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PRELIMINARY STUDIES OF AUTOIGNITION AND FLASHBACK IN A PREMIXING-PREVAPORIZING FLAME TUBE USING JET-A FUEL AT LEAN EQUIVALENCE RATIOS

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16. Abstract

Autoignition delay times are reported for a premixing-prevaporizing tube operated with liquid Jet-A fuel. Lean equivalence ratios ranged from 0.3 to 0.7. Combustor inlet air pressures were varied from 0.54 to 2.5 MPa, combustor inlet air temperatures from 550 to 700 K, and reference velocities from 8 to 35 meters per second. Autoignition delay times ranged from 15 to 100 milliseconds and varied inversely with pressure. The Arrhenius activation energy was 41 840 joules per mole (10 000 cal/mole). Temperature rise data were obtained in a long premixing-prevaporizing tube at a pressure of 0.56 MPa. Preflame temperature rise data were a function of equivalence ratio, inlet air temperature, and tube residence time. Significant temperature rise occurred above temperatures of 760 K, with autoignition occurring at 775 K for equivalence ratios greater than 0.47. The reactions were similar to cool-flame phenomena. Flashback velocities were measured at temperatures of 610 and 700 K, a pressure of 0.56 MPa and equivalence ratios from 0.6 to 1. Flashback velocities varied from 30 to 65 meters per second.

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PRELIMINARY STUDIES OF AUTOIGNITION AND FLASHBACK IN A PREMIXING-PREVAPORIZING FLAME TUBE USING JET-A FUEL AT LEAN EQUIVALENCE RATIOS

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SUMMARY

Autoignition delay times were determined for Jet-A fuel in a premixing-prevaporizing tube at high combustor inlet air pressures, from 0.54 to 2.5 MPa, and combustor inlet air temperatures from 550 to 700 K. Equivalence ratios ranged from 0.3 to 0.7.

Autoignition delay times ranged from 15 to 100 milliseconds and varied inversely with pressure. The premixing tube was 0.26 meter long, and reference velocities varied from 8 to 35 meters per second. The Arrhenius activation energy was 41 840 joules per mole (10 000 cal/mole).

The preflame temperature rise and flashback velocities were measured in another premixing tube that was 5.25 centimeters in diameter and 1.64 meters long. This tube was operated at a constant pressure of 0.56 MPa. Preflame temperature rise data were a function of equivalence ratio, inlet air temperature, and tube residence time. Significant temperature rise occurred above temperatures of 760 K, with autoignition occurring at 775 K for equivalence ratios greater than 0.47. The reactions were similar to cool-flame phenomena.

Flashback velocities were measured at temperatures of 610 and 700 K, a pressure of 0.56 MPa, and equivalence ratios from 0.6 to 1. Flashback velocities varied from 30 to 65 meters per second.

INTRODUCTION

An experimental investigation was conducted to determine the autoignition and flashback characteristics of Jet-A fuel in a premixing-prevaporizing tube.

The high combustor inlet air temperatures and pressures of advanced high-pressure-ratio engines increase the emissions of oxides of nitrogen (NO_x) pollutants. An order-of-magnitude reduction in oxides of nitrogen can be achieved by premixing and prevaporizing the fuel-air mixture and by burning at lean equivalence ratios in the primary zone of the combustor. However, as the inlet air temperature and pressure increase, the autoignition delay times decrease and flashback velocities increase. The mixing and vaporizing process must be completed rapidly before autoignition occurs. When the flame flashes into the premixing tube, the NO_x emission index increases rapidly and extensive damage can occur to the premixing tube and the combustor.

A knowledge of autoignition delay times as a function of inlet air temperature and pressure and equivalence ratio is required to properly design the premixing tube. To prevent flashback, the velocity at the flameholder downstream of the premixing tube must exceed the flashback velocity.

