

DOE/NASA/51040-19
NASA TM-81645

(NASA-TM-81645) IGNITION OF LEAN FUEL-AIR
MIXTURES IN A PREMIXING-PREVAPORIZING DUCT
AT TEMPERATURES UP TO 1000 K (NASA) 16 p
HC A02/MF A01 CSCL 21B

N81-13465

Unclas
G3/44 29445

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Washington, D.C. 20545
Under Interagency Agreement DE-AI01-77CS51040

IGNITION OF LEAN FUEL-AIR MIXTURES IN A PREMIXING-PREVAPORIZING
DUCT AT TEMPERATURES UP TO 1000 K*

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E-9356-3

ABSTRACT

Conditions were determined in a premixing-prevaporizing fuel preparation duct at which ignition occurred. An air-blast-type fuel injector with nineteen fuel injection points was used to provide a uniform spatial fuel-air mixture. The range of inlet conditions where ignition occurred were: inlet air temperatures of 600 to 1000 K, air pressures of 180 to 660 kPa, equivalence ratios (fuel-air ratio divided by stoichiometric fuel-air ratio) from 0.13 to 1.05, and velocities from 3.5 to 30 m/s. The duct was insulated and the diameter was 12 cm. Mixing lengths were varied from 16.5 to 47.6 cm and residence times ranged from 4.6 to 107 ms. The fuel was no. 2 diesel. Results showed a strong effect of equivalence ratio, pressure and temperature on the conditions where ignition occurred. The data did not fit the most commonly used model of autoignition. In particular, the effect of length or residence time on ignition delay is not clear in these tests. A correlation of the conditions where ignition would occur which apply to this test apparatus over the conditions tested is $(p/V)\phi^{1.3} = 0.62 e^{2800/T}$ where p is the pressure in kPa, V is the velocity in m/s, ϕ is the equivalence ratio, and T is the temperature in K. The data scatter was considerable, varying by a maximum value of 5 at a given temperature and equivalence ratio. There was wide spread in the autoignition data contained in the references. The data from this report are in reasonable agreement with those of the references.

INTRODUCTION

This report presents ignition data (autoignition and/or flashback) of lean fuel-air mixtures in a premixing-prevaporizing fuel preparation duct at conditions applicable to the automotive gas turbine or Stirling engine. These data are necessary to design a low NO_x premixed-prevaporized combustor. The work was done in support of the DOE (low emission, high fuel economy) automotive gas turbine and Stirling engine programs.

Ignition of the fuel in a premixing-prevaporizing fuel preparation system is to be avoided because of the possibility of damage to the system and the creation of NO_x . Autoignition data in a premixing-prevaporizing duct are presented in references 1 to 3. However, there are considerable differences in the results; in particular, the effect of fuel-air ratio is not clear. Reference 1 shows a strong effect of fuel-air ratio on the conditions where ignition occurs although most of the data is at fuel rich

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conditions. Reference 2 took extensive data at lean fuel-air ratios but does not report any effect of equivalence ratio on ignition based on inlet conditions. Also, the data in references 1 to 3 were taken at higher pressures (greater than 1.0 MPa) than would be encountered in an automotive application (less than 0.5 MPa). For the study reported herein ignition data were taken in a premixing-prevaporizing duct over a range of lean fuel-air ratios and at lower pressures with a previously developed multiple point fuel injector and the results compared to that which had been reported previously.

In the present study inlet temperatures from 600 to 1000 K were investigated. The maximum combustor inlet temperatures for a Stirling engine is a 1000 K and for the advanced gas turbine engine the inlet temperatures may be higher than 1300 K. The limit of the nonvitiated preheater employed in this study was 1000 K. Pressures where ignition was obtained ranged from 180 to 660 kPa. This compares to a maximum of 150 for the Stirling engine and 450 kPa for the gas turbine engine. Equivalence ratios (fuel-air ratio divided by stoichiometric fuel-air ratio) investigated varied from 0.13 to 1.05. In the advanced gas turbine engine, overall equivalence ratios range from 0.044 to 0.210; and for the Stirling engine, they range from 0.6 to 1.0. The fuel used was no. 2 diesel, which is a likely fuel for the gas turbine and Stirling engines.

APPARATUS

Test Rig

The experiment was performed in a 12-cm-diameter, insulated tubular duct. It consisted of the following: a 0.1-cm-thick stainless steel - 12 cm inside-diameter tube, 1.5-cm-thick Carborundum T30R Fiberfrax insulation, and finally a 15.2-cm inside-diameter pipe. The air was heated indirectly to temperatures between 600 and 1000 K. There were 12 Chromel-Alumel thermocouples and a pressure tap located 10 cm upstream of the fuel injector to measure inlet air conditions. The fuel to the injector was at ambient temperature. The fuel injector was inserted in a spool piece that could be changed to vary the mixing-ignition length. Two Chromel-Alumel thermocouples and a pressure tap were located 1.2 cm upstream of the flameholder. One thermocouple was used for data and the other connected to a fuel shutoff in case of ignition in the mixing section. Only the tips of the thermocouples protruded into the stream. A hydrogen enriched afterburner was used to burn the unreacted fuel. The flameholder used was water cooled and contained 62 0.6-cm-diameter holes that resulted in a 75 percent blockage. Water was injected downstream of the afterburner to cool the gases before going through the back pressure valve and atmospheric exhaust.

