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Study on Ignition Characteristics of Rocket Kerosene in Oxygen-rich Atmosphere

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ABSTRACT

In order to understand the ignition risk and fire hazard of LOX/kerosene leakage at space rocket launching sites, the experimental methods of kerosene ignition in oxygen-rich atmosphere will be established focusing on fire safety issues of kerosene. The mixture of oxygen and kerosene vapor was formed in a semi-closed experimental space by heating rocket kerosene, while the ignition test of rocket kerosene under different initial kerosene temperature and oxygen concentration were carried out by electric ignition. The results showed that the ignition risk of kerosene vapor increased with the increase of oxygen concentration, while the ignition energy required for kerosene ignition decreased with the increase of oxygen concentration. The ignition energy required for ignition of kerosene had a better linear relationship with the reciprocal of the kerosene initial kerosene temperature. Under the condition of same oxygen concentration, the higher initial kerosene temperature, the smaller the ignition energy required for ignition of kerosene. By theoretical analysis of the relationship between kerosene ignition energy(*E*) and ignition time(τ), oxygen concentration (x) and initial oil temperature(*T*), the ln(E/T^2) and ln(*t*) can be correlated well with the form of (k/T+C(x)), where *k* is a constant and C(x) is also a constant related to the oxygen concentration. The research results can provide key scientific data and models for the fire risk assessment of LOX/kerosene leakage.

Keywords: oxygen-rich atmosphere, rocket kerosene, initial kerosene temperature, ignition time, ignition energy

NONMENCLATURE

Abbreviations	
min	Minimum
conv	Convective
rad	Radiant
l	Loss
vap	Vapor
ox	Oxygen
Symbols	
E	Ignition energy
E_{min}	Minimum ignition energy
$\dot{q}''_{conv}$	Convective heat
T	Kerosene temperature
x	Oxygen concentration percent
$\dot{q}''_{rad}$	Radiant heat
$\dot{q}''_{vap}$	Vapor heat
h	Convective heat transfer coefficient
T_f	Temperature of ignition spark
T_b	Boiling temperature
σ	Radiant heat transfer coefficient
h_e	Heat transfer coefficient of electrode
T_∞	Environmental temperature
k	Correction factor
r_{min}	Minimum ignition energy corresponds to the fireball radius
ρ	Density
c_p	Isobaric heat capacity
T_m	Adiabatic flame temperature
E_a	Activation energy
λ	Thermal diffusion coefficient
R	Gas constant
Y_F	Fuel concentration
Y_{ox}	Oxygen concentration
h_{fg}	Enthalpy of vaporization

1. INTRODUCTION

Among all kinds of accident risks in the space launch site, fire and explosion caused by propellant leakage is

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the most serious [1-2]. For example, the Nedelin catastrophe or Nedelin disaster was a launch site accident which occurred on 24 October 1960 at Baikonur test range due to unexpected firing ignited leaking fuel. And Falcon 9 of the United States exploded due to an electrostatic spark near the liquid oxygen storage tank during the pre-launch fuel filling process [3-4]. This series of tragic accidents caused new thinking about the safety of domestic space launch technology, especially the critical safety condition for fuel leakage.

The rocket propellant combination of liquid oxygen and kerosene has the advantages of high thrust, high density specific impulse and good economy, and is one of the main propellant combinations of launch vehicles in the world. LOX/kerosene is prone to leakage during the filling and transfer operation, and the leakage of liquid oxygen can form potentially dangerous high oxygen concentration. The mixture of kerosene and oxygen may cause deflagration, detonation, explosion and other dangerous accidents when a small electric spark or flame is encountered [5]. Different from standard atmosphere, the rocket kerosene is easily ignited by an unexpected spark in oxygen-rich atmosphere although the rocket kerosene has a higher flashing point [6]. According to activation energy theory, the increase of oxygen concentration will significantly improve molecular collision probability and the chemical reactivity, and the critical ignition temperature of combustible should be reduced, and the ignition energy should be smaller and easier to be ignited [7]. To date, researchers have put emphasis on the combustion efficiency of engine and exhaust emission; however, less work has been conducted to reveal the safety issue of this fuel, especially in oxygen-rich atmosphere even pure oxygen.