Several investigators have measured autoignition delay times at high pressures and temperatures, usually at high equivalence ratios. Stringer, Clarke, and Clarke (ref. 1) measured autoignition times for several fuels in a flowing system at velocities to 21 meters per second, pressures from 3 to 6 MPa, and temperatures from 770 to 980 K. For an "Avtur" fuel similar to Jet-A, autoignition times of 8.1 to 0.47 millisecond were obtained. In this work, only a minor effect of equivalence ratio and air velocity on autoignition delay times was found. Mestre and Ducourneau (ref. 2) and Ducourneau (ref. 3) measured the autoignition delay times for kerosene. They report a large effect of equivalence ratio at pressures of 0.5 and 1.2 MPa and temperatures from 700 to 1070 K. Their autoignition delay times ranged from 15 to 3 milliseconds. They also report an effect of injector configuration on autoignition delay times. Spadaccini (ref. 4) reports autoignition delay times for JP-4 fuel, No. 2 fuel oil, and No. 6 fuel oil at pressures of 0.68 to 1.63 MPa and temperatures from 670 to 870 K. Measured autoignition delay times ranged from 50 to 5 milliseconds for the fuels tested, but no effect of overall equivalence ratio was determined.

This report presents the results of a study of autoignition characteristics and flashback velocities for Jet-A fuel in a premixing-prevaporizing tube. Autoignition delay times were measured at pressures from 0.54 to 2.5 MPa, temperatures from 550 to 700 K, and equivalence ratios less than 0.7. In addition, a long premixing tube was operated at 0.56 MPa to determine preflame temperature rise and flashback velocities.

The data were taken in the U.S. customary system of units and converted to the SI system for this report.

APPARATUS AND PROCEDURE

Two separate facilities were used in this investigation to examine the conditions under which a flame would occur in a premixing tube for Jet-A fuel. A high-pressure facility was used to determine autoignition delay times and was operated at pressures from 0.54 to 2.5 MPa and temperatures from 550 to 700 K. A moderate-pressure facility was used to determine the preflame temperature rise data and the flashback velocity data. The latter facility was operated at 0.56 MPa and at temperatures from 590 to 833 K.

Autoignition Delay Times

The premixing configuration of reference 5 was placed in the high-pressure facility to determine the stable operating conditions (fig. 1). The 10.2-centimeter-diameter test tube was placed within the pressure duct and bypass air was used to maintain the tube at the inlet air temperature, to cool the combustor walls after autoignition, and to dilute the exhaust stream to below the flammability limit.

Figure 1 shows the location of the 25-percent-open-area, perforated-plate flameholder. The flameholder was uncooled. Static-pressure taps were located upstream and downstream of the flameholder. The airflow split between the premixing tube and the bypass was determined from the flameholder pressure drop and checked with the total-static probe in the bypass stream and with the area ratios of the flameholder and the blockage plate in the bypass. Good agreement was obtained among the various methods for calculating the airflow split.

Chromel-Alumel thermocouples were attached to the liner wall, and two thermocouples were inserted 1 centimeter into the premixing tube upstream of the perforated plate to determine when burning was occurring in the premixing tube. The autoignition delay time is reported as the computed time based on the velocity of the gas at the inlet air temperature and the static pressure in the premixing tube and the distance between the fuel injector and the flameholder, which was 0.65 meter. No corrections were made for the change in temperature of the fuel-air mixture caused by cooling that resulted from fuel injection or by heating that resulted from preflame reactions in the premixing tube.

The procedure for determining the autoignition delay time was (1) to establish the airflow rate and the inlet air temperature and pressure; (2) to slowly begin the fuel flow without the ignitor on, over a period of 5 seconds to an equivalence ratio as high as 0.7 in order to determine if autoignition occurred in the premixing tube; (3) if autoignition did not occur within 10 more seconds, to turn off the fuel flow, wait 3 minutes for purging the system, increase the pressure to a new point, and repeat the procedure.

Preflame Temperature Rise and Flashback Velocities

In the moderate-pressure facility, a premixing-prevaporizing tube was installed.

The premixing tube was 5.25 centimeters in diameter and 1.64 meters long, as shown in figure 2. A high-velocity premixed-prevaporized fuel-air mixture was established before it entered the dump combustor. No flameholder device was inserted at the exit of the tube so that the flashback velocity could be determined.