Fuel Injector

A photograph of the multiple venturi tube fuel injector is shown in figure 2. The purpose of the air tubes was to uniformly meter the inlet air to each tube and also provide high velocity air for atomization and mixing. A cross-section of the air passages and the spacing of the passages is shown in figure 3. The blockage at the plane of the throats is 92 percent of the

duct area. Fuel was injected perpendicular to the airstream at the throat of each passage by an open end fuel tube (see fig. 4). Each fuel tube has a uniform length of 25.4 cm and an inside diameter of 0.5 mm. To insure uniform fuel flow to each passage. A spatial fuel-air distribution that was within 10 percent of the mean was obtained 16.5 cm from the fuel injection plane (ref. 4). The degree of vaporization was nearly 100 percent at an inlet air temperature of 600 K, pressure of 300 kPa, an inlet velocity of 10 m/s and a vaporization length of 16.5 cm.

RESULTS AND DISCUSSION

Data are presented for the conditions where the fuel ignited (autoignition and/or flashback) in the premixing-prevaporizing duct. The data are first presented using a standard autoignition correlation. Then the data are presented in an alternate form suggested by the data.

The method used to obtain ignition data was to establish the air flow and inlet air temperature, then vary either pressure or fuel flow to obtain ignition. Usually fuel flow was established and pressure varied; however, a comparison of the method of variation showed no difference in the results. The data points in the plots are at conditions where ignition occurred.

Autoignition Correlation

A convenient form for presenting the data is $\tau = (k e^{E/RT})/p^n$ (refs. 2 and 3) where τ is the autoignition delay time or residence time, k is a constant for a constant equivalence ratio, R is the gas constant, T is the inlet air temperature, p is the pressure, and n is a constant determined experimentally. The equation is derived from chemical reaction theory and does not include a mixing and vaporization time even though it is included in the autoignition delay time. Thus the actual data may not be of this form although it is still a useful way to plot the data. The value of n found in the references varies. Spadaccini and TeVelde (ref. 2) used a value of $n = 2.0$, Du Courneau (ref. 1) used $n = 1.0$, and Stringer, Clarke, and Clarke (ref. 5) used $n = 0.83$. In this report a value of $n = 1.0$ was used.

Effect of equivalence ratio. - Data of residence time multiplied by pressure, τp , are plotted versus the equivalence ratio where ignition occurred in figure 5. Data were taken at constant values of inlet air temperature of 1000, 900, 800, 750, 700 and 600 K. Two things noteworthy in the data are the effect of equivalence ratio on ignition and the fact that length acts as a parameter. The longest lengths gave the largest values of residence time multiplied by pressure τp . This result was unexpected since the effect of length should be contained in the residence time $\tau = L/V$. One explanation could be that flashback occurred; another could be that ignition occurred in recirculation zones at the fuel injector.

The value of τp increased as equivalence ratio decreased. This can be an important effect. For example, at an inlet air temperature of 1000 K and a length of 16.5 cm the value of τp at an equivalence ratio of 0.2 is about five times that at an equivalence ratio of 1.0.

Effect of inlet air temperature. - If the autoignition delay time τ is assumed to be a function of pressure p and inlet air temperature T

by $\tau = (k e^{E/RT})/p$ for a constant value of equivalence ratio, then a plot of the $\log \tau_p$ versus $1/T$ would be a straight line. In figure o(a) the $\log \tau_p$ is plotted versus $1/T$ for an equivalence ratio of 1.0.

The data separate according to length as in the previous plot. There is a general increase in the value of τ_p as $1/T$ increases (or a decrease in τ_p as T increases) but there is too much data scatter to define a relationship.

In figure b(b) these data are represented by the shaded region and are compared to the data from Marek, Papathakos, and Verbulecz (ref. 3), Spadaccini and TeVelde (ref. 2), Du Courneau (ref. 1), and Stringer, Clarke, and Clarke (ref. 5).

