Altitude Ignition by Reducing IDT at Low Pressure with Additive

Zhijia Chen

School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai, P. R. China

E-mail: czj2018@sjtu.edu.cn

Xiaobin Huang (corresponding author)

School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai, P. R. China

Fax: +021 54747142

E-mail: xbhuang@sjtu.edu.cn

Hong Liu

School of Aeronautics and Astronautics, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, P. R. China

Abstract: Altitude ignition is essential for the design of aero-engines, which is critical to the aircraft flight safety. Various factors have been studied to stimulate the success of ignition. However, the study on the ignition at low pressure (less than 1 atm) is rare. At the altitude of 10,000m, the typical pressure of combustor inlet lowers to 0.26 atm. Such low pressure leads to significant increase of the ignition delay time (IDT) and may result in flameout and unsuccessful relight. Not only the range of flight envelope is limited, but also it is a hidden danger during flight. This paper is dedicated to investigate an additive to enhance the low-pressure ignition by reducing the IDT of the fuel. Particularly, methoxydiethylborane (MDEB) was chosen as the additive with n-decane as the surrogate fuel. The modified fuel with different concentrations all performed well in a hot surface experiment. The results show that the IDT is decreased from 1235ms to 70ms at 0.9 atm with 20% MDEB even with a lower ignition temperature of 623K with respect to 923K. The results on other pressures also validate the efficacy of the MDEB additive for reducing the IDT or even enhance the ignition success. Two kinetic parameters A and B were introduced to explain the reaction mechanism among different conditions. This work shows a novel paradigm to reduce the IDT at low pressure by adjusting the fuel combustion characteristic. Moreover, the IDT with different initial pressures can also be derived by the proposed predictor with boundary condition.

Keywords: *low pressure, fuel additive, n-decane, ignition delay time, correlation*

1 Introduction

Aero-engine plays a vital role in the performance of flight, as it is the power plant for almost all aircrafts. Thus, several basic requirements of combustor are listed although the relative importance varies between different engine types, e.g., reliable ignition and short ignition delay, not only on the ground but also at high altitude [1]. At high altitude, fuel may be unignited due to the narrowed ignition range [2] and the flight safety of aircraft will not be guaranteed [3]. The characteristic "time" is generally used to describe the limit of ignition, which associates with multiple physical and chemical processes such as evaporation, mixing and chemical reaction [4]. A countermeasure against high altitude ignition is to reduce the characteristic "time".

There are a lot of published researches on fuel preparation and operating conditions. Tomoaki et al. [5] found that the evaporation rate of droplet is decreased with the increasing of pressure, and nature convection will accelerate droplet evaporation more effective. Experiments were also conducted on different samples at atmospheric pressure to investigate the evaporation characteristics, which were used to verify the practicable of PME as an alternative fuel [6]. A new trapped vortex annular combustor was developed, in which the concept of the trapped vortex combustion is used in aero-engines design to improve the high altitude ignition [7]. Fuel will be introduced into the cavities, which will enhance mixing of fuel and air to reduce the mixing time. These studies set out with the same aim of discovering the influencing factors of physical processes and minimizing the required characteristic times.

Among the combustion properties of fuel, ignition delay time makes a contribute to total ignition delay and is examined carefully to evaluating the combustor design [8]. Zhukov et al. [9] measured the IDT for mixture of Jet-A with air at pressures of 10 and 20atm. The experimental data is fitted to an expression where the IDT has the quasi-Arrhenius dependence on pressure, temperature and equivalence ratio. Zhang et al. [10] studied the IDT of gas-phase RP-3/air mixture in a heated shock tube at a wide pressure range of 1-20 atm. And these data are in good agreement with those obtained from Jet-A. Mao et al. [11] carried out similar studies in a heated rapid compression machine and a heated shock tube, which provides a further insight into the effect of pressure on IDT of RP-3. The IDT of n-decane which is used as jet fuel surrogates [12], was investigated both at a low pressure range of 1.82- 20 atm [13] and at a high pressure range from 10 atm to 80 atm [14]. In these detailed studies, it conclusively shows that IDT is strongly associated with pressure. The value of IDT increased with the decline of pressure within the test situation.