Two separate fuel injector configurations were used in the experiment. The initial injector was a 60°-spray-angle simplex pressure-atomizing nozzle rated at 0.09 m^3/hr (24 gal/hr) at a pressure differential of 0.69 MPa (100 psid). The nozzle was flush with the wall, and the fuel was sprayed normal to the airflow. A second injector was later used that consisted of five tubes with 0.5-millimeter-diameter orifices in the ends. The injection tubes were spaced around the circumference of the premixing tube and mounted flush with the walls.

Chromel-Alumel thermocouples were placed every 15 centimeters along the premixing tube and staggered at 30° so that no two thermocouples were in line. The thermocouples penetrated the gas flow approximately 0.5 centimeter. The tube was insulated to minimize heat losses.

A gas analysis probe was used to sample the recirculation zones of the dump combustor, to determine the combustion efficiency in the neighborhood of the premixing tube exhaust, and to determine the fuel-air ratio uniformity of the premixing jet.

The flashback data were determined by igniting the combustor at lean equivalence ratios below 0.6 and then gradually increasing the equivalence ratio until flashback occurred.

RESULTS AND DISCUSSION

The autoignition delay times obtained in the high-pressure facility are presented first, followed by the premixing-tube (preflame) temperature rise and flashback velocity experiments.

Autoignition Delay Times

The autoignition delay data obtained at temperatures of 550, 590, 640, 700, and 833 K are presented in figure 3. The autoignition delay times were computed from the distance between the injector and the flameholder divided by the velocity in the premixing tube at the inlet air temperature and pressure. As expected, the times decreased with increasing temperature and pressure. Also shown are autoignition times determined in references 5 and 6 that were obtained with premixing configurations.

Considerable scatter is present in the data. It is difficult to determine the slope of the time-pressure line. However, from the data of reference 5 at 640 K, which were for a 2.6-meter-long configuration, a slope of -1 appears adequate. Thus, the autoignition delay time is inversely proportional to the pressure. Mullins (ref. 7) also found the slope to be -1 for kerosene at pressures of 0.1 MPa and below.

In figure 4, the autoignition delay times for several references are compared. The data of references 2 and 3 are for equivalence ratios of 1 and richer, which can be expected to ignite quicker than lean mixtures. The data of reference 4 were for JP-4 fuel. References 2 to 4 determined that the autoignition time varied inversely as the 1.5 to 1.8 power of the pressure. These references used an injector spraying downstream, whereupon mixing and fuel dispersion affected the local conditions and resulted in autoignition. The effect of fuel in the injector wake may be the explanation for the greater slope. The injector of reference 1 had a nozzle flush with the wall and spraying normal to the airflow. Good agreement exists between the data of reference 1 and the data reported herein for the premixing configuration.

References 1, 4, and 7 (as well as others) correlate the autoignition delay time t as a function of temperature T and pressure p by an Arrhenius type of equation

$$t = \frac{ke^{E/RT}}{p^n} \tag{1}$$

where E is the Arrhenius activation energy, R is the universal gas constant, and k and n are empirical constants. A plot of time versus $1/T$ was made for a fixed pressure from the data of figure 3. An Arrhenius activation energy of 41 840 joules per mole (10 000 cal/mole) was determined. This value is in agreement with the data of reference 1 for fuels with cetane numbers of about 30. Reference 1 found that the activation energy decreased as the cetane number of the fuel increased and reports a value of 64 881 joules/mole (15 507 cal/mole) for Avtur fuel. References 2 and 3 found that equation (1) did not hold; that is, a constant activation energy could not be found for kerosene. Reference 4 also found the activation energy to vary with the temperature and pressure levels, reporting values of 184 096 joules per mole (44 000 cal/mole) at temperatures below 750 K to 62 760 joules per mole (15 000 cal/mole) at 800 K.

As the injected fuel flows in the duct, evaporative cooling occurs, as well as preflame reactions including pyrolysis and oxidation. These heat effects result in local changes in the fuel-air mixture temperature. A second experiment was devised to obtain the magnitude and rate of the temperature variations.

Preflame Temperature Rise

References 2, 3, and 5 report a temperature rise attributable to preflame oxidation.