Since differences in data can be the result of differences in mixing and vaporizing the fuel, the type of fuel injection is important. Spadaccini used a multiple point injector similar to the one used in this report. Du Courneau used a multiple point fuel injector that consisted of a number of fuel tubes with holes. Marek used a single simplex fuel spray nozzle, spraying upstream. Stringer's data were obtained for diesel engine application: fuel was pulsed into a slow moving air stream and the time measured for autoignition to occur. The fuels used in the references were all kerosene-type fuels. Spadaccini and Stringer used no. 2 diesel, Marek used Jet A, and Du Courneau refers to his fuel as kerosene. There should not be a difference in data due to these different fuels being used since Spadaccini showed little difference between Jet A, no. 2 diesel, and JP-4.

The data are plotted for the references with length as a parameter. The length for Marek, Spadaccini, and Du Courneau data was equal to the length from the fuel injector to the quench section. Since Stringer only sent a pulse of fuel into the airstream, there was no need for a quench section and thus no specific length.

In figure b(b), the data at an equivalence ratio of 1.0 are plotted. Marek's data were taken at an equivalence ratio of 0.7 but, since a single point injector was used, the mixing may not have been as fast and behaved as a richer mixture.

There is a wide range of values of τ_p between the different sets of data in figure b(b). The dependence on temperature as seen by the slopes of the curves are quite different. The data of Spadaccini and Stringer agree very well. Their data show a strong dependence on temperature at low inlet air temperatures; this dependence decreases as inlet air temperature increases. The data of Du Courneau show the least dependence on temperature with the data of Marek and this report falling in between.

An explanation for the differences may be that the autoignition delay time is not only made up of the chemical delay time but also of a vaporization time and a mixing time. Since the injectors are different there will be a difference of vaporization and mixing times which would result in a different ignition delay time.

The data of Du Courneau and Spadaccini both were taken with length as a variable. Their data as well as the data of this report separate according to length. The longest lengths have the highest values of τ_p , or for a fixed pressure have the longest residence times. Note that the data taken by Spadaccini at the two longest lengths agree very well but the data at the shorter lengths separate.

Pressure/Velocity Correlation

Effect of equivalence ratio. - Since the short length data in figure 5 had low values of τ_p and long length data had high values of τ_p , the length term in $\tau_p = (L/V)p$ was eliminated and the data plotted as p/V versus ϕ in figure 7.

No noticeable effect of length is seen in the plots. However, there is also no time term. This would imply that the data are not autoignition data, but flashback data. More experimental data will be required to determine the true cause.

A curve fit was made of the data and is shown in the figures. One curve was used to fit the data at all inlet air temperatures. The curve fit chosen was $(p/V)\phi^{1.3} = 0.62 e^{2800/T}$ where p is the pressure in kPa, V is the velocity in m/s, and T is the temperature in K. Note that the 2800 in the Arrhenius term is not an activation energy.

The curve does not fit the data well at all inlet air temperatures. At an inlet air temperature of 1000 K there is a portion of the data that remains level and below the curve fit as the equivalence ratio decreases from a value of 1.0. As the equivalence ratio further decreases below 0.4, all the data approach the curve fit. The reason for these data falling below the curve fit is not clear. The data scatter is not from data taken on the same day but the result of data taken on different days. Possibly slight changes in geometry caused the change in data. The data varied by a maximum factor of 5 at a given temperature and equivalence ratio.

Effect of inlet air temperature. - Using the same correlating parameter p/V , the data at an equivalence ratio of 1.0 were plotted versus inlet air temperature in figure 8. The curve fit described previously is also shown.

Since the data of Du Courneau and Spadaccini also show the effect of length, their data and Marek's were plotted as p/V versus $1/T$ in figure 8(b). Stringer's data were not plotted because there was no fixed length with a quench zone. The data in this report are indicated by the shaded region in figure 8(b).

The agreement between the sets of data is still not good. The slopes are quite different. Spadaccini shows the greatest temperature dependence and Du Courneau the least.

The data again separate into sets of length for the data of Spadaccini and Du Courneau. However, the trend is reversed with the tendency to ignite increasing as the length increases. So completely eliminating length for these sets of data was too extreme.

IGNITION AT AUTOMOTIVE CONDITIONS

In this section the applicability of these data are discussed for pre-mixing-prevaporizing the fuel at automotive Stirling and gas turbine conditions.

To find the minimum ignition delay time, which gives the maximum residence time to design for, the minimum value of τ_p needs to be found at the inlet conditions. The Stirling engine combustor inlet conditions are an inlet air temperature of 1000 K, pressures below 150 kPa, and equivalence ratios between 0.6 and 1.0. At these conditions, from figure 5(a), the minimum τ_p is 0.8 ms-MPa at a length of 16.5 cm. Using this value and a pressure of 150 kPa gives an autoignition delay time of 5 ms. Alternately

the p/V correlation can be used as a criteria for ignition. Using figure 7(a) with ignition as a function of p/V , the minimum value of p/V is 6 kPa/(m/s). Assuming $p = 150$ kPa, a minimum velocity of 25 m/s is necessary to prevent ignition. Either criteria, 5-ms maximum residence time or 25-m/s minimum velocity, does not impose a severe restriction on the fuel preparation system.