Fuel additives offer an effective way of enhancing the ignition characteristic. It has been extensively reported that metal nanoparticles can be implemented to reduce the IDT due to the availability of high reactive surface area [15]. But the stability aspect of nanofluids and the limited experimental findings hindered the usage in commercial applications. In order to increase the sensitivity of JP-10 in air with high temperature and high pressure, some additives have been studied, which are methylated PCU alkene dimer, nitronorbornane, dinitronorbornane, and ethyl–hexylnitrate. But the results showed that the IDT of JP-10 did not lower obviously [16]. While some aluminum alkyls show a significant capability in reducing the IDT of JP-10 at an initial pressure approximate to 30 atm in a constant volume combustion bomb [17]. This rather surprising finding might provide a feasible method in reducing IDT of fuel by using metal alkyls as fuel additives under an extreme condition. However, rare studies have attempt to investigate the effect of additive acting in a low pressure.

This study set out to explore the effect of fuel additive on IDT and proposed a predictor of IDT with different initial pressure. N-decane and MDEB were chosen as the surrogate fuel and fuel additive respectively. The data obtained from these experiments show a well performance of this method at a low pressure. A further exploration of the effect of low pressure on IDT is provided.

2 Experimental methods

2.1. Modification of fuel

First, in this study, n-decane (CAS No: 124-18-5) with a purity of 99% was procured from Aladdin Industrial Corporation and MDEB (CAS No: 7397-46-8) with a purity of 97% was procured from Infinity Scientific (Beijing) Co. Ltd. The basic physical and chemical properties of these two reagents are listed in table 1.

The formula of modified fuel was as follows: the volume ratios of n-decane to MDEB were 9:1, 8:2 and7:3. The pure n-decane and modified fuel with different MDEB concentrations will be tested both in the atmosphere and in a low pressure.

Table 1 Properties of two reagents

	Physical State	Density, g/cm3 @20℃	Molecular Weight, g/mol	Flash Point, ℃
n-Decane	Liquid	0.735	142.28	46
MDEB	Liquid	0.868	99.97	-6

2.2. Experimental setup

Fig. 1 shows an overview of the experiment device. It is observed that a hot surface is placed on the stainless chamber. The hot surface is made of copper and a rectangular dimension of 150 mm×150 mm×20 mm. The temperature of the hot surface is measured by a K-type thermocouple which is located below the hot surface and has an accuracy of ±2 K.

The instantaneous temperature data is transmitted to the temperature controller. A PID pattern is used to keep the constancy of temperature. The temperature of hot surface may range from ambient temperature to 950K. A vacuum pump is used to regulate the pressure inside the stainless chamber. The pressure varies from 1 atm to 0.1atm which is measured by a pressure gauge with an accuracy of 0.02 atm. In the center of the surface, a hemispherical groove, with a radius of 5 mm, was built for inhibiting the falling droplets from sliding off. The needle tube enters the chamber through an opening. The droplet is allowed to fall at a height of 15 mm. The ignition process is recorded by a high speed camera with a sample rate of 500 pps. A typical process is followed during these experiments. The droplet is generated by a medical syringe, and falls onto the groove. After a short delay, the droplet may be ignited and the whole process is recorded.

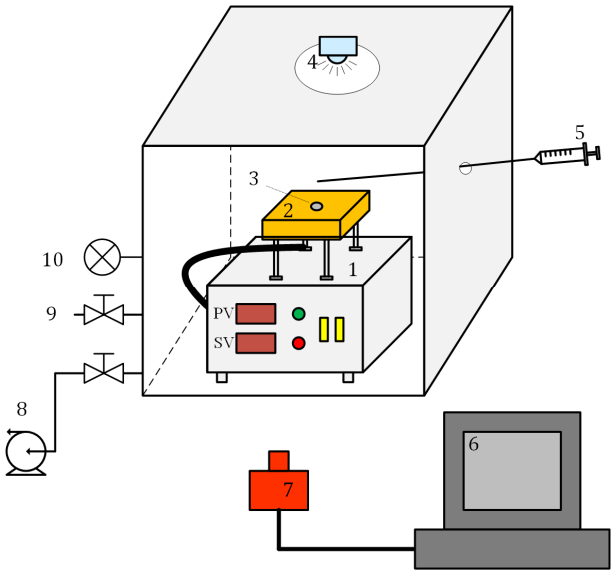

Fig. 1. Scheme of the experimental device. (1) Temperature controller, (2) Hot surface, (3) Fuel drop, (4) LED light, (5) Injector, (6) Computer, sealed chamber, (7) High speed camera, (8) Vacuum pump, (9) gas inlet/outlet pipes, (10) pressure gauge.

