Experiments on Ignition Delay and Low Limit Boundary for RP-3 Kerosene

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1 Introduction

Ignition delay was measured at different pressure, temperature and equivalence ratio for RP-3 aviation kerosene. Then, the low limit of ignition can be obtained for combustion organization and chamber design in a scramjet.

In experiments, to form a premixed kerosene air mixture is a tough work. Shock tube(ST) is almost a unique test facility for liquid fuel ignition study. Previously, to heat a driven section is used to get kerosene vapour. Possible distillation occurs during heating and makes change of kerosene composition.. Atomized kerosene is identical to the real state in a combustor. So, the first thing is how to form kerosene aerosol and the second to fill it into a driven section in ST. Davidson et al[1] used nebulizer to kerosene drizzle droplets by bath gas argon into ST at the early stage. Subsequently, an aerosol chamber is attached to the test section end in ST by a connecting gate valve[2]. In this paper, an additional tank was used to form the aerosol which is quite similar to inchoate gasoline carburetor. Combined with large tank volume, equivalence can be computed from prescribe pressure and kerosene density. The air instead of argon and oxygen mixes with kerosene by injecting kerosene vertically into a fuel nozzle throat at one plate of the tank with constant aera cross section.

2 Test rig description

A ST with circular cross-section was adopted to study kerosene ignition delay in in Figure1, including a driver section, diaphragm and driven sections and a test section, a mixing tank. A double diaphragm section and a needle piercing section can be interchangeable in ST depending on the pressure difference. The size of each section is illustrated in table 1.

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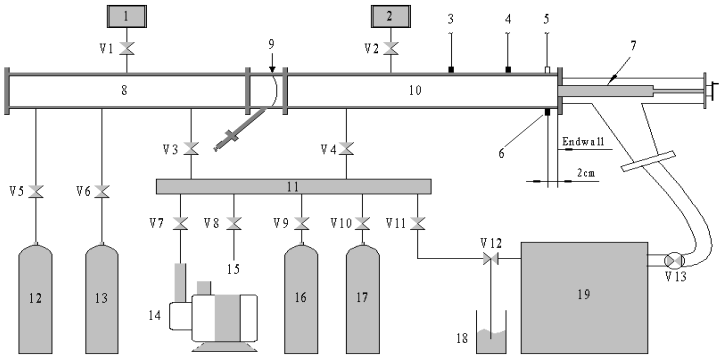
Single BOPP diaphragms (25-100 μm thick, for 90-775 kPa pressure differences) were used for low-pressure tests, ruptured pneumatically. Double diaphragms were used for high-pressure differences,



ruptured by gas discharge. A solenoid, triggered by a DG645 time synchronizer (linked to high-speed imaging), controlled the low-pressure rupture.

Figure1 Schematic of shock tube and auxiliary system(1 pressure gauge 2 vacuometer 3 PCB1 sensor 4 PCB2 sensor 5 optical fiber 6 PCB3 sensor 7 end-inlet piston 8 driver section 9 diaphragm section 10 driven section 11 valve panel 12 nitrogen 13 argon 14 vacuum pumps 15 discharge 16 other bottles 17 air bottle 18 kerosene 19 mixing tank).

Table 1 lengths of components of ST（unit：mm）

driver section	driven section		driven section			inlet piston section
3750	double diaphragm	80	3170	vacuum section	190	630
				low pressure section	2480	
	needle piercing	315		test section	500	

In figure 2 three PCB sensors(model 113A) and one optical port are installed in the test section. A photomultiplier (PMT, R928) to detect OH emission at wavelength 306nm. PMT locates oppositely to PCB3. In figure 5, light from the optical port was collected by lens behind the window and transferred to an optical fiber. Beams pass through a band pass filter before entering into the PMT. The filter central wavelength is 307nm corresponds to OH emission.