Ignition energy and ignition time are important parameters for studying ignition characteristics of kerosene, which is usually carried out on flow reaction devices by shock tube[8-10]. The most representative work in this period was done by Mullins, who used a device as flow reaction tube to conduct experimental research on ignition characteristics of kerosene [11]. Vasu et al. used shock tubes to investigate the ignition characteristics of Jet-A and JP-8. The experimental pressure range was 1.7 -5.1 MPa, and the temperature range was 715-1229 K. but oxygen content is only 10% and 21% [12-15]. Korzhavin et al. studied the spread of oil film fire on metal plates when the oil film was ignited, but did not pay attention to the ignition conditions and mechanism [16]. In order to study the fire safety of space launch site, Kwon measured the minimum ignition energy of Jet-A droplets under different oxygen concentrations. The oxygen concentration increased from 20% to 40%, and the minimum ignition energy decreased slightly [17]. However, their experiments were conducted in normal atmosphere even low oxygen. The ignition and combustion of rocket kerosene in oxygen-rich atmosphere is obviously different from that under normal pressure [18-19]. In terms of safety issues, NASA in the Apollo project and the subsequent space launch system, continued to promote the safety of manned spacecraft, rocket and launch sites in view of the huge propellant volume of heavy launch vehicles and the special needs of manned spaceflight. Roth reviewed the literature on the fire and explosion risk of manned spacecraft [20]. Farber studied the explosion characteristics of liquid launch vehicle and predicted the explosion equivalent by using numerical analysis and experiment [21]. However, reliable evidence has not yet been found to show that the ignition risk and ignition parameters of kerosene are available in oxygen-rich atmosphere, so it is not possible to accurately assess the ignition possibility and ignition conditions of leaking LOX/kerosene. The effect of oxygen concertation on ignition characteristics of liquid pool fires has not been studied in detail.

The overall objective of this study is to gain an improved understanding of the effect of oxygen-rich concertation on ignition conditions of small-scale kerosene pool fires. The ignition energy and time were measured and compared over a wide oxygen concentration range of 21%-100%. The ignition model was established and analyzed to explain the relationship between critical condition of kerosene ignition and oxygen concentration, which provides theoretical and data reference for the development of LOX/kerosene leakage safety monitoring instrument and the design of LOX/kerosene leakage monitoring scheme in space launch sites. Also, this key safety theoretical support is helpful to analysis the consequences of propellant leakage accidents and to promote fire prevention technology.

2. EXPERIMENTAL SETUP

To achieve the ignition parameters of kerosene in a stable oxygen-rich atmosphere, the experimental platform was designed, as shown in Fig. 1 The platform consists of the ignition system, oxygen control system, oil temperature control system, and data collection system. The chamber is surrounded by tempered glass, which is the length of 30×30×50 cm. And controlled oxygen goes from the bottom of chamber and is released from the

top, where this semi-closed experimental platform greatly ensures the safety of the experiment.

Oxygen control system controls not only the oxygen-rich atmosphere, but also the adjustable of oxygen concentration from 21%-100%. During the preparation stage, a computer-controlled O_2/N_2 gas supply system had been incorporated into the setup at the rate of 20L/min, which simulate the oxygen-rich atmosphere formed by liquid oxygen leaking into the air. And the oxygen concentration depended on an oxygen sensor installed at the top of chamber.

Oil temperature control system controls the initial kerosene temperature. The oil pool made of steel was 40.0 mm in diameter and 1.0 mm in height, which located on 20 ×20 mm square oil bath, and the initial fuel temperature was adjusted to designed temperature by high sensitivity thermocouple embedded in the bottom of the oil pool, which control fuel temperature from 273.15 K to 373.15 K. The temperature range considered covers the maximum and lowest temperature range of a typical high-thrust space launch site throughout the year. The 1.0 mm fuel thickness satisfied the deep pool condition and the fuels would not flow out of the pool.