3 Results and discussion

3.1. Derivation of the Arrhenius expressions for IDT

Ignition will occur when the rate of chemical reaction suddenly increases sharply. While ignition phenomenon is of great relevant to the chemical process which contains many interwoven reactions among varies reactant. It is meaningful to build a simple model to describe the ignition behavior. By assuming that an equivalent aggregate reaction will substituting for complex combustion process, the gross parameters have a general form [18]:

$$\frac{d(x)}{dt} = \Phi_1(P,T,t), \quad \Phi_2(F, chemical\ \text{composition}, etc.) \tag{1}$$

where (x) in mol/L, t in millisecond, P in atm, and T in K, are concentration of pertinent reaction products, reaction time, pressure and temperature, respectively. F is a proportional coefficient that represents the fuel-air ratio. And Φ_1, Φ_2 are empirical functions.

For the ignition occurs in the gas phase, it is practicable to have the following expression [19]:

$$\frac{d(x)}{dt} = K_1 P^n \Phi_2(F, chemical\ \text{composition}, etc.) \tag{2}$$

where K_1 is a rate constant related to temperature, pressure etc., which can be determined either in a computational method or in an experimental method. The power n varies from 0.5 to 2.5 in the literature, which represents the reaction order. Particularly, n is a constant without unit. The unit of K_1 depends on the value of n and has a general formula [20], $(mol/L)^{1-n} \cdot s^{-1}$.

Then the temperature is considered. Temperature influences the rates of chemical reactions almost always in terms of what is known as the Arrhenius equation [21]. In this equation, the rate constant K_1 can be calculated by multiplying the front factor A and the exponential term. So, Eq. (2) can be written as

$$\frac{d(x)}{dt} = Ae^{(-\frac{E}{RT})} P^n \Phi_2(F, chemical\ \text{composition}, etc.) \quad (3)$$

where the ideal gas law constant R is 8.314 $J \cdot \text{mol}^{-1} \cdot K^{-1}$ and E is the activation energy in $J \cdot \text{mol}^{-1}$. Often A and E can be treated as temperature independent. Thus, $\frac{E}{R}$ can usually be rewritten as B.

When pressure and temperature are constant, kinds of species and equivalent ratio are also determined before the reaction. Time t at which ignition occurs is obtained by a straightforward integration of Eq. (3) from the start of the reaction to ignition. It becomes [22]

$$t = AP^{-n} \exp\frac{B}{T} \quad (4)$$

This is the most common method of correlating ignition delay to temperature and pressure. Once the empirical constant A, n and B are determined, the IDT at a specific temperature and pressure can be predicted by this expression.

3.2. Effect of additive on ignition delay time

Here, IDT is defined as the time interval from the droplet contacts with the surface of the hot plate to the occurrence of fire. To assess whether the selected additive works well in this system, the IDT of pure n-decane and modified fuel with different MDEB concentrations were measured. The ignition data measured at 1 atm are presented in Fig. 2. Particularly for pure n-decane, its IDT are 1094ms and 1235ms corresponding to the pressure of 1 atm and 0.9 atm at 873K, respectively. And the pure n-decane was not ignited when the pressure reduced to 0.8 atm.

Since P is a constant equal to 1 atm in this case, Eq (4) can be rewritten as

$$t = A\exp\frac{B}{T} \quad (5)$$

The correlation between IDT and temperature was established in Fig. 2. Table 2 presents the value of parameters and correlation coefficients R^2 of these expressions. Although it shows a good fit to the Arrhenius expression in MDEB concentrates of 20% and 30%, the relevance coefficient is

only 0.731 when the concentrate of MDEB is 10%.

It is noticed that the IDT increased when the temperature changed from 573 K to 623K. It might attribute to the NTC (negative temperature coefficient) phenomenon [23] which is related to the formation of alkylperoxy: R + O2 = ROO. In this condition, a two-stage ignition must be employed, instead of the single-stage ignition as we assumed before. Considering this situation and the convenience of operation, the modified fuel with a MDEB concentration of 20% was chose for further study.