For the automotive gas turbine, the data do not extend to the high inlet air temperatures that will be encountered at the combustor inlet. The inlet air temperatures may be 1300 K or higher. Therefore, estimates have to be made by extrapolating the effect of inlet air temperatures. The extrapolation will be uncertain because of the large data scatter.

Also extrapolating the effect of equivalence ratio to higher inlet air temperatures may not be valid. This possibility is shown in figure 5(a) or 7(a), where at 1000 K inlet air temperatures there is a level portion of the curve between equivalence ratios of 0.6 and 1.0.

Keeping in mind these limitations, we estimated the minimum value of p to be 1.0 ms-MPa and that of p/V to be 25 kPa/(m/s) at an inlet air temperature of 1250 K and an equivalence ratio of 0.3. If a maximum pressure of 400 kPa is used, then the ignition delay would be 2.5 ms and the velocity from p/V would be 10 m/s to prevent ignition. These would result in only moderately difficult design goals. If the effect of equivalence ratio did not extrapolate to higher inlet air temperatures, then the ignition delay would be only 0.5 ms or a velocity from the p/V curve of 70 m/s would be required. These would result in more difficult design criteria.

SUMMARY OF RESULTS

Ignition data (autoignition and/or flashback) were taken in a premixing-prevaporizing fuel preparation duct at the following conditions: inlet air temperatures of 600 to 1000 K, air pressures of 180 to 600 kPa, equivalence ratios from 0.13 to 1.05, inlet air velocities from 3.5 to 30 m/s, mixing lengths of 16.5 to 47.6 cm, and residence times from 4.6 to 107 ms. The fuel was no. 2 diesel.

The following results were obtained:

1. For an automotive Stirling engine application it is possible to mix and vaporize the fuel before ignition (combustion). At an inlet air temperature of 1000 K, a pressure of 150 kPa and equivalence ratios between 0.6 and 1.0, the fuel will not ignite in the premixing-prevaporizing duct if the residence time is below 5 ms or the velocity above 25 m/s.

2. For the automotive gas turbine application the data has to be extrapolated to higher inlet air temperatures. A wide range of estimates can be obtained which are inconclusive as to whether mixing and vaporization can be accomplished before ignition. The most conservative estimate, at an inlet-air temperature of 1250 K, pressure of 400 kPa, and assuming no dependence on equivalence ratio, would require a residence time of less than 0.5 ms or a velocity greater than 70 m/s to prevent ignition in the premixing-prevaporizing duct.

3. There was a strong effect of equivalence ratio, pressure and temperature on the conditions where ignition occurred. At an inlet air temperature of 1000 K and a mixing-vaporizing length of 16.5 cm the value of τp (residence time x pressure) increased by a factor of 5 as the equivalence ratio went from 1.0 to 0.2.

4. The data did not fit the most commonly accepted model of autoignition. In particular, the effect of length or residence time on ignition is not clear in these tests.

5. A correlation of the conditions where ignition would occur which would apply to this test apparatus over the conditions tested is $(p/V)\phi^{1.3} = 0.62 e^{2800/T}$ where p is the pressure in kPa, V is the velocity in m/s, ϕ is the equivalence ratio, and T is the temperature in K. However, the autoignition data in the references did not fit this correlation.

6. There was a wide spread of autoignition data among the references. The data from this report were in reasonable agreement with that of the references.

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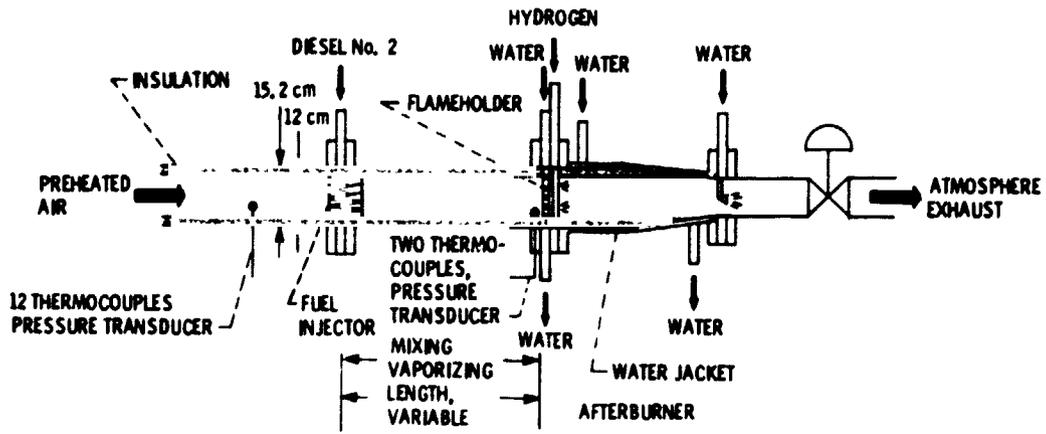


Figure 1 - Rig schematic.