The ignition system includes an ignition electrode and an ignition energy controller. The ignition electrode was kept at a fixed location about 3 mm above the liquid surface of kerosene, which accurately release different ignition energies(*E*) because of the following unique properties: (1) the energy range is broad (from 0.01mJ to 20J) and discharge duration time is from 0s to 30s;(2) the accuracy is ±1% full scale; and (3) the repeatability is ±0.5% full scale. Besides, the evidences show that within a short distance above the liquid level, the concentration of oil and gas in different locations was very close, and close to the concentration of saturated oil and gas.

The data collection system recorded on the flame video. Through the tempered windows, a CCD camera (1280 × 720 resolution, 100 frames per second) and a high-speed camera (512 × 384 resolution, 500 frames per second) were utilized to record the flame appearance.

According to the ignition point experiment criterion as well as ignition criterion, when the oil film of a certain thickness catches fire under the action of ignition energy and can continue to burn for more than 5s after the ignition device is withdrawn, the oil film is considered on fire.

In this study, studies on ignition characteristics of rocket kerosene were conducted under different oxygen conditions ranging from 21% to 100% at intervals of 20%. The initial kerosene temperature of kerosene was adjusted from 273.15 K to 573.15 K, respectively. Each Test with the same configuration was repeated at least three times to ensure repeatability.

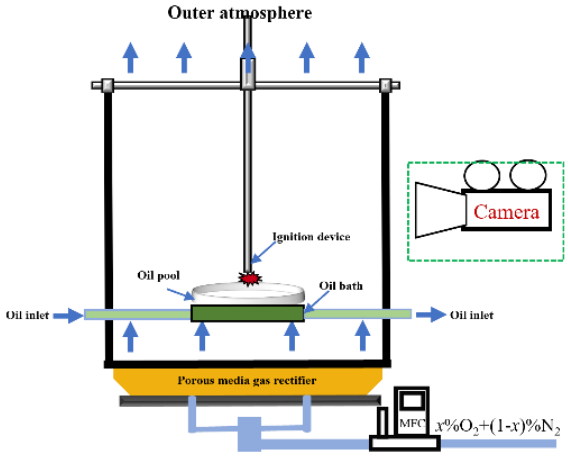


Fig.1. Experimental setup

3. *DISCUSSION AND RESULTS*

3.1 Ignition energy

3.1.1 The effect of oxygen concentration

The experimental results of ignition energy of kerosene under different oxygen concentration and initial kerosene temperature were showed in Fig.2. At the same initial kerosene temperature, the ignition energy of kerosene ignition decreased with the increase of oxygen concentration. The combustion and explosion were a form of flammable gas explosion, and its combustion and explosion mechanism can be explained by the thermal explosion mechanism and the chain reaction theory.

According to the theory of forced ignition and the calculation formula of minimum ignition energy, the fuel ignited by electric spark to the fire spread, roughly divided into two stages: Firstly, the electric spark heating premixed gas to ignite the locally mixture, forming the initial flame center. Then the initial flame front propagates to the unburned mixture, and when oxygen and fuel vapor were enough, the fire would spread sustainably. The representative flame images of ignition process of kerosene in pure oxygen atmosphere were showed in Fig.3.

When the electric spark was generated, the oxygen generated near the electrode gap to participate in the reaction increases, increasing the probability of collision with the flammable liquid vapor, so the required energy was lower. Meanwhile, high oxygen concertation speeds up the redox reaction and releases more heat, which significantly increases the adiabatic flame temperature. Higher flame temperatures accelerate kerosene evaporation through heat conduction and radiation, thus

promoting more fuel vapor to participate in the combustion reaction leading to continuous flame propagation.