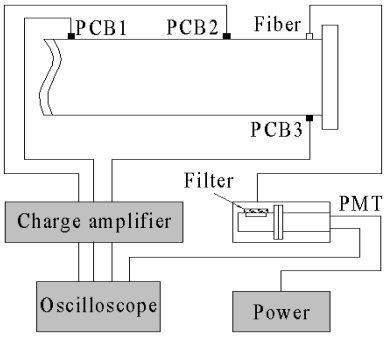
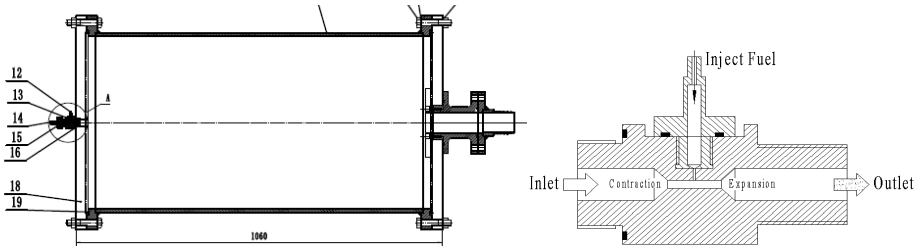


Figure 2Pressure and OH radiations gauges at test section

An inlet piston (60mm diameter) connected the ST end to the mixing tank (Figure 1). Aerosol filled the ST via 64mm pipes when the inlet valve opened; this valve formed the end-wall when closed. This

end-inlet configuration, with a 45° side flange, helped maintain equivalence ratio during filling. The large diameter reduced intake velocity and wall impaction. Phase equilibrium was assumed after wall wetting minimized droplet absorption. Satisfactory repeatability was achieved.

In figure 3a), the stainless mixing tank is in diameter of 0.5m and length of 1.5m. the tank volume is 0.2945m3. Two end plates are made of transparent material PMMA(Polymethyl Methacrylate，PMMA) for observing droplet sedimentation, absorption and hangover during aerosol formation. In figure 3b), a nozzle in diameter of 8mm is screwed into one plate with constant cross section and kerosene is injected vertically from an orifice diameter 1mm at throat into air inflow at sonic speed. Vacuum rubber hose connects to the other plate by a valve to the side flange of the inlet piston. The SMD is 4μm and 5 μm by of laser scattering measurement.



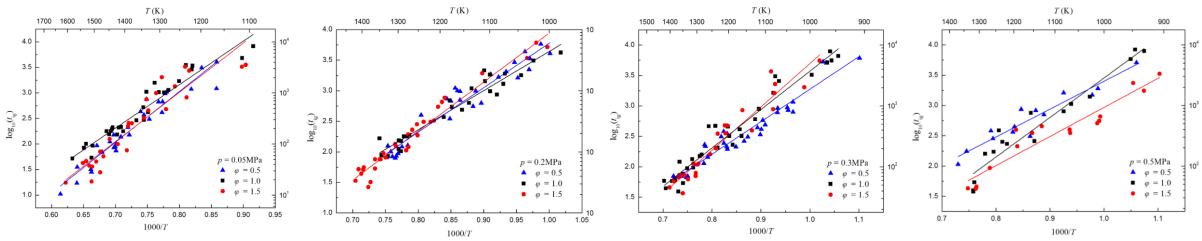
（a）premixed tank （b）kerosene nozzle

Figure 3Premixed tank and kerosene atomizer

3 Results and discussions

3.1 ignition delay

At different pressure, equivalence ratio and temperature, figure 4 depicts ignition delay of kerosene air aerosol. In figure 4 ignition delay decreases with temperature increase as equivalence ratio and pressure are constant. In contrast to gas fuel, kerosene ignition delay data scatter widely. The variation of ignition delay changes with temperature also distinct obviously. i.e. the fitted line slops are different at different equivalence ratio. For the same temperature. The higher pressure complies with the smaller ignition delay. it seems that ignition delay doesn't change so much when pressure is more than 0.2MPa.