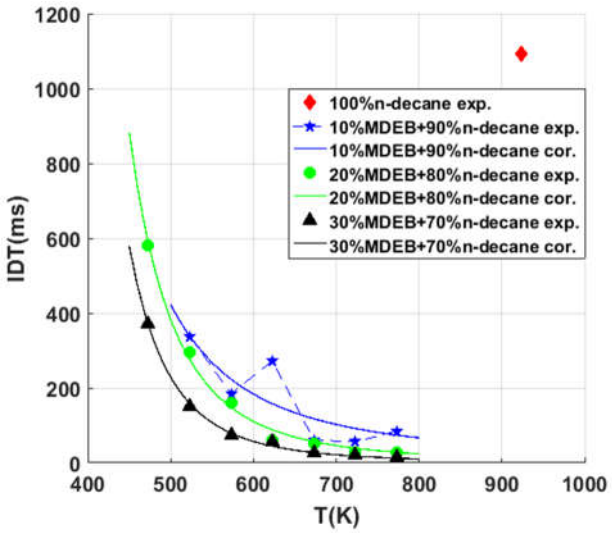

Fig. 2. Ignition delay time vs. temperature with different concerntration of MDEB

Table 2 Correlation parameters for mixtures using $t = A\exp(\frac{B}{T})$ at 1 atm

	A	B	R2
10%[a].	3.001	2471	0.731
20%	0.2212	3730	0.9943
30%	0.0559	4160	0.9971

[a.] concentration of MDEB

According to the experimental data, the expression of ignition delay time over a certain range operating conditions is fitted by Eq. (4). With a correlation coefficient (R^2) of 0.99, the IDT can be calculated with the formula:

$$t = 0.05832 * P^{-1.522} \exp\frac{4408}{T} \qquad (6)$$

where the power n of P equals to 1.522, which is consistent with the empirical range of 0.5 to 2.5 mentioned in literature [20]. And this predictor may play an important role in verifying combustion reaction mechanism and chemical kinetics modeling. Furthermore, Fig.3 depicts IDT as a function of temperature and pressure in a three-dimensional view. It may be helpful when the data matches the engine conditions.

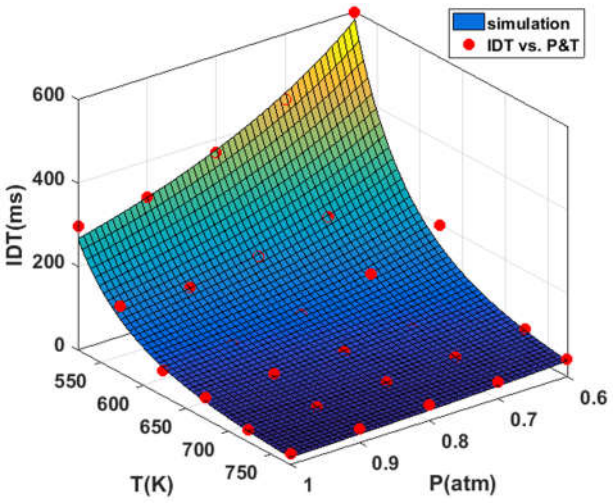

Fig. 3. Three-dimensional view of the ignition delay time surface for 20% MDEB.

In order to get a better understanding on how the pressure affects the IDT, a series of experiment data of the IDT versus temperature at several different pressures were employed. Although a modified fuel with a MDEB

concentration of 20% can be ignited at a lower pressure, only the case of 0.6 atm or more was studied due to the difficulty in realization of experimental operation. According to different pressure classifications, these data were also fitted to the form of Eq. (4). respectively. It should be emphasized that the value of n here is 1.5, which is calculated before. The parameter results from the fitted data are shown in Table 3. In these class, all values show a good fit with correlation coefficients (R^2) higher than 0.99.

The correlation between IDT and pressure is interesting because the curves representing 1 atm and 0.9 atm are so close that the effect of pressure on the IDT in this range can not be easily distinguished from Fig. 4. Turning now to table 3, a tendency of kinetic parameters A and B to be associated with pressure was found. In fact, the physical meaning represented by A is the collision frequency and B is a parameter positively related to activation energy. The parameter A decreases as the pressure reduces, which may be due to the lower concentration of species at low pressures resulting in low collision frequencies. The parameter B increases with decreasing pressure, which indicates that the global activation energy increases when the pressure decreases.