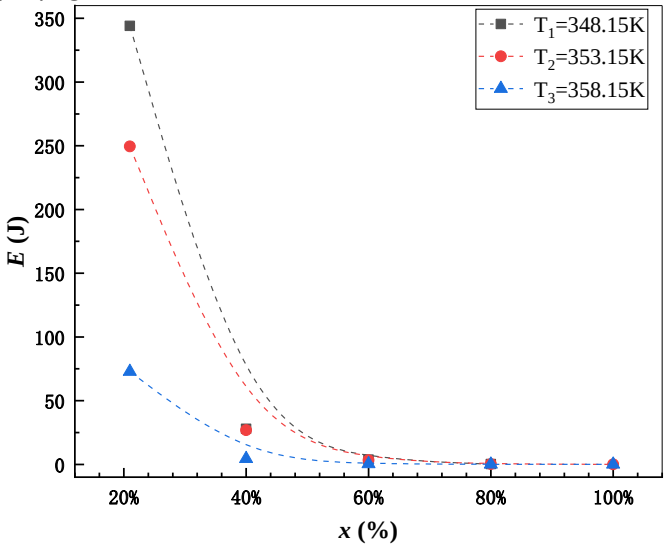


Fig.2. The variation of ignition energy of kerosene with different oxygen concentration

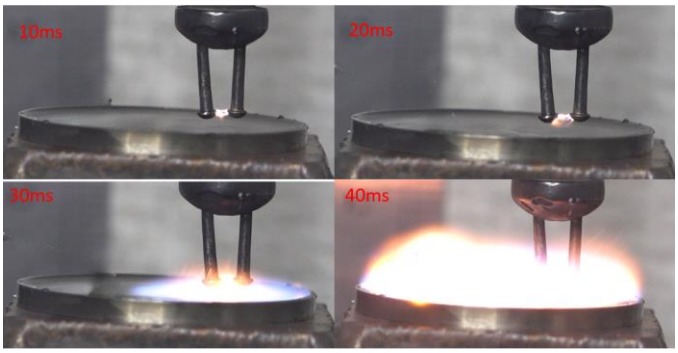


Fig.3. Flame images of ignition process of kerosene in pure oxygen atmosphere

3.1.2 The effect of initial kerosene temperature

The experimental results of ignition energy of kerosene under different initial kerosene temperature were showed in Fig.4. In accordance with the heat transport theory, the increased initial oil temperature accelerates the evaporation of kerosene, which increased the concentration of kerosene vapor near the electrode and approached the combustion limit of kerosene vapor. Thus, smaller ignition energy could fire the mixture of oxygen and kerosene vapor. And the initial kerosene temperature represented the temperature of mixture gas above fuel surface. Besides, with the increase of oxygen concertation speeds up the redox reaction and releases more heat, so the ignition energy required less.

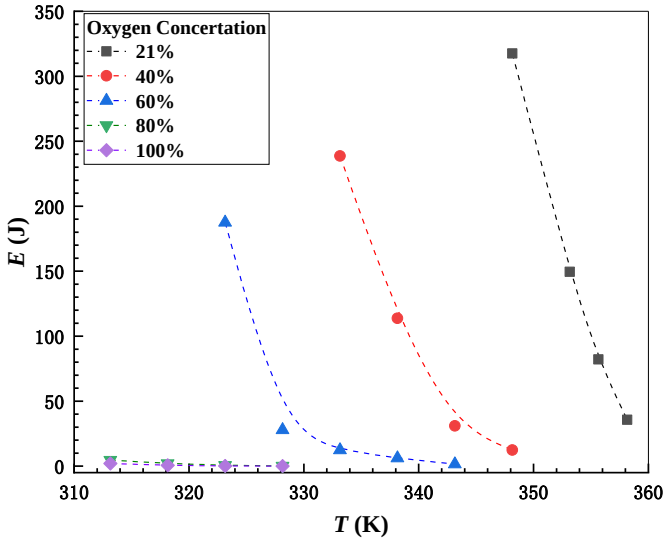


Fig.4. The variation of ignition energy of kerosene with different initial kerosene temperature