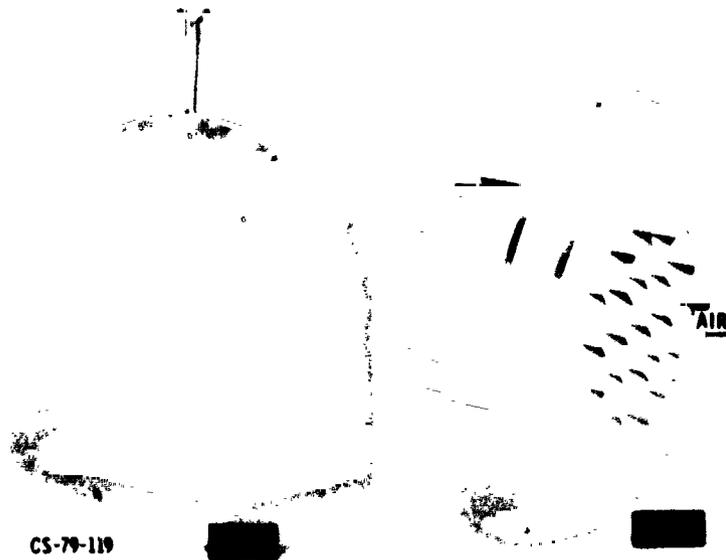


Figure 2 - Multiple venturi tube fuel injector.

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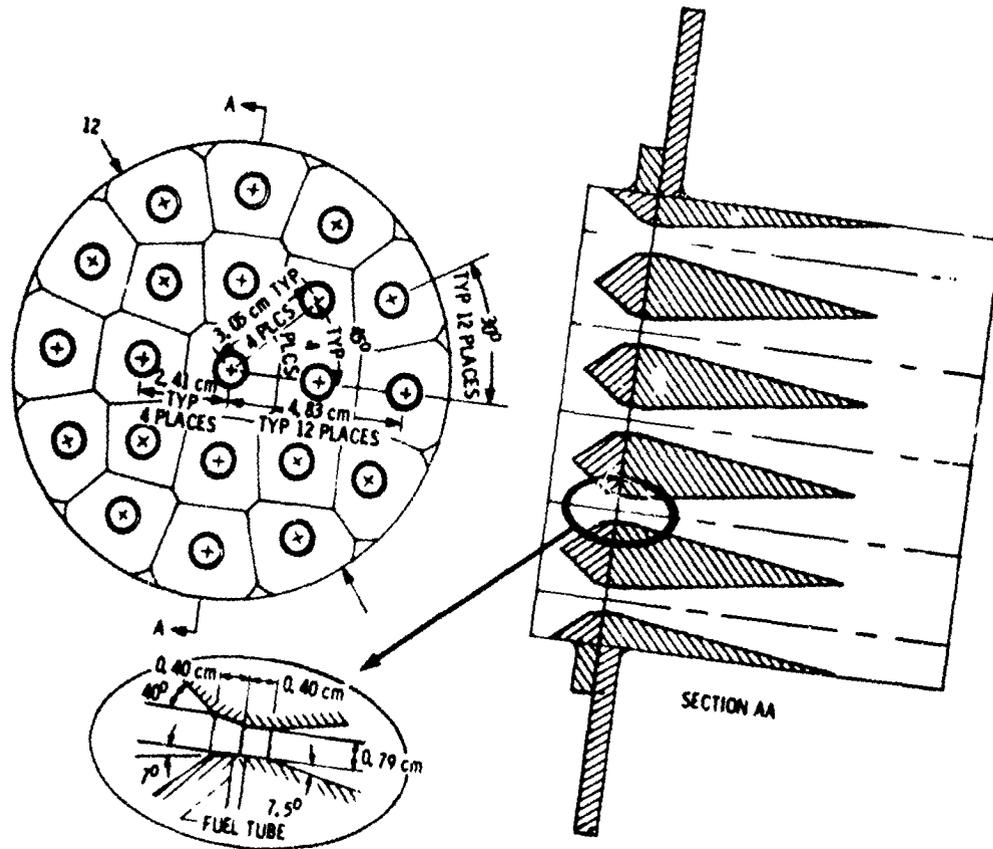


Figure 3. - Multiple Venturi fuel injector, passage cross-section and hole spacing.