Moreover, there is a significant difference in the case of 0.8 atm. It does not meet the trend mentioned above. Since this difference has not been reported in previous experimental studies, it is probably due to a coupling of gas phase species accumulation and collision frequency. Although the low pressure causes a decrease in the frequency of collision of fuel with oxygen, it contributes to a thicker fuel profile in the gas phase due to worse heat loss. The detailed reaction mechanism will be studied in future research.

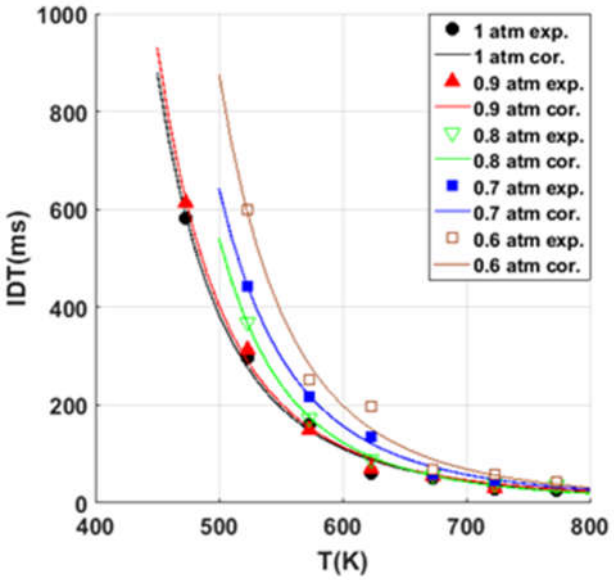

Fig. 4. Ignition delay time vs. temperature with different pressure.

Table 3 Correlation parameters for mixtures using $t = AP^{-1.522}\exp(\frac{B}{T})$ with 20% MDEB.

	A	B	R2
1 atm	0.2212	3730	0.9943
0.9 atm	0.1828	3769	0.9958
0.8 atm	0.05585	4419	0.9974
0.7 atm	0.08175	4213	0.9960
0.6 atm	0.05534	4447	0.9841

4 Conclusions

This study has examined the impact of pressure on low pressure ignition. According

to the results of the hot plate test, the pure n-decane will have a long IDT which may be as high as 1235ms at 0.9atm when the setting temperature is 923K. While fuel modified by MDEB shows a good ability in reducing ignition delay. Experiments have been carried out to prove that the ignition delay time will be more effectively reduced as the concentration of the additive increases. With 20%MDEB, all recorded IDTs are less than 700ms with a wide pressure ranged from 0.6 atm to 1 atm and a lower temperature ranged from 473K to 773K. These results suggest that MDEB is an effective additive in n-decane.

In order to find out the variation law of IDT and mechanism of effects of on ignition. A correlation expression was derived. As expected, IDT is positively correlated with temperature and pressure. Then the change of IDT is attributed to the kinetic constants A and B. Since there are still some unverified assumptions and the expression of the ignition delay time is successfully constructed, a further study examining the detailed reaction kinetics would be practicable.

Overall this study confirmed that it is a feasible method for reducing IDT at low pressure with MDEB as the fuel additive. It provides a viable idea for improving the ignition performance at high altitude. It is believed that this method will contribute to widening the flight envelope through careful design.

Acknowledgment

The authors gratefully appreciate the financial supports from the National Natural Science Foundation of China (No. 91441205).

References

[1] Lefebvre, Arthur H., and Dilip R. Ballal. Gas turbine combustion: alternative fuels and emissions. CRC press, 2010.

[2] DiPiazza, James T. Limits of flammability of pure hydrocarbon-air mixtures at reduced pressures and room temperature.1951.

[3] Rosa, Nicolas Garcia, Guillaume Linassier, Renaud Lecourt, Philippe Villedieu, and Gerard Lavergne. Experimental and numerical study of high-altitude ignition of a turbojet combustor. Heat Transfer Engineering 2011, 32(11-12), 949-956.

