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# EFFECTS OF RATIO OF ETHANOL AND BUTANOL IN ABE (ACETONE-BUTANOL-ETHANOL) ON MICRO-EXPLOSION CHARACTERISTICS OF ABE/KEROSENE DROPLET

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**ABSTRACT**

This paper presents an experiment study on the composition effect on droplet combustion of ABE mixture fuel. The ratios of ethanol and butanol in ABE are varied. Experimental results show that the micro-explosion characteristics of the two ABE/kerosene droplets are different, which is obviously reflected by $(D/D_0)^2$ curves. Increasing proportion of ethanol will lead to more intense micro-explosion. The process of nucleation in droplets in the early stage of micro-explosion is recorded to investigate the underlying physics. These experimental results show that besides the boiling point difference of ethanol and butanol, ethanol will tend to cause more intense micro-explosion due to insoluble in kerosene than butanol under the same conditions.

**Keywords:** micro-explosion, ABE, ethanol, butanol, bubble nucleation, lipophilic

## 1. INTRODUCTION

Energy crisis and environment pollution are two major problems in the 21st century. Alcohol as a renewable fuel is one of the good alternatives to fossil fuels. The addition of alcohol to vehicle fuels can also reduce the use of fossil fuels and soot emissions. The ABE (Acetone-Butanol-Ethanol) mixture is an intermediate product from grain fermentation to alcohols, including acetone, butanol and ethanol. It can be used directly as an alternative fuel and the production cost will be reduced significantly [1].

It is well recognized that the combustion of mixed alcohol and kerosene will cause micro-explosion due to different boiling points. The same is for ABE and fossil fuels. Micro-explosion has a great impact on atomization and combustion of fuel [2]. Zhang et al. studied the combustion process of butanol/kerosene droplet through the $(D/D_0)^2$ curve and the temperature curve during the combustion of the droplets. The difference in combustion characteristics between pure kerosene and butane/kerosene blended is studied. [3]. A mathematical model was proposed for data processing which is crucial to predict the micro-explosion overheat limit of droplets, and measured the intensity of the micro-explosion of the droplet according to the vibration amplitude of the $(D/D_0)^2$ curve [4]. Madan et al. observed the nucleation before the micro-explosion of droplets, and concluded that the generation and development of bubbles inside the droplet had a great influence on the micro-explosion behind the droplet. Micro-explosion intensity decreased with the number of bubble nucleation increasing inside the droplet [5]. Hirotatsu et al.pointed out that water, insoluble in diesel, caused oil-water separation inside the oil droplets before micro-explosion occurs. Based on the results of this experiment, a mathematical model for predicting water vapor mass generated in micro-explosion was proposed [6]. In this study, two ABE solutions with different ethanol and butanol ratios were prepared, and ABE was mixed with kerosene. The experiment was carried out in accordance with the method of [3, 4] and $(D/D_0)^2$ correlation has been obtained. The micro-explosion characteristics of the two series of emulsions are analyzed. Bubble nucleation before the micro-explosion in the droplet is captured.

## 2. EXPERIMENTAL APPARATUS AND METHOD

The purpose of this experiment is to study the effect of different ethanol and butanol ratios in ABE on the micro-explosive properties of ABE/kerosene. The basic components included acetone, ethanol, butanol and kerosene. The key physical parameters such as density

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(ρ), ignition temperature ($T_{ig}$), boiling point ($T_{boil}$) are shown in the following Table 1.