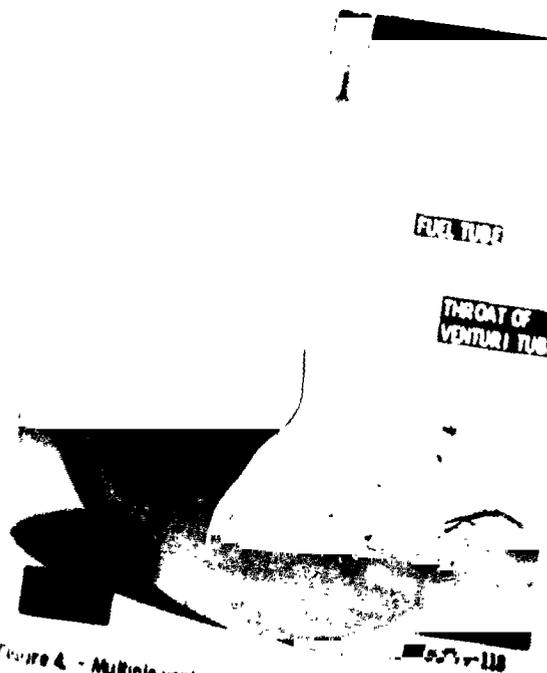


Figure 4. - Multiple venturi tube fuel injector fuel tubes at split zone of throat, looking downstream.