Schematic diagram of heat transfer model of oil under iginition spark was shown in Fig.5. The heat feedback of the spark to the oil pool determined the burning rate of the oil pool.The ignition condition of kerosene pool fire could be expressed as Eq. (1), where ignition energy (*E*) is greater than the minimum ignition energy required (E_{min}). Moreover, the right-hand terms represent the conduction term, which refers to heat transfer through the convective heat transfer from the gas above the fuel surface ($\dot{q}''_{conv}$), the radiant heat transfer from the ignition spark ($\dot{q}''_{rad}$), the heat dispersed to the exterior through near the electrode ($\dot{q}''_{loss}$), and the vapor heat($\dot{q}''_{vap}$).[22-23]

$$E_{min} \le E = \dot{q}''_{conv} + \dot{q}''_{rad} + \dot{q}''_{loss} + \dot{q}''_{vap} \quad (1)$$

The convective heat release flux can be simplified as follows:

$$\dot{q}''_{conv} = h(T_f - T_b) \quad (2)$$

The Eq. (2) can be calculated by the temperature of ignition spark (T_f) and the boiling temperature (T_b) of fuel, where the temperature of ignition spark could be assumed as flame temperature. The convective heat transfer coefficient(*h*) can be calculated using the Nusselt number, which not affected by temperature.

The radiant heat flux $\dot{q}''_{rad}$ transmitted from the isothermal and homogeneous flame is calculated as follows :[24-26]

$$\dot{q}''_{rad} \propto \sigma\left(T_f^4 - T_b^4\right) \quad (3)$$

$\dot{q}''_{loss}$ can be written as follows:

$$\dot{q}''_{loss} \propto h_e(T_f - T_\infty) \quad (4)$$

The calculated results confirmed that h_e minimally affects ignition and burning rate [27]. The temperature distribution of the electrode may be directly correlated with electrode material and thickness, regardless of environmental temperature (T_∞).

Above equation confirmed that the ignition energy correlates well with the temperature Eq.5 . That is, the required ignition energy would decrease as the initial kerosene temperature

$$E \sim \sigma T_{\infty}^{n} \quad (5)$$

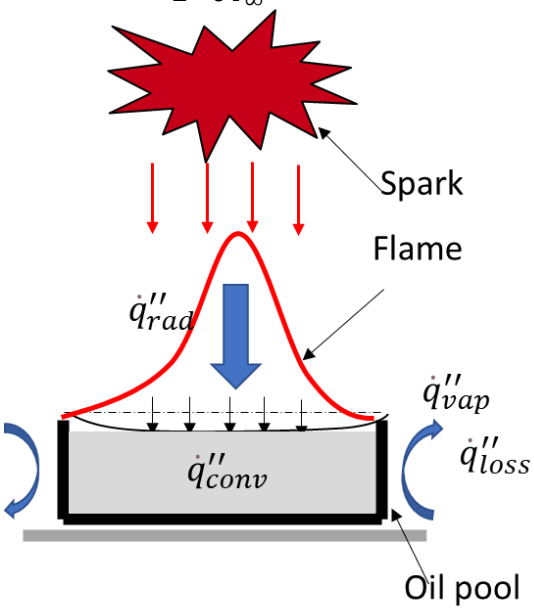


Fig.5. Schematic diagram of heat transfer model in oil pool under iginition spark

3.1.3 Relationship between ignition energy and initial kerosene temperature in oxygen-rich atmosphere

According to the theory of forced ignition and the calculation formula of minimum ignition energy, the ignition spark could be assumed to be a sphere, where the spark energy releases energy around it. Since the actual ignition energy is greater than the required one, and correlated well with the minimum ignition energy, i.e., $E_{min} = k\frac{4}{3}\pi r_{min}^{3}\rho c_p(T_m - T)$, where adiabatic flame temperature (T_m) is equal to temperature of ignition spark (T_f), then *E* can be expressed as follows:

$$E = kE_{min} = k\frac{4}{3}\pi r_{min}^{3}\rho c_p(T_m - T) \quad (6)$$

where k is a correction factor, r_{min} is defined as follow :

$$r_{min} = \left(\frac{3\lambda(T_m - T)e^{\frac{E_a}{RT_m}}}{Q_i\rho^2 Y_F Y_{ox}}\right)^{1/2} \quad (7)$$