Table 1 Fuel Properties [2][7]

| Components | Kerosene | Acetone | Buhanol | Ethanol |
|---|---|---|---|---|
| formula | $C_8$-$C_{16}$ | $C_3H_6O$ | $C_4H_9OH$ | $C_2H_5OH$ |
| ρ*(g/mL) | 0.82-0.86 | 0.791 | 0.813 | 0.795 |
| $T_{ig}$ (K) | 503 | 833 | 658 | 707 |
| $T_{boil}^*$(K) | 453-613 | 329.22 | 390.88 | 351.8 |

*: at 288K, 1bar

In order to meet the experimental requirements, two different ABE mixtures are configured. The ratio of acetone-butanol-ethanol in the first ABE is 3:6:1. In The second mixture changed the ratio of the three components to acetone: ethanol: butanol = 3:6:1, which is labeled as AEB. ABE and AEB are separately mixed with kerosene, and the emulsion labeled ABE30 represents a volume ratio of ABE to kerosene of 3:7. A total of seven fuels were prepared in this experiment. They are K100 (pure kerosene), ABE30, ABE50, ABE70, AEB30, AEB50 and AEB70. All blends are thoroughly stirred and then placed for long periods of time to ensure that no component separation is performed.

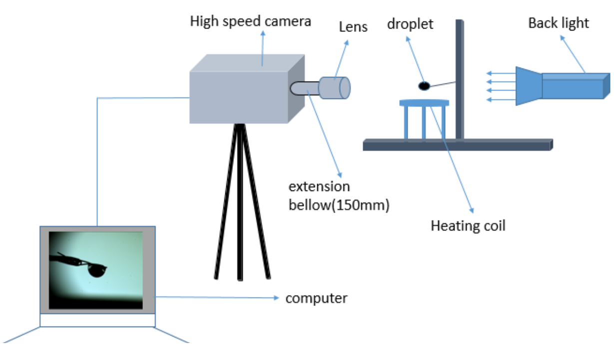



Fig.1 Schematic diagram of experimental apparatus.

Fig.1 shows a schematic diagram of experimental apparatus. The experimental equipment is arranged according to [2,3]. In this work, a micro-pipette was used to place a ternary fuel emulsion of approximately 3 μL capacity on the junction of a thermocouple wires having a thickness of 0.1 mm, resulting in a spherical emulsion droplet with a diameter of approximately 1.8 mm. Since the size of thermocouple is less than 1/10th of the droplet size, its influence on triggering micro-explosion or puffing is neglectable [5,6]. Out of the droplets 0.5 cm below, there is an electric heating wire to provide a high temperature environment of about 700K for the location of the droplets. The burning process of droplets is recorded with a high speed camera. High-speed camera is set as 2000 fps and 1/2700000 sec shutter. The captured images are processed with MATLAB to get the droplet size. The ratio of the size to the initial size of the droplet is obtained to obtain the value of $(D/D_0)^2$. This value is taken as the ordinate and time as the abscissa. Obtain a $(D/D_0)^2$ curve to represent the combustion history of the droplet. The process of MATLAB processing droplets is elaborated in [3]. In all the cases, the initial droplet diameter and the thermal boundary conditions are the same.

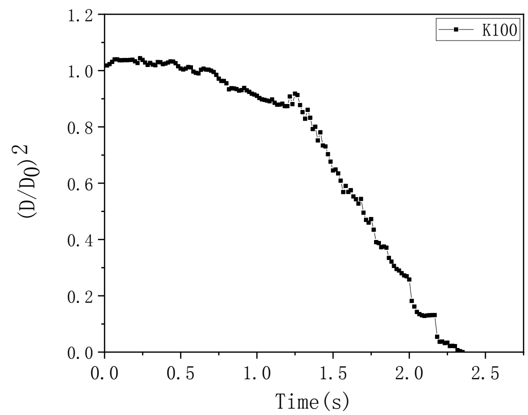
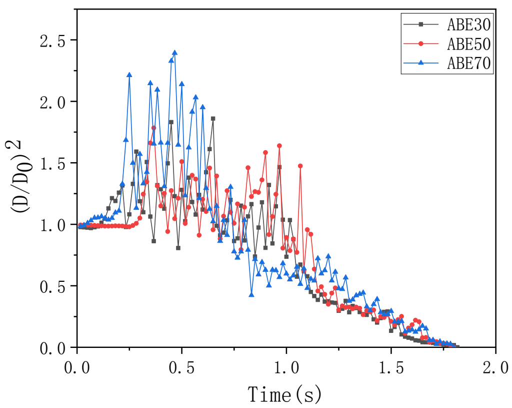



