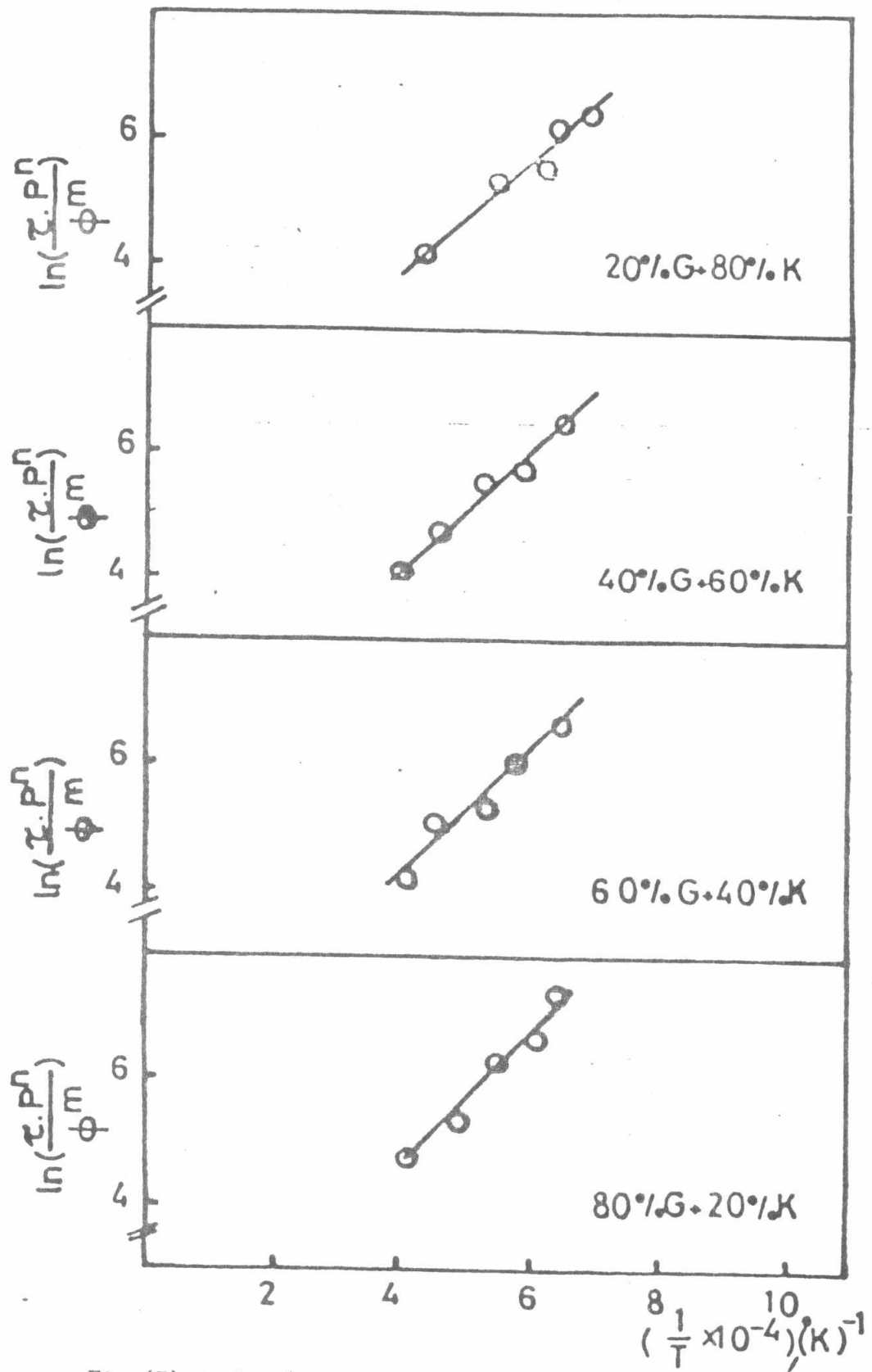


Fig.(7) Arrhenius Plot For Gasolene-Kerosene Blends



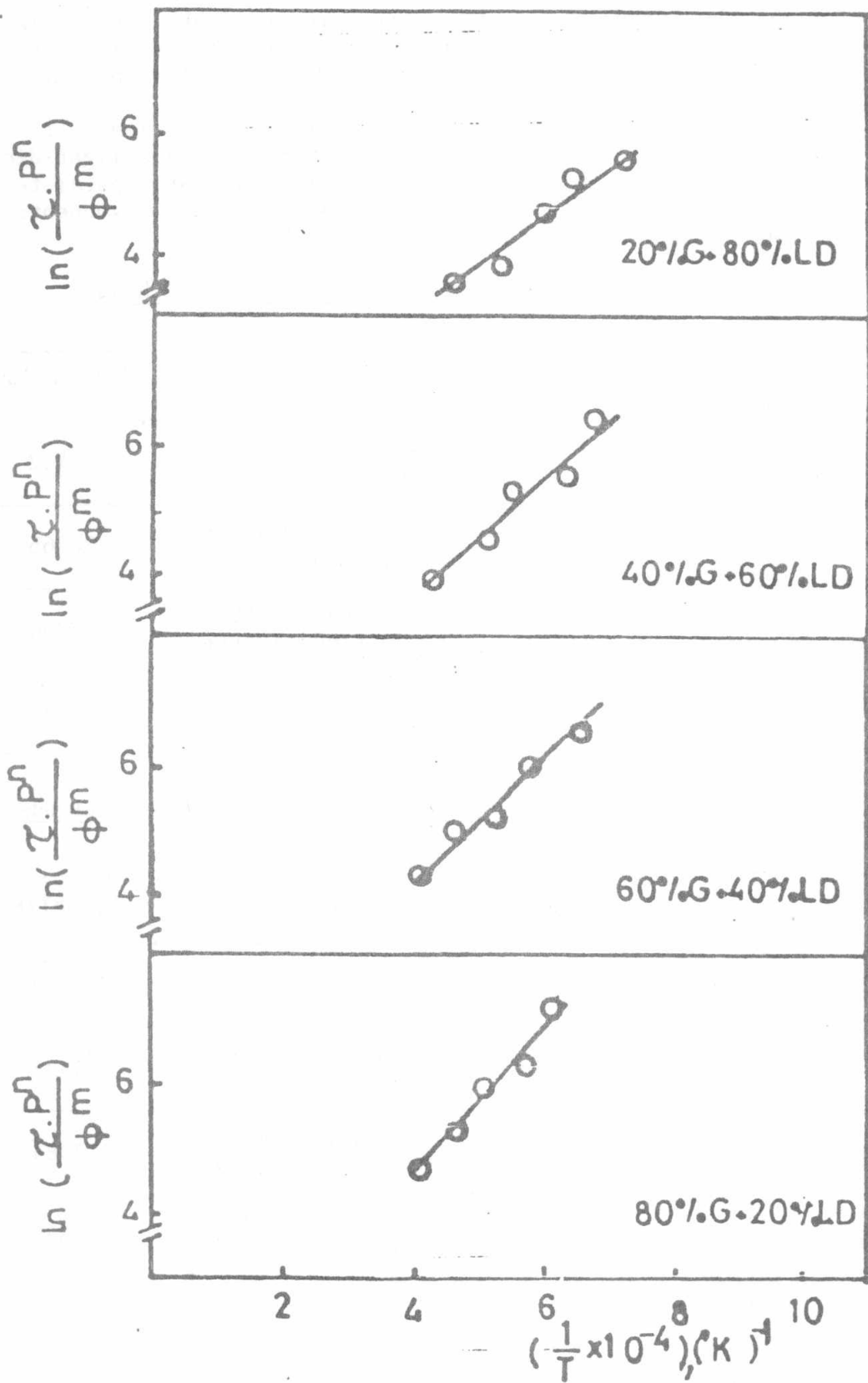


Fig.(8) Arrhenius Plot For Gasolene-Light Diesel Blends

80% LD). Finally, the Arrhenius plots for the kerosene-light diesel blends are shown in Fig.9. The notes just mentioned above for the gasolene-kerosene and gasolene-light diesel blends are also applicable for this mixture.

The values of the various parameters of the various studied blends are given in tables 1, 2 and 3 for the gasolene-kerosene, gasolene-light diesel and kerosene-light diesel blends, respectively. The calculated parameters are the activation energy, the pressure and equivalence ratio exponents and the preexponential factor.

