Experimental Research on the Disruptive Evaporation and the Motion Characteristics of Secondary Droplets for Emulsified Biodiesel with a Suspended Droplet Configuration

Jialong Zhu, Zhong Wang,* Ruina Li, and Shuai Liu

ABSTRACT: The secondary atomization of droplets is one of the means to improve the efficiency of diesel fuel injection atomization. As a promising biomass fuel, emulsified biodiesel showed a good prospect in improving the atomization effect of diesel engines. In this study, a high-temperature and pressure-resistant evaporator was designed to simulate diesel-like conditions, and the evaporation and combustion experiments of emulsified biodiesel droplets were carried out. The morphological changes in the droplets were dynamically captured using a high-speed camera. According to the collected images, the characteristic parameters showed the potential for optimization. The more percentage of alcohols resulted in a less characteristic parameters showed the potential for optimization. The more percentage of alcohols resulted in a less characteristic parameters showed the potential for optimization. The more percentage of alcohols resulted in a less characteristic parameters showed the potential for optimization.

1. INTRODUCTION

In order to improve the combustion efficiency of an internal combustion engine cylinder, improving the quality of fuel atomization became one of the main methods. In the application of diesel spray technology, the mainstream solution was to utilize the high-pressure common rail technology with an ultrahigh fuel injection pressure. The increase in the frequency of secondary atomization was attributed to the injection of a multicomponent fuel by the fuel system. This phenomenon accelerated the rate at which the fuel was refined into smaller droplets in the spray process. Microscale droplets reduced the unevenness of fuel distribution inside the cylinder to a certain extent and improved the combustion efficiency.

Biodiesel is a promising alternative fuel, but its high viscosity inhibited the high-pressure spray from passing through the nozzle and affected fuel atomization. One of the main methods to improve fuel properties by blending different emulsifiers is to enhance the atomization effect of the biodiesel-blended fuel and thereby improve emissions. The effect of the biodiesel–alcohol emulsion fuel on diesel engine performance has been widely studied.
pentanol and titanium oxide nanoparticles with the fuel at different ppm concentrations. The Brake power and Brake thermal efficiency of the emulsified biodiesel were 22 and 8% higher compared to diesel.

Emulsified biodiesel showed a good application prospect in the test, but microthermodynamic characteristics were needed to prove it. Components with lower boiling points were more likely to enter the superheated state first and form gas nuclei inside the droplets. The air core gradually grew during the development process, forming bubbles visible to the naked eye. The bubble continued to absorb heat and moved to the boundary of the droplet, the interfacial tension of the liquid film could not continue to support the growth of the bubble, and the droplet exploded in a relatively short time. Under appropriate conditions, a part of the components was stripped from the original droplets by the energy released by the explosion, forming secondary droplets with smaller diameters. The effect of pressure on the droplets was reported, and the effect of ambient pressure on microexplosions is thought to be highly dependent on ambient temperature. At high temperatures, the rate of droplet expansion decreased with the increase of ambient pressure. Secondary droplets were an effective way to achieve secondary atomization, and related pilot studies were conducted.

The latest experimental studies focused on the relationship between the size of secondary droplets and the temperature of the water core and the influence of additives in droplets on the formation of secondary droplets. The numerical studies focused on the droplet nucleation temperature of the heating rate and the influence of puffing/microexplosion time. Meng et al. observed secondary droplets caused by the secondary explosion of the jet fuel (RP-3), biodiesel, and ethanol-mixed droplets. The calculation equation of the microexplosion intensity was established to assess the degree of secondary droplet ejection. In the limited spray experiments of emulsified ethanol−diesel mixtures, the microexplosion was detected for large droplets near the nozzle outlet at the end of injection. Shen et al. focused on the evaporation and microexplosion of droplets under normal pressure conditions. They studied the heating behavior of emulsified fuel droplets at high temperatures, and the results showed that the breaking mode and strength of the droplets during microexplosion were closely related to