[4] Andreadis, Dean. Altitude Ignition/Lean Decel Study. No. P/W/GPD-FR-18710. PRATT AND WHITNEY WEST PALM BEACH FL GOVERNMENT PRODUCTS DIV, 1985.

[5] Kitano, T.; Nishio, J.; Kurose, R.; Komori, S., Effects of ambient pressure, gas temperature and combustion reaction on droplet evaporation. Combustion & Flame 2014, 161 (2), 551-564.

[6] Hashimoto,N. ; Nomura, H. ; Suzuki, M.; Matsumoto, T.; Nishida, H.; Ozawa, Y., Evaporation characteristics of a palm methyl ester droplet at high ambient temperatures. Fuel 2015, 143, 202-210

[7] Zhao, Dan, Ephraim Gutmark, and Philip de Goey. A review of cavity-based trapped vortex, ultra-compact, high-g, inter-turbine combustors. Progress in Energy and Combustion Science 2018,66 , 42-82.

[8] Keller, J. O., T. T. Bramlette, C. K. Westbrook, and John E. Dec. Pulse combustion: The quantification of characteristic times. Combustion and flame 1990, 79(2), 151-161.

[9] Zhukov, Victor P., Vladislav A. Sechenov, and Andrey Yu Starikovskiy. Autoignition of kerosene (Jet-A)/air mixtures behind reflected shock waves. Fuel 2014, 126, 169-176.

[10] Zhang, Changhua, Bin Li, Fan Rao, Ping Li, and Xiangyuan Li. A shock tube study of the autoignition characteristics of RP-3 jet fuel. Proceedings of the Combustion Institute 2015, 35(3), 3151-3158.

[11] Mao, Yebing, Liang Yu, Zhiyong Wu, Wencao Tao, Sixu Wang, Can Ruan, Lei Zhu, and Xingcai Lu. Experimental and kinetic modeling study of ignition characteristics of RP-3 kerosene over low-to-high temperature ranges in a heated rapid compression machine and a heated shock tube. Combustion and Flame 2019, 203, 157-169.

[12] Pitz, William J., and Charles J. Mueller. Recent progress in the development of diesel surrogate fuels. Progress in Energy and Combustion Science 2011, 37(3), 330-350.

[13] Olchanski, Erna, and Alexander Burcat. Decane oxidation in a shock tube. International journal of chemical kinetics 2006, 38(12), 703-713.

[14] Zhukov, Victor P., Vladislav A. Sechenov, and Andrey Yu Starikovskii. Autoignition of n-decane at high pressure. Combustion and Flame 2008, 153(1-2) , 130-136.

[15] Saxena, Vishal, Niraj Kumar, and Vinod Kumar Saxena. A comprehensive review on combustion and stability aspects of metal nanoparticles and its additive effect on diesel and biodiesel fuelled CI engine. Renewable and Sustainable Energy Reviews 2017, 70, 563-588.

[16] Mikolaitis, David W., Corin Segal, and Abhilash Chandy. Ignition delay for jet propellant 10/air and jet propellant 10/high-energy density fuel/air mixtures. Journal of propulsion and power 2003, 19(4),601-606.

[17] Ryan III, T. W., S. T. Schwab, and W. Harlowe. Aluminum alkyl derivatives-Ignition and combustion enhancers for supersonic combustors. Journal of Propulsion and Power 1995, 11(1) ,124-129.

[18] Livengood, J. C., and P. C. Wu. Correlation of autoignition phenomena in internal combustion engines and rapid compression machines. In Symposium (international) on combustion, 1955, 5(1), 347-356.

[19] Lefebvre, Arthur Henry, William G. Freeman, and Luke H. Cowell. Spontaneous ignition delay characteristics of hydrocarbon fuel-air mixtures. 1986.

[20] Levenspiel, Octave. Chemical reaction engineering. Industrial & engineering chemistry research.1999.

[21] Laidler, Keith J. The development of the Arrhenius equation. Journal of Chemical Education 1984, 61(6), 494.

[22] Douaud, A. M., and P. Eyzat. Four-octane-number method for predicting the anti-knock behavior of fuels and engines. SAE Transactions 1978, 294-308.

[23] Fu, Xiao, and Suresh K. Aggarwal. "Two-stage ignition and NTC phenomenon in diesel engines." Fuel 2015,144, 188-196.