Table 1 Ignition delay parameters for gasolene-kerosene blends

Fuel	A	n	m	E, Kcal/Kmol
80%G+20%K	0.013	1.05	-0.42 lean mixture +0.82 rich mixture	22452
60%G+40%K	0.025	1.05	-0.41 lean mixture +0.75 rich mixture	20365
40%G+60%K	0.042	1.05	-0.39 lean mixture +0.70 rich mixture	18258
20%G+80%K	0.092	1.05	-0.39 lean mixture +0.70 rich mixture	15981

Table 2 Ignition delay parameters for gasolene-light diesel blends

Fuel	A	n	m	E, Kcal/Kmol
80%G+20%LD	0.0164	1.05	-0.33 lean mixture +0.83 rich mixture	21589
60%G+40%K	0.0299	1.05	-0.55 lean mixture +0.74 rich mixture	19337
40%G+60%K	0.0556	1.05	-0.63 lean mixture +0.80 rich mixture	17684
20%G+80%K	0.1001	1.05	-0.66 lean mixture +0.81 rich mixture	14832

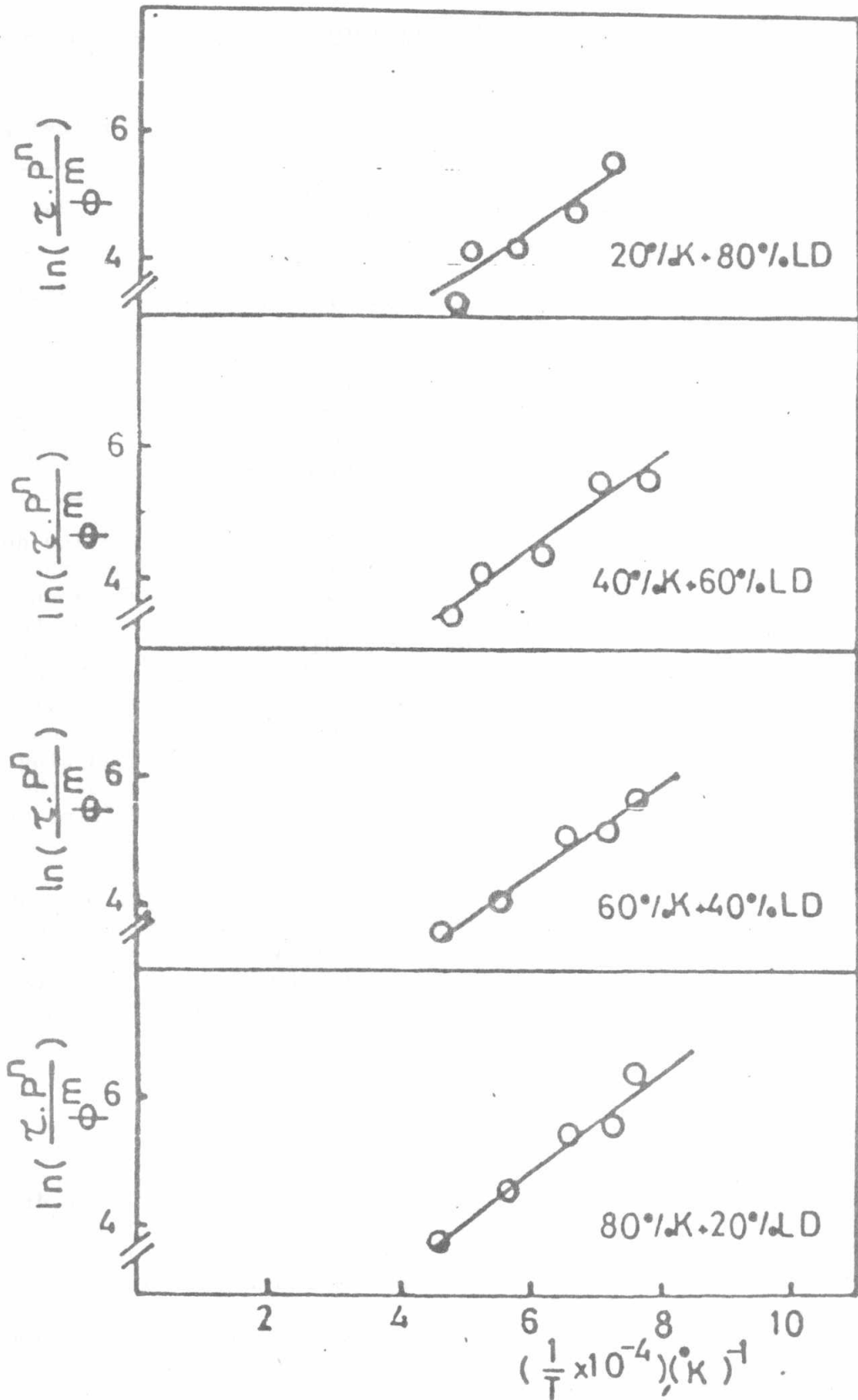


Fig.(9) Arrhenius Plot For Kerosene-Light Diesel Blends

Table 3 Ignition delay parameters for kerosene-light diesel blends

Fuel	A	n	m	E, Kcal/Kmol
80%K+20%LD	0.1782	1.05	-0.43 lean mixture +0.58 rich mixture	13441
60%K+40%LD	0.1796	1.05	-0.48 lean mixture +0.62 rich mixture	13228
40%K+60%LD	0.1819	1.05	-0.56 lean mixture +0.69 rich mixture	13022
20%K+80%LD	0.1852	1.05	-0.59 lean mixture +0.72 rich mixture	12799

Looking into the previous three tables one can see that the ignition delay is almost invariably inversely proportional with pressure. As for the variation with the equivalence ratio, the negative and positive exponents for the lean and rich mixtures, respectively, reflect the fact that the ignition delay is minimum at stoichiometric condition, and starts increasing on both sides of stoichiometric condition. The extent of such increase differs