The magnitude of the rise depended on both the inlet air temperature and the tube residence time. Reference 5 reports a preflame temperature rise for Jet-A fuel at an inlet air temperature of 650 K and a pressure of 0. 56 MPa. The magnitudes of the temperature rise depended on equivalence ratio. The local mixture temperature is a function of the fuel mixing, the evaporation rate, the stoichiometry, and the residence time. Reference 2 reports a temperature rise occurring at temperatures above 793 K for an overall equivalence ratio of 2. 2 at 0. 54 MPa pressure.

Figure 5 shows the temperature rise divided by the overall equivalence ratio φ at three levels of inlet air temperature as a function of the tube residence time t. In this figure the residence time was computed by the equation

$$t = \frac{T_{in}}{V_{in}} \int_{x}^{0} \frac{dx}{T} \tag{2}$$

This equation takes into account the temperature variations down the tube for a given tube inlet velocity V_{in} and inlet air temperature T_{in}. The data of figure 5(a) show that at temperatures up to 700 K only cooling occurred, even for equivalence ratios of 1. 0. The fuel-air mixture was cooled as a result of fuel addition and after 5 milliseconds remained constant. The first two thermocouples were probably wetted by liquid fuel. At 760 K (fig. 5(b)), initial preflame reactions occurred; but, after 10 milliseconds, the temperature remained constant. However, at 775 K for an equivalence ratio of 0. 47 (fig. 5(c)), the temperature continued to rise; and, after 22 milliseconds, autoignition occurred. For equivalence ratios greater than 0. 47, autoignition occurred before the data could be recorded. The data in figure 3 and equation (1) predict that a time of 33 milliseconds would be needed before autoignition would be expected to occur. The difference in the two experiments is that the long tube has a high surface area, possibly leading to surface reactions or boundary layer effects. It is also possible that reaction was occurring in the thermocouples wakes. However, the thermocouples could be withdrawn from the center of the tube with no change in the results.

From the data of figure 5, Jet-A fuel exhibits a cool-flame phenomenon, that is, a preflame reaction at 760 K. This temperature rise must be known to size the flameholder open area properly. If the temperature rise is large, the pressure drop across the flameholder will change and the flow split between the primary and secondary zones will change. As the pressure drop across the flameholder increases, less air flows through the premixing tube and the mixture equivalence ratio increases. The resulting situation is unstable and may lead to ignition in the premixing tube depending on the flow pressure drop characteristics.

Flashback Velocities

The long-tube experiment was used to establish fully developed flow at the combustor entrance so that the flashback velocities could be determined. The tube Reynolds number was greater than 1.3×10^5 for all operating conditions. The length to diameter ratio of the tube was 30. By using the gas analysis probe, the mixture distribution leaving the premixing tube was determined to be very uniform. The combustion efficiencies of the step recirculation zone were always greater than 95 percent for all data reported at a location 2.5 centimeters downstream of the step and 3.8 centimeters from the centerline.

The flashback velocities determined from the mass flow rate, pressure, and temperature in the tube, are presented in figure 6. Flashback was determined when the last thermocouple before the tube exit exceeded 1200 K. The flashback velocities ranged from 30 to 65 meters per second and were a strong function of the equivalence ratio. There was not a large increase in flashback velocity as the inlet air temperature was varied from 610 to 700 K. Below an equivalence ratio of 0.55 the combustor would blow out and no flashback data could be taken. The minimum velocity that could be tested was 30 meters per second, which was a facility limitation. The values were identical for the two fuel injectors tested. For the long-tube experiment at higher temperatures, flashback data could not be determined because autoignition would occur. If poor mixing occurs in the premixing tube, flashback may occur in the fuel-rich zones. The flashback velocities reported herein are higher than those at 1 atmosphere reported in the literature.

SUMMARY OF RESULTS

An experimental investigation was conducted to determine the autoignition and flashback characteristics of Jet-A fuel in a premixing-prevaporizing passage. The autoignition delay times are reported at combustor inlet air pressures ranging from 0.54 to 2.5 MPa and temperatures from 550 to 700 K and equivalence ratios from 0.3 to 0.7. The autoignition delay times obtained ranged from 15 to 100 milliseconds and varied inversely with pressure. The Arrhenius activation energy was determined to be 41 840 joules per mole (10 000 cal/mole).