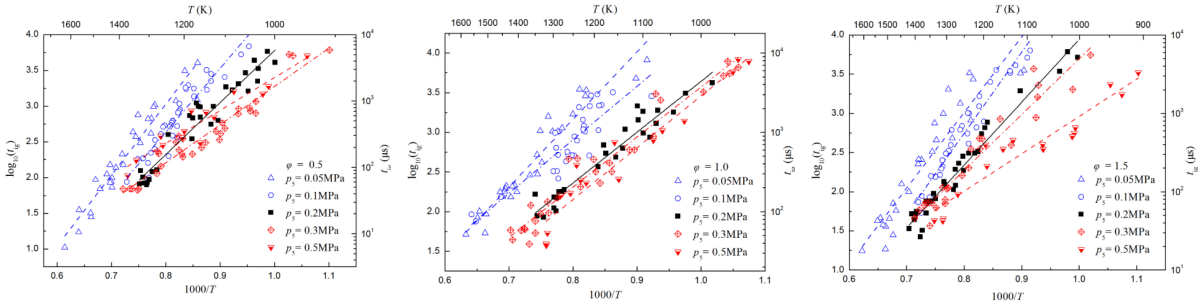


(a) p5 = 0.05MPa (b) p5 = 0.2MPa (c) p5 = 0.3MPa (d) p5 = 0.5MPa

Figure 4ignition delay for RP-3 kerosene at different pressure

Figure 5 presents kerosene ignition delay at different pressures. In figure 6, for a given equivalence ratio ang temperature, ignition delay increases with decrease of pressure. Such difference is evident at low temperature but not at high temperature, For a given equivalence ratio, high pressure extends ignition low temperature limit. In the range of pressures, ignition

delay can be fitted linearly with temperature but with different slopes at different pressure. The reasons are not so clearly.



(a) φ = 0.5 (b) φ = 1.0 (c) φ = 1.5

Figure 5 Ignition delay for RP-3 kerosene at different equivalent ratio

Figure 6 compares stoichiometric ignition delays (τ_ig) with referenced studies. Differences observed likely stem from experimental variations. For instance, Liao[3] used a rectangular shock tube, which can induce flow non-uniformities due to complex shock/boundary layer interactions not present in our circular tube. Additionally, Liang[4] heated the driven section, potentially altering the kerosene composition before experiments.Measured τ_ig includes both physical delay (droplet heating, breakup, evaporation) and chemical delay (reaction kinetics). While chemical delay often dominates at high temperatures, the physical delay becomes increasingly important for kerosene aerosols at lower pressures and temperatures, as droplet phase change time contributes significantly to the overall τ_ig. Thus, especially when evaporation isn't instantaneous, the measured delay reflects both physical and chemical processes.

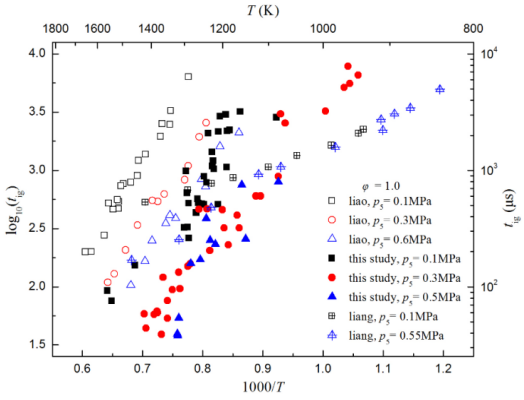


Figure 6 Comparison of RP-3 kerosene ignition in this paper and references

3.2 fitted relation for ignition delay

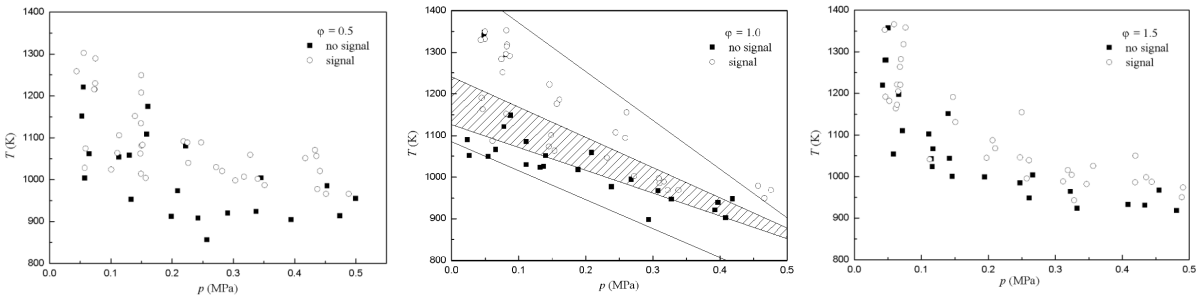
To know some data outside the experimental cases and general dependence on variables, ignition delay can be fitted as function of pressure, temperature and equivalence ratio by regression of polynomial linear function. The generalized Arrhenius function is obtained.