Fig.2 The $D^2$ history of droplet of K100

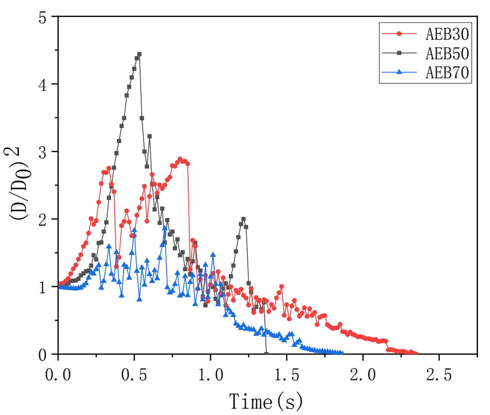
Fig.2 shows the temporal evolution of the normalized droplets diameter $(D/D_0)^2$ for K100 fuel under the ambient temperature of 700 K. D0 is the original droplet diameter and D the instanteous one. It is seen that the pure kerosene droplet burns smoothly. Note that thermal expansion, hot air disturbance, and combustion instability of pure kerosene due to buoyance have little effect on the curve because the burning duration time is short.

## 3. RESULTS AND DISCUSSION

Fig.3(a) and (b) show the temporal evolution of $(D/D_0)^2$ for ABE/kerosene and AEB/kerosene droplets, respectively. In both cases, all the curves are wiggly indicating that the droplet explodes frequently during the burning process, but the intensity is weaker in Fig.3 than that of Fig. 3(b). Here, we define the weak explosion as micro-explosion It is known that alcohols burn faster than kerosene due to their high volatility [3]. Fig.3(a) also shows that with the same butanol and ethanol percentage (6:1), the different ABE/kerosene ratios have a certain effect on the micro-explosion, but the margin is not large.




(a)




(b)

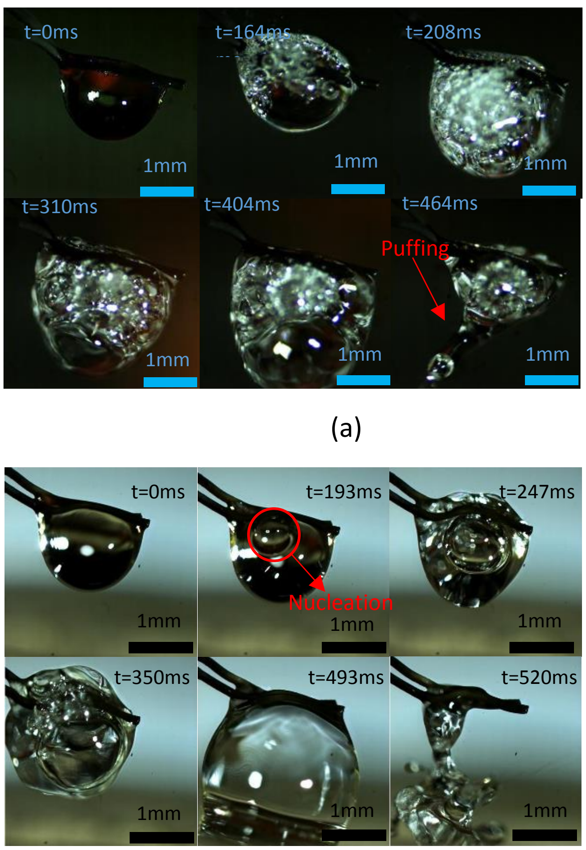
Fig.3 $D^2$ histories of (a) ABE/kerosene and (b) AEB/kerosene

In Fig.3(b), increasing ethanol/butanol ratio leads to a rapid increase in the micro-explosion strength of the droplets, indicating that the effect of ethanol in current cases on the micro-explosion is stronger than that of butanol. Also, the micro-explosion in Fig. 3(b) is sufficiently intense, which has a significant impact on the lifetime of droplet combustion. Each drop volume is the same size in the experiment. The shorter lifetime indicates the greater the overall burning rate of the droplets.Although the micro-explosion of AEB70 is weaker than AEB30, the burning time of AEB70 is shorter than that of AEB30. However, comparing ABE50 with ABE70, AEB50 has the faster burning rate. The micro-explosion is strong enough to make up for the difference in the proportion of alcohols. Therefore, among the three fuels, it also demonstrates that the micro-explosion can greatly promote the burning rate of the droplet such that the total time for the droplet burning out is the shortest in AEB50.