with the various blends as indicated by the various numerical values of these blends. Concerning the activation energy, the previous tables indicate clearly what has been pointed out to earlier regarding that its value decreases with the increase of fuel weight. The value of the activation energy of the fuel reflects also the extent of the effect of temperature on ignition delay.

Investigating further the results of the previous three tables, one can notice that when blending either kerosene or light diesel fuel with gasoline the values of E/R for both types of blends vary linearly with gasoline percentage as depicted in Fig.10. Moreover, the value of the parameter A decreases with the increase of gasoline percentage as shown in Fig.11.

### CONCLUSIONS

In view of what has been presented the following conclusions can be drawn

1. The shock tube technique is a powerful tool to study the ignition behavior of multi-component liquid fuels resulting from blending any two of the three basic fuels, gasoline, kerosene and light diesel, at different proportions.
2. The thermal ignition delay decreases with the increase of pressure for the various blends. Its variation is almost inversely proportional with pressure for all different blends.
3. The ignition delay period decreases with the increase of ignition temperature for all blends. The blends having high proportion of diesel fuel are more affected by temperature than the others. Further, the temperature

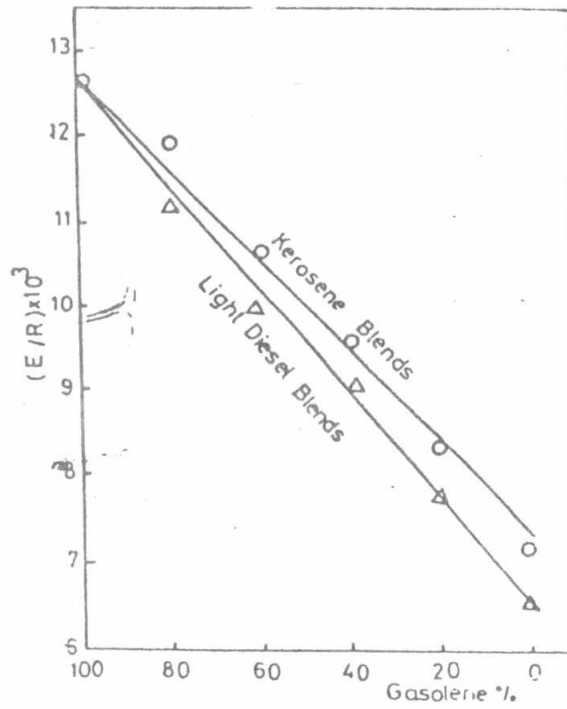


Fig.10. Activation Energy vs. % Of Gasolene For Gasolene-Kerosene And Gasolene-Light Diesel Blends