The fuel-air mixture underwent a temperature rise above 760 K that was measured in a long premixing-prevaporizing tube. This preflame temperature rise was a function of equivalence ratio, inlet air temperature, and tube residence time at a pressure of 0.56 MPa. Significant temperature rise occurred above temperatures of 760 K, with autoignition occurring at 775 K for equivalence ratios greater than 0.47. The reactions were similar to cool-flame phenomena.

Flashback velocities were measured at temperatures of 610 and 700 K, a pressure of 0.56 MPa, and equivalence ratios from 0.6 to 1. Flashback velocities varied from 30 to 65 meters per second.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 4, 1977,
505-03.

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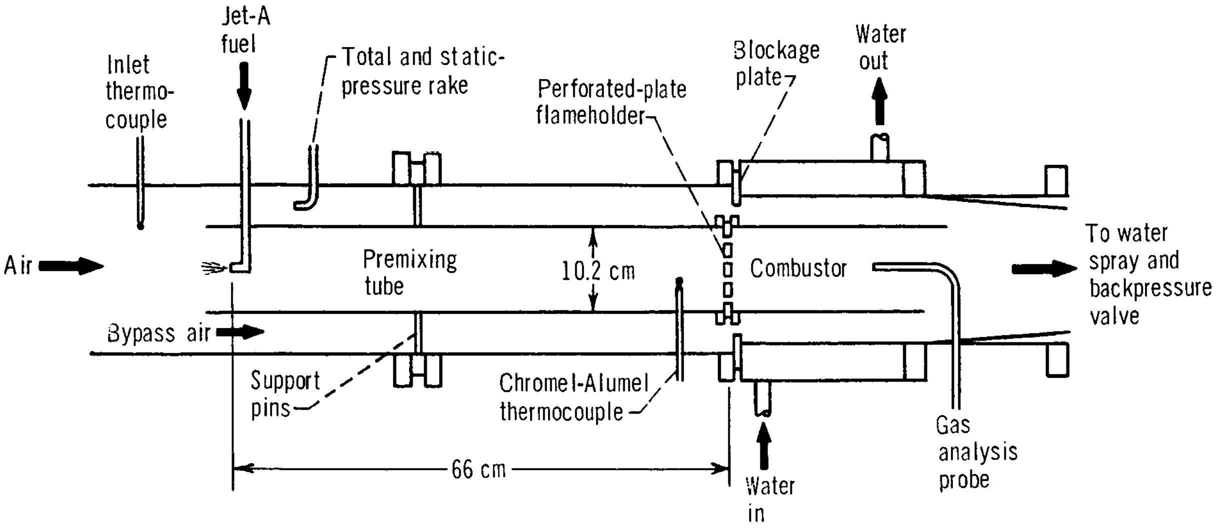


Figure 1. - High-pressure premixing test facility used in autoignition delay time testing.