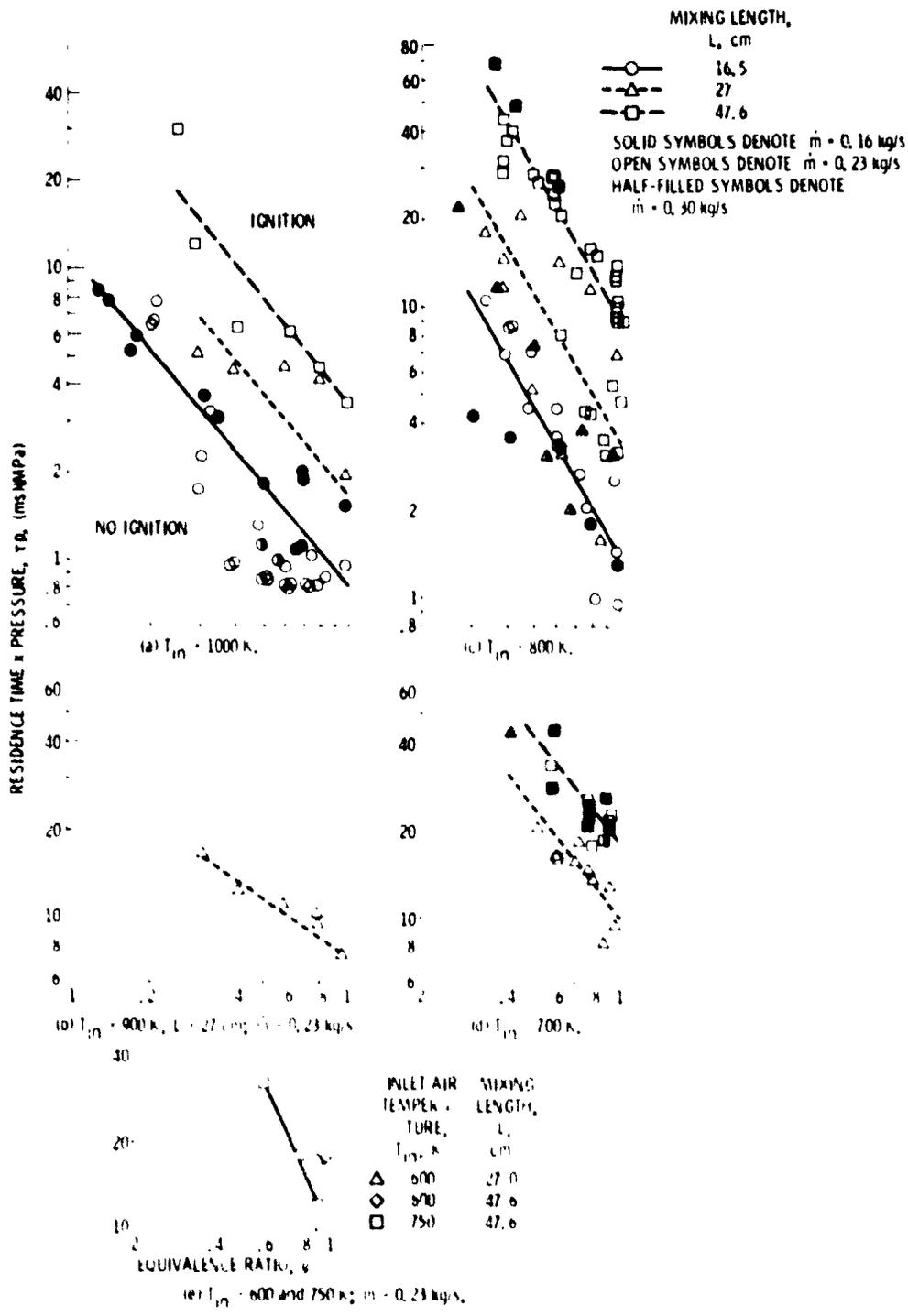
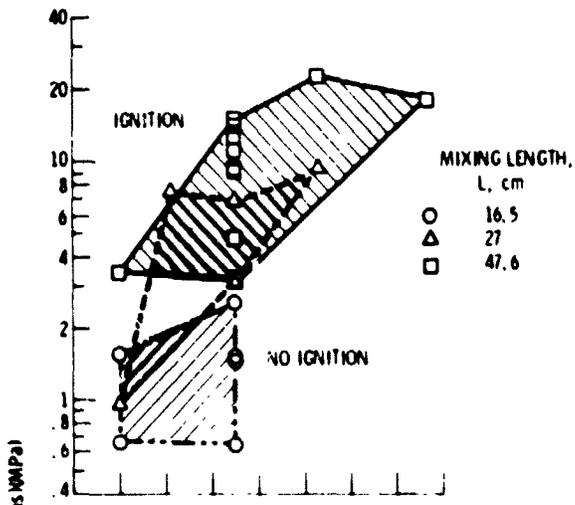
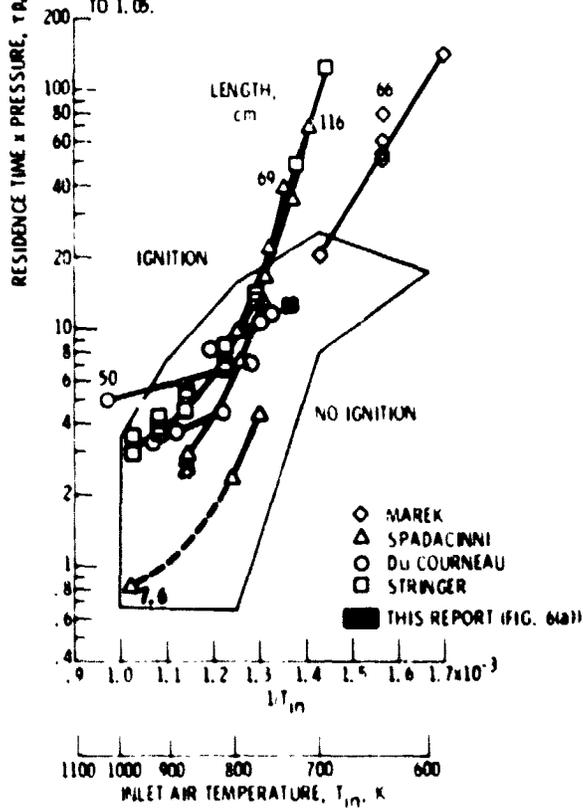