It is assumed that the fuel concentration (Y_F) and oxygen concentration (Y_{ox}) participate in the combustion reaction according to the chemical equivalent ratio. In accordance with the ideal gas law and Clausius-Clapeyron equation, Y_F is defined as:

$$Y_F \sim \frac{X_F\rho_F}{\rho} \sim e^{\frac{h_{fg}M_g}{R}\left(\frac{1}{T_b}-\frac{1}{T}\right)} \quad (8)$$

Hence, the ignition energy can be written as follows from Eq. (6) to Eq. (8):

$$E = ke^{\frac{3E_a}{2RT_m}}e^{\frac{3h_{fg}M_g}{RT}}T^2(T_m - T)^{5/2} \quad (9)$$

Taking the logarithm of both sides of Eq. (9), the equation can be expressed as follows:

$$\ln E = \ln k + \frac{3E_a}{2RT_m} + \frac{3h_{fg}M_g}{RT} + 2\ln T + \frac{5}{2}\ln(T_m - T) \quad (10)$$

The adiabatic flame temperature (T_m) is affected by oxygen and T_m is geater than T.At the same oxygen concertation, the item of $\left(\ln k + \frac{3E_a}{2RT_m} + \frac{5}{2}\ln(T_m - T)\right)$ can be asscumed as a constant associated with oxygen ($C(x)$). Thus, the Eq. (10) can be expressed as follows:

$$\ln\frac{E}{T^2} = \frac{3h_{fg}M_g}{R}\frac{1}{T} + C(x) \quad (11)$$

When T=T_0,

$$\ln\frac{E_1}{T_0^2} = \frac{3h_{fg}M_g}{R}\frac{1}{T_0} + C(x) \quad (12)$$

The calculated result from Eq. (11) and Eq. (12) can be expressed as follow:

$$\ln\frac{E/T^2}{E_0/T_0^2} = \frac{3h_{fg}M_g}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right) \quad (13)$$

Based on the mathematical model from Eq. (13), the relationship between ignition energy and initial kerosene temperature under different oxygen concentration could be derived as showed in Fig.6. The results showed the item of $\ln\frac{E}{T^2}$ had a better linear relationship with the reciprocal of the initial kerosene temperature. Under the condition of same oxygen concentration, the higher the initial kerosene temperature, the smaller the ignition energy required for ignition of kerosene. Meanwhile, the enthalpy of evaporation of kerosene can be obtained from the slope of the fitted line, and the result of h_{fg} is calculated about 431 kJ/kg, which is slightly higher than the true value of 376 kJ/kg. The result of enthalpy of evaporation of kerosene could confirmed that above derivation and conclusion are reasonable.

At the same time, the relationship between $C(x)$ and oxygen concentration could be derived as showed in Fig.7, which also confirmed that $C(x)$ had a better linear relationship with oxygen concentration. That meant $C(x)$ was smaller with the increase of oxygen concentration.