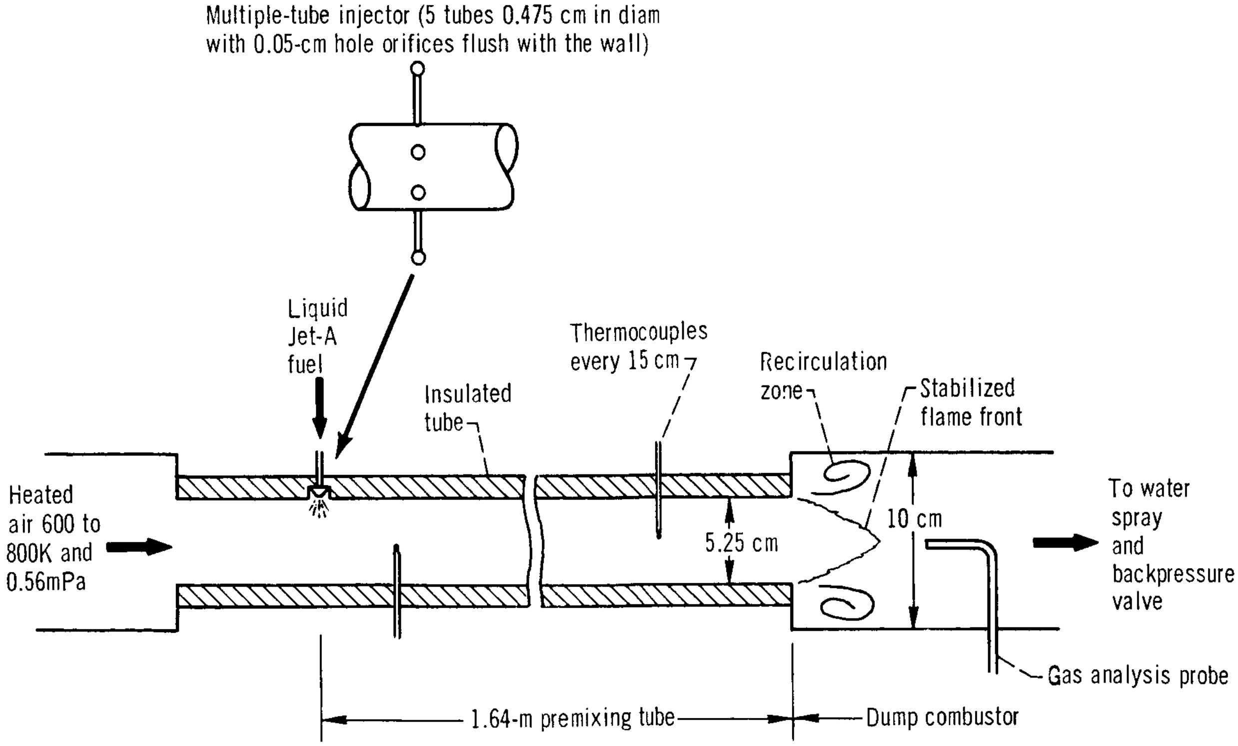


Figure 2. - Long premixing-prevaporizing tube used in preflame temperature rise and flashback velocity testing.

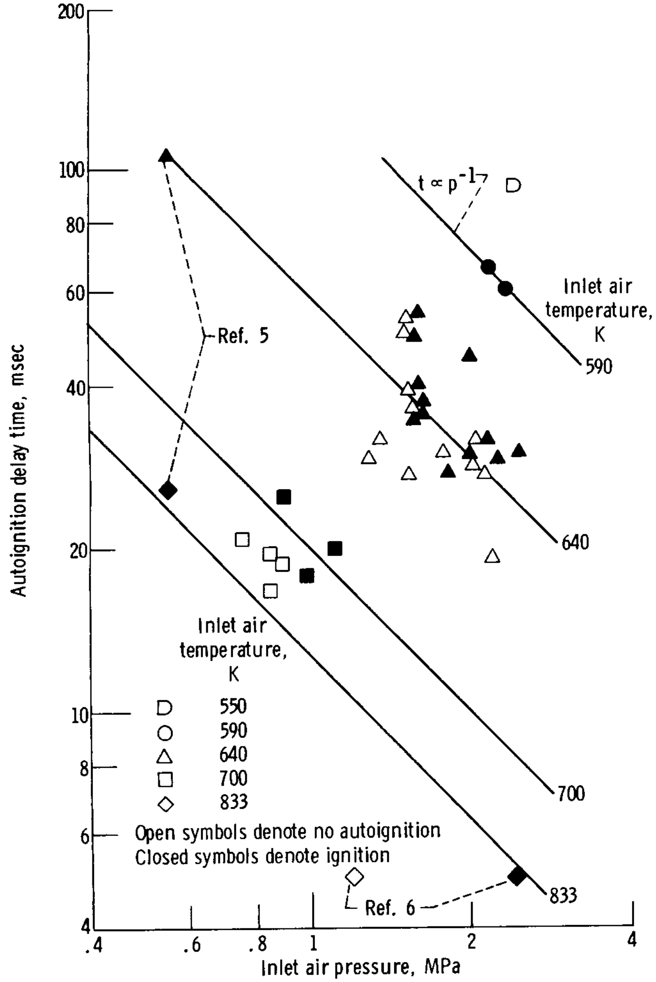


Figure 3. - Autoignition delay time as function of inlet air pressure for several inlet air temperatures.