Figure 5. Effect of equivalence ratio on autoignition.



(a) DATA FROM THIS REPORT. EQUIVALENCE RATIO $\phi = 0.95$ TO 1.05.



(b) COMPARISON WITH REFERENCES. EQUIVALENCE RATIO $\phi = 1.0$.

Figure 6. - Effect of inlet air temperature on autoignition.

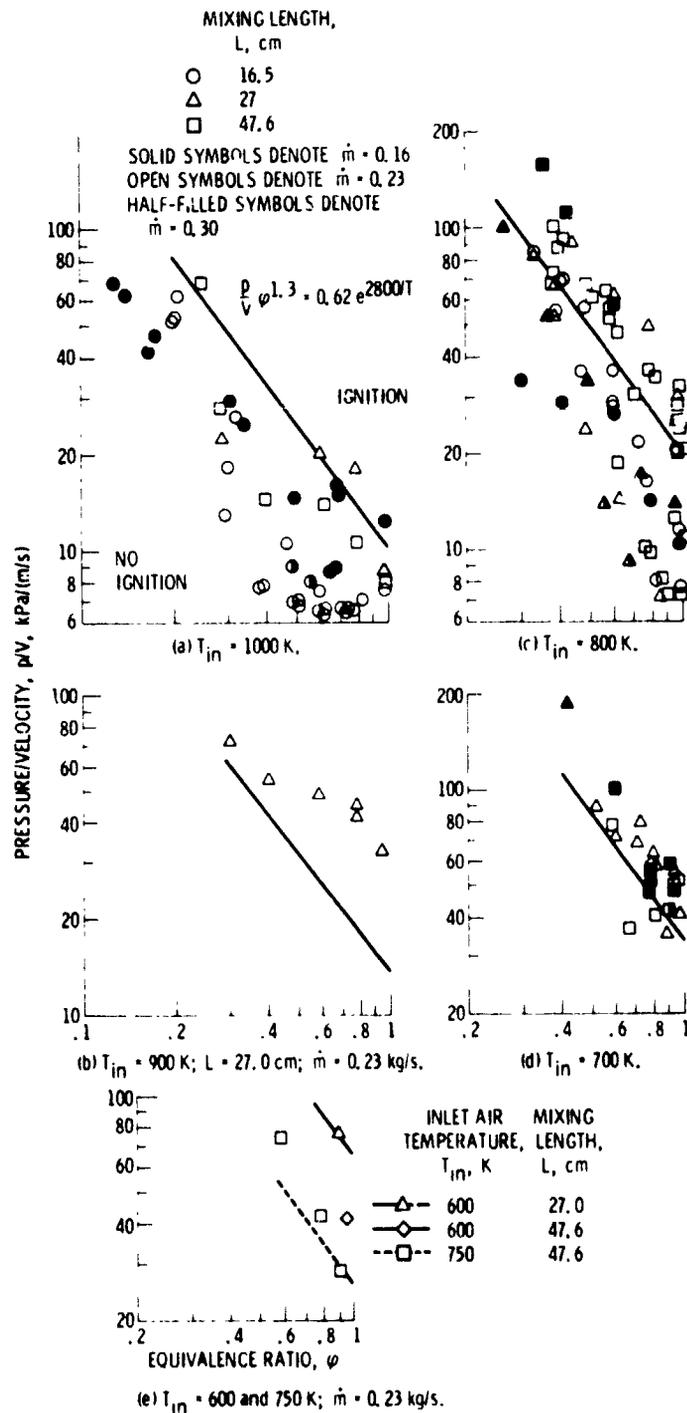


Figure 7. - Effect of equivalence ratio on p/V correlation of ignition data.

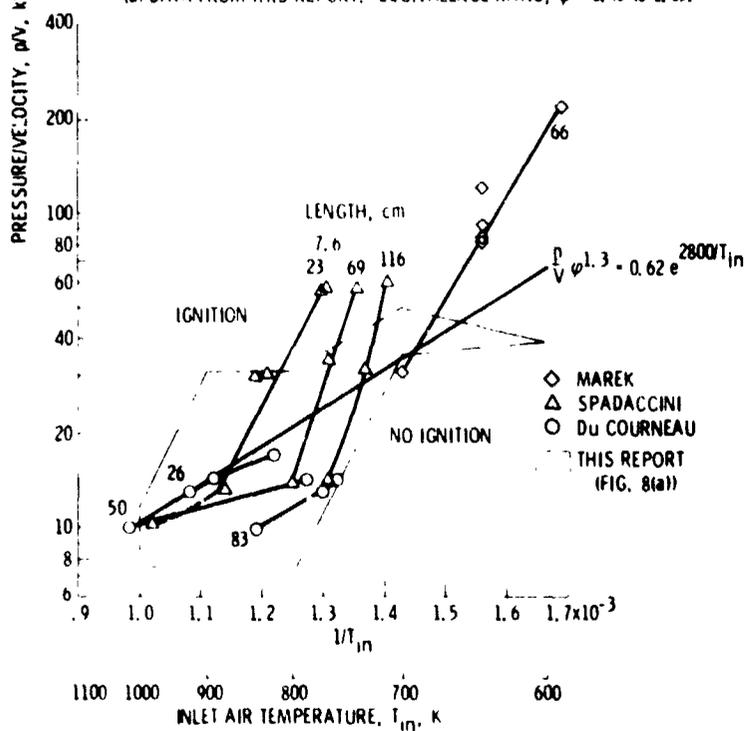
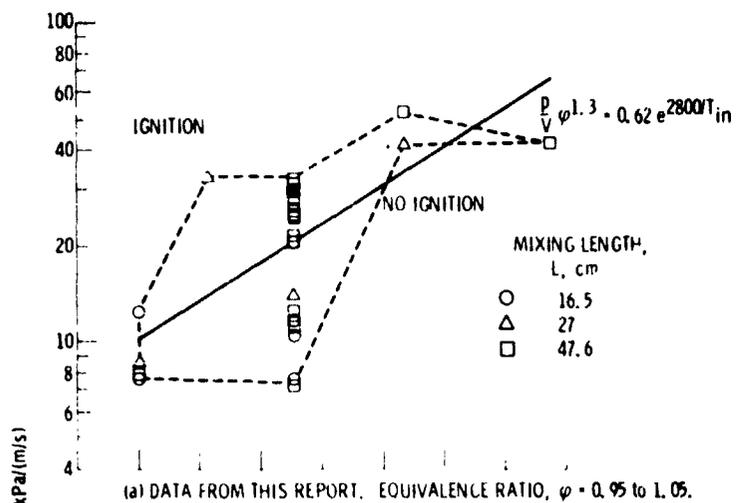


Figure 8. - Effect of inlet air temperature on p/v correlation of ignition data.