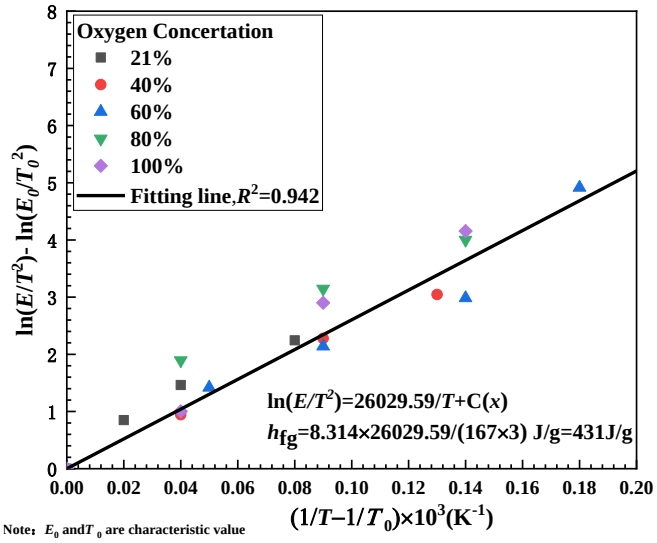


Fig.6. Correlation for ignition energy under different initial kerosene temperature

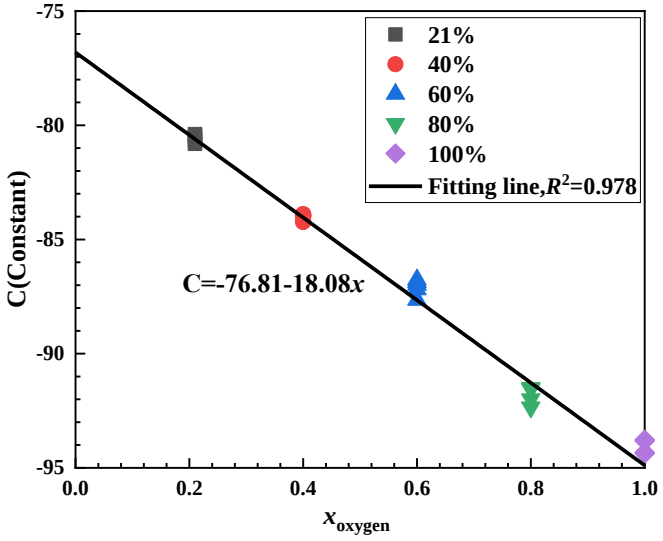


Fig.7. Correlation for $C(x)$ under different oxygen concentration

3.2 Ignition time

When the mixture of oxygen and kerosene vapor had reached the ignition condition, it takes a certain time from the initial state to the moment of sudden rise in temperature, which is ignition time [28-30]. Due to the relationship between ignition and temperature conforms to the Arrhenius formula, taking the logarithm of the ignition time ($\ln(t)$) and the reciprocal of the temperature($1/T$) as showed in Fig.8. The results showed the ignition time of kerosene decreased with the increase of initial kerosene temperature, the relationship between ignition time and initial kerosene temperature was shown in Eq. (14) as follows:

$$\ln t = \frac{k'}{T} + c' \quad (14)$$

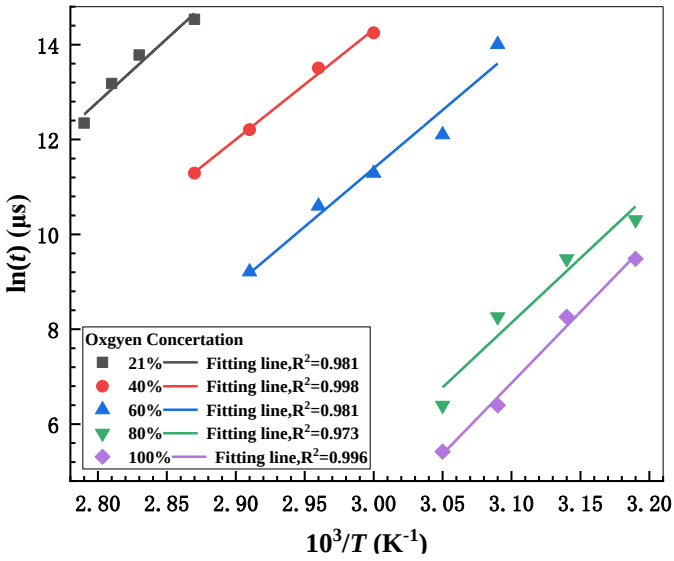


Fig. 8. The variation of ignition time under different initial kerosene temperature