$$t_{ig} = 1.93 \times 10^{-4} p^{-0.907\pm0.041} \varphi^{0.043\pm0.062} exp(\frac{15626 \pm 332}{T}) R^2 = 0.874 (1)$$

Where t_{ig} is ignition delay and unit is μs. p is pressure and unit is MPa, φ is aerosol equivalence ratio. Regression coefficients express the variable sensitivity. Equation (1) denotes that ignition delay is strongly depends on pressure and temperature, but weakly on the equivalence ratio due to the correlation coefficient is 0.043 which is approximately to zero. Referring to the state pressure is 0.1MPa and equivalence ratio is 1.

3.3 Ignition boundary for RP-3 kerosene

The low-temperature ignition boundary (success/fail points in Figure 7) was found by reducing temperature at constant P and φ. The transition occurred over a temperature range ('transition zone'), indicating probabilistic ignition near the limit. This zone likely results from: (1) ST shot-to-shot variations; (2) competing low-T reactions; (3) flow non-uniformities; (4) complex chemistry-flow interactions; and increased wall heat loss at long τ_ig.Meanwhile, long delay leads to high wall heat loss rate at low temperature.



(a) φ = 0.5 (b) φ = 1.0 (c) φ = 1.5

Figure 7 Low limit for RP-3 kerosene ignition

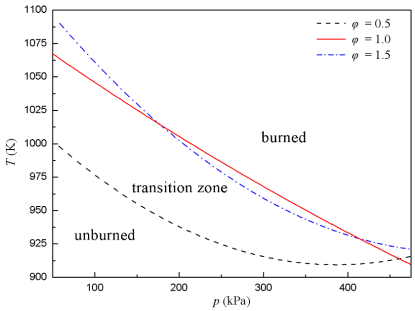


Figure 8 Fitted curve of kerosene ignition delay boundary

In order to get rough understanding of ignition low limit, the data in ignition transition zone was fitted at different equivalence ratio, by using quadratic polynomial fitting software Origin Pro, i.e. $y = y_0 + Bx + Cx^2$. Figure 8 illustrates the low limit curve of kerosene ignition delay after fitting the data. In figure 8, the ignition delay boundaries for equivalence ratio 1.5 and 1 are quite close but differs from that of equivalence ratio 0.5. Obviously, for fuel lean mixture(φ =0.5), the ignition boundary is extended to low pressure and high temperature. But in high pressure, the low limits of ignition boundary delay are all very close to each other, but the reasons are not clearly at present.

4 Conclusions

(1) In the range of pressure at 0.05MPa, 0.1MPa, 0.2MPa, 0.3MPa and 0.5MPa, and equivalence ratio at 0.5, 1.0 and 1.5 and temperature from 900K to 1700K, the ignition delay is from 11μs to 8384μs. At the same pressure and equivalence ratio, ignition delay decreases with increasing temperature. Log 10(τ_ig) changes with 1000/T linearly. This function is just an approximate Arrhenius experimental correlation. The measure data scatters across the both sides of the line. Line slopes depend on pressure and equivalence ratio.

(2) Ignition delay can be fitted as a function of pressure, temperature and equivalence ratio. The fitted ignition delay strongly depends on pressure and temperature but less on equivalence ratio.

(3) Low limit boundary of ignition is not a discontinuity but a transition region with bounded pressure, temperature and equivalence ratio. For simplicity, a two-dimensional curve and three dimensional surface can be fitter by a polynormal formulation with two or three variables. Success and fail ignition can be reached across the discontinuous curve and surface.

(4) Ignition delays in this paper differ from those in references but not so much. Fuel composition, diaphragm bursting, bath gas and ST cross-section affect the kerosene ignition delay. Kerosene composition and bath gas argon instead of nitrogen both influence the elementary reactions. Rectangular cross section ST lead to complex shock and boundary interaction and induce inhomogeneous flow field in spite of easy observation. Aerosol formation and filling process, bursting diaphragm determines the repeatability of test conditions.

References

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