Comparison of Fig. 3(a) and (b), the micro-explosion of the AEB is significantly stronger than that of ABE. The size of the droplets of ABE/kerosene vibrates significantly more frequently than that of AEB/kerosene. This phenomenon represents the rapid expansion of bubbles and puffing in ABE/kerosene droplets. However, the size amplitude of ABE/kerosene droplets is significantly smaller than AEB/kerosene, indicating that the bubble volume inside the former is smaller than the latter.According to the physical parameters in Table 1, the boiling point of butanol is about 39 K higher than ethanol. This difference can explain the strength of the micro-explosion of the two fuels to some extent. In order to better explain the different micro-explosion characteristics of ABE and AEB, bubble nucleation for ABE50 and AEB50 in the early stage of droplet micro-explosion is studied, because the results show that the micro-explosion in the two cases are more obvious.

Fig.4 a,b show the evolution of bubbles in ABE50 and AEB50 droplets, respectively. In Fig.4(a), no bubble can be found initially. At 164 ms, a large number of small bubbles are generated in the above half region. Then at 208 ms, the whole droplet filled with small bubbles with different sizes since the earlier formed bubbles grow as the time goes by and the droplet is bulging. Later at 310 ms, and 440 ms, some small bubbles disappear because they merge to bigger ones. The droplet does not keep spherical any more. Finally, at 464 ms, a large bubble at the bottom of the droplet escapes and the droplet collapses, which is called puffing. This phenomenon is also discussed in [3-5]. The underlying physics is that the micro-explosion is weak, such that the bubbles can not explode and break out the droplet dramatically, but only spurt from surface of droplet. In comparison, Fig.4(b) shows the generation and growth of bubbles for AEB50 case. It is found that the number of bubbles inside the droplet is few. Until 193 ms, but it is very bulky and grows rapidly in the later stages. The droplet rapidly expand and then burst, causing a violent micro-explosion.

The reason for the difference between Fig. 4a and 4 b is that for ABE50 droplets, the low volatility components ethanol and butanol are evenly distributed in kerosene before bubble nucleation. Distribution of low volatility components in kerosene is not uniform. The explanation is that the AEB50 has a similar oil-water separation phenomenon as seen in [6] during heating. In ABE, both butanol and acetone are miscible with kerosene. The droplet heating does not separate the low volatile component ethanol from the kerosene. In contrast, for AEB50, a large amount of ethanol insoluble in kerosene is distributed separately during the droplet heating process. It is easier for ethanol to aggregate. Once they boiling point is achieved the explosion is strong.




(a)

(b)

Fig.4 Bubble growth in (a) ABE50 droplets and (b) AEB50 droplets

The above experimental data and experimental phenomena show that the lipophilicity of alternative fuels plays an important role in droplet microburst. The component that is insoluble in kerosene has a greater contribution to causing a strong micro-explosion, while the component dissolved in kerosene has a small effect in the micro-explosion of the droplet. Of course, this is only a preliminary conclusion, and more experiments need to be carried out to form a persuasive conclusion.

## 4. CONCLUSION

- The micro-explosion can greatly increase the burning rate of the droplets.
- The increased ethanol/butanol proportion in the ABE/kerosene mixture results in a more intense micro-explosion.
- For AEB fuels, the ethanol is no longer uniformly distributed in the kerosene but gathers to form a large bubble core, which in turn causes a strong micro-explosion than ABE fuels.

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