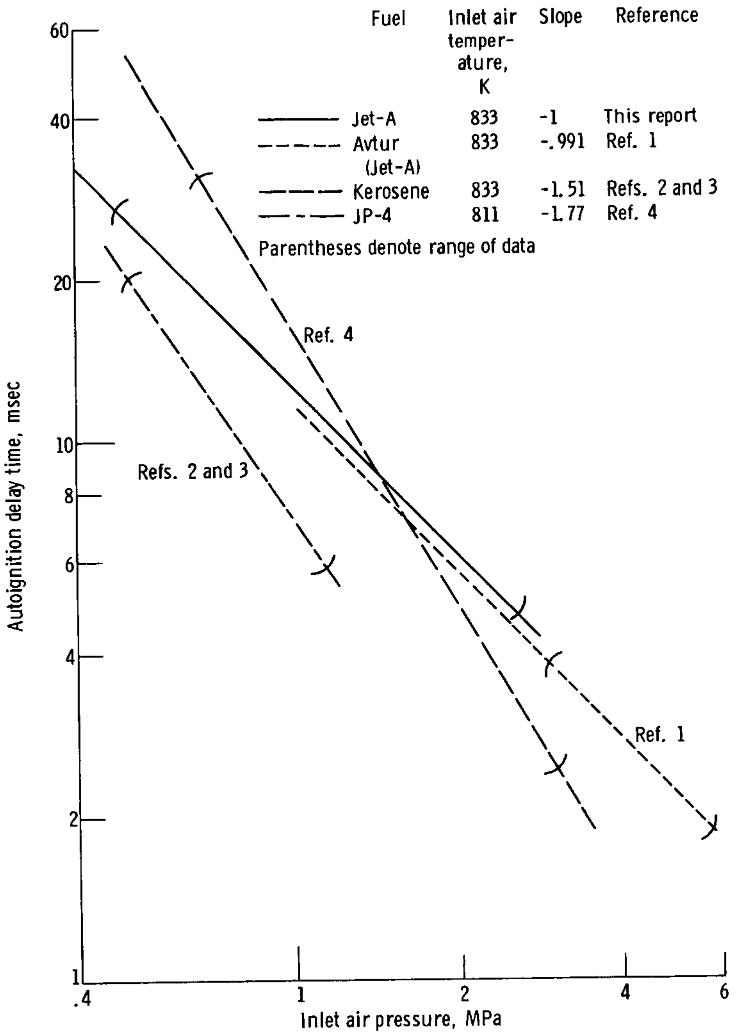
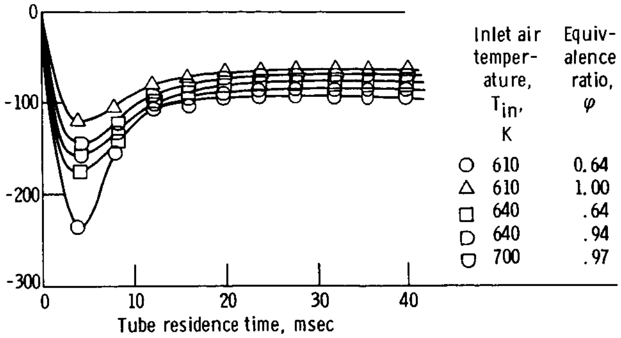
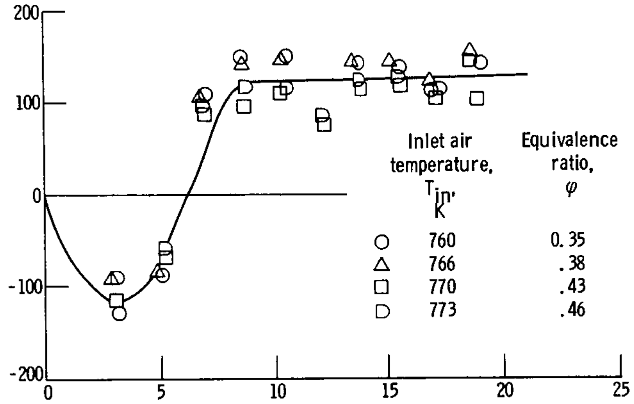