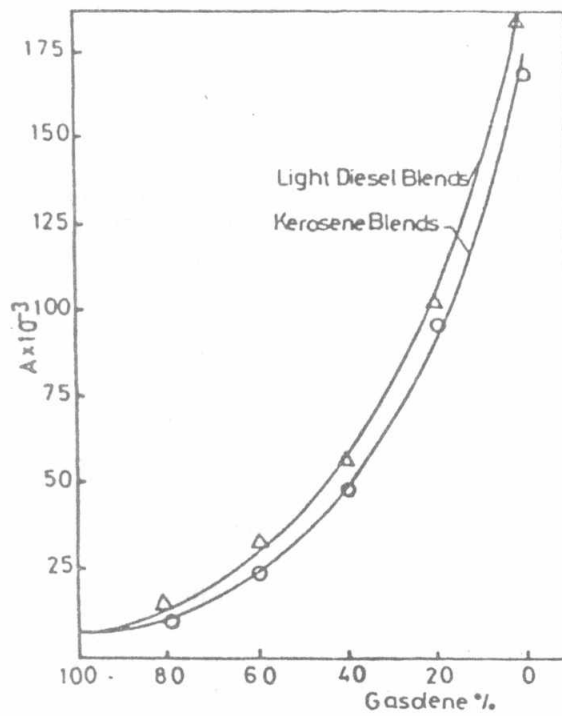


Fig.11. Preexponential Factor vs. % Of Gasolene For Gasolene-Kerosene And Gasolene-Light Diesel Blends

has a greater effect on ignition delay than the pressure for the different studied blends.

4. The Arrhenius plots of the various blends yield the activation energy, the pressure exponent, the equivalence ratio exponent and the preexponential factor of blended fuels. High proportion diesel fuel blends enjoy low activation energy as compared to high proportion gasoline blends; high proportion kerosene blends show intermediate behavior.

5. The experimental results of the various multi-component (blended) fuels are all well correlated using the following formula

$$\tau = (A/p^n) \phi^{+m_2} e^{-m_1 E/RT}$$

where the (-ve) and (+ve) exponents of equivalence ratio represent the lean and rich regions, respectively.

#### REFERENCES

1. Asaba, T., Yoneda, K., Kolcochara, N. and Hikita, T., 9th Symposium "International" on Combustion, pp.193, (1963).
2. Cooke, D.F. and Williams, A., 13th Symposium "International" on Combustion, pp.756, (1971).
3. Seery, D.J. and Bowman, C.T., Combustion and Flame, 14, pp.37, (1970).
4. Higgen, R.M.R. and Williams, A., 12th Symposium "International" on Combustion, pp.579, (1969).
5. Heffington, W.M., Parks, G.E., Sulzmann, K.G.P. and Penner, S.S., 16th Symposium "International" on Combustion, pp.997, (1977).
6. Tsubai, T. and Wagner, H.C., 15th Symposium "International" on Combustion, pp.883, (1974).
7. Bazhenova, T.V. and Soloukhen, R.I., 7th Symposium "International" on Combustion, pp.886, (1958).
8. Eubank, C.S., Rabinowitz, M.J., Gardiner, W.C. Jr and Zellner, R.E., 18th Symposium "International" on Combustion, pp.1767, (1981).
9. Burcat, A., Lifshitz, A., Scheller, K. and Skinner, G.B., Combustion and Flame, 16, pp.311, (1971).
10. Coats, C.M. and Williams, A., 17th Symposium "International" on Combustion, pp.611, (1979).
11. Natarajan, K. and Bhaskaran, K.A., Combustion and Flame, 43, pp.35, (1981).
12. Becley, P., Grieffiths, J.F., Hunt, B.A. and Williams, A., 16th Symposium "International" on Combustion, pp.1013, (1976).
13. Asaba, T. and Fujii, N., 13th Symposium "International" on Combustion, pp.155, (1971).
14. Asaba, T. and Fujii, N., 14th Symposium "International" on Combustion, pp.433, (1973).
15. Asaba, T. and Fujii, N., 8th International Shock Tube Symposium, pp.46, (1971).
16. El-Kotb, M.M., Aly, S.L. and El-Bahnasy, Sh.M., 5th International Conference For Mechanical Power Engineering, Ain Shams University, (1984).
17. El-Bahnasy, Sh.M., M.Sc. Thesis, Mechanical Power Department, Faculty of Engineering, Cairo University, (1985).

## NOMENCLATURE

A	preexponential factor
CN	cetane number
E	activation energy, Kcal/Kmol
G	gasolene
K	kerosene
LD	light diesel
M	molecular weight
m	exponent of equivalence ratio
	exponent of pressure
p	pressure, bar
R	universal gas constant, 1.986 Kcal/Kmol <sup>o</sup> K
SG	specific gravity
T	absolute temperature, <sup>o</sup> K
t	temperature, <sup>o</sup> C
γ	specific heat ratio
μs	microseconds
τ	ignition delay period
φ	equivalence ratio
	subscripts
ev	evaporation