In accordance with the thermal combustion theory[31], the relationship between ignition time and initial kerosene temperature was expressed as: $\ln t \propto \frac{E_a}{RT}$, which meant the k' could be written as $\frac{E_a}{R}$.The Eq.(14) can also be expressed as follows:

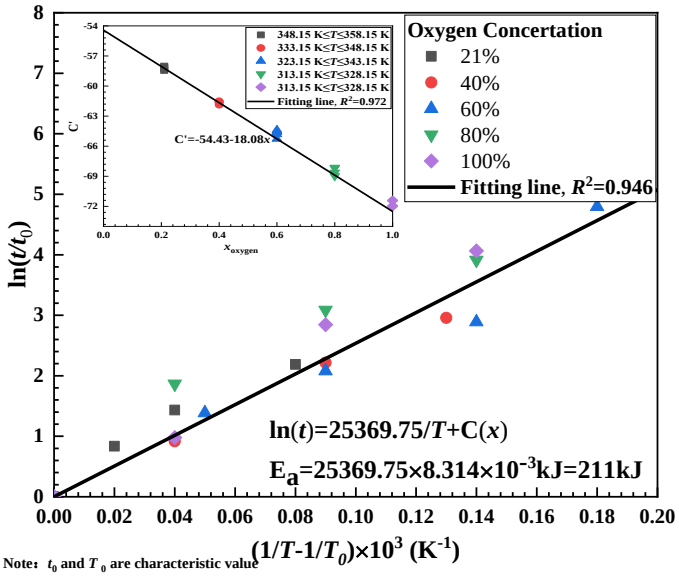
$$\ln t = \frac{E_a}{RT} + c' \quad (15)$$

The calculation results showed that the activation energies of kerosene at different oxygen concentrations were 221.1 kJ/mol,202.6 kJ/mol,204.3 kJ/mol,226.5 kJ/mol and 240.0 kJ/mol from Fig.8, which is similar to the calculated value.

Meanwhile, the results from Fig.8 indicated that the oxygen concertation was higher, the ignition time was smaller, which was believed that the ignition time was affected by oxygen concentration. This may be caused by high oxygen concentration speeding up the rate of chemical reactions. Referred to the method of Eq. (13), the ignition time and temperature were normalized under different oxygen concentrations, and the results showed as shown:

$$\ln(t/t_0) = \frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right) \quad (16)$$

Based on the mathematical model from Eq. (16), the relationship between ignition time and initial kerosene temperature under different oxygen concentration could be derived as showed in Fig.9. The results also showed that C' had a better linear relationship with oxygen concentration. That meant C' was smaller with the increase of oxygen concentration.



Note: t_0 and T_0 are characteristic value

Fig.9. Correlation for ignition time under different initial kerosene temperature and $C(x)$

4. CONCLUSIONS

This study examined the effect of oxygen concentration and initial kerosene temperature on the ignition energy of kerosene using small-scale pool. The oxygen concentration investigated was within the range of 21%–100%. Major findings are:

（1）The ignition risk of vapor increased with the increase of oxygen concentration, while the required ignition decreased with the increase of oxygen concentration.

（2）The ignition energy had a better linear relationship with the reciprocal of the initial kerosene temperature. Under the condition of same oxygen concentration, the higher the initial kerosene temperature, the smaller the ignition energy required for ignition of kerosene. This due to the increase of the initial oil temperature accelerated the evaporation rate of kerosene, making vapor ignite and maintain flame propagation at a lower ignition energy.

（3）By theoretical analysis of the relationship between ignition energy and ignition time, oxygen concentration and initial oil temperature, the $\ln(E/T^2)$ and $\ln(t)$ can be correlated well with the form of $(k/T+C(x))$, where $C(x)$ is also a constant related to the oxygen concentration. The research results can provide key scientific data and models for the fire risk assessment of LOX/kerosene leakage.

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