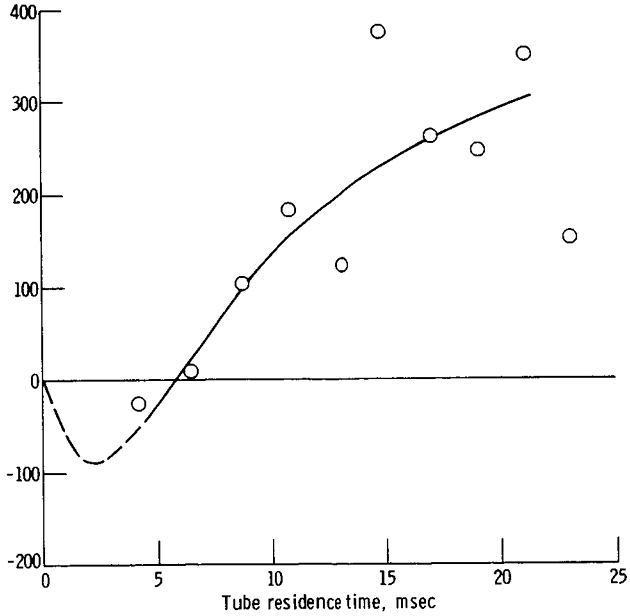
Figure 4. - Comparison of autoignition delay data with literature results.



(a) Inlet air temperature, 610 to 700 K; equivalence ratio, 0.6 to 1.0; tube inlet velocity, 40 meters per second.



(b) Inlet air temperature, 760 to 775 K; equivalence ratio, 0.35 to 0.46; tube inlet velocity, 83 meters per second.



(c) Inlet air temperature, 775 K; equivalence ratio, 0.47; tube inlet velocity, 83 meters per second.

Figure 5. - Preflame temperature rise as function of tube residence time. Inlet air pressure, 0.56 MPa.

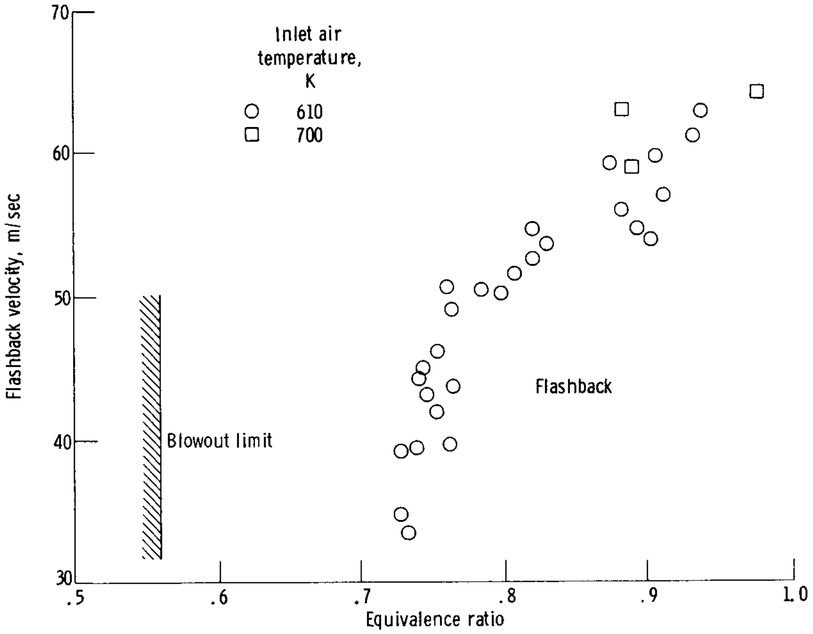


Figure 6. - Flashback velocities for Jet-A fuel as function of equivalence ratio. Inlet air pressure, 0.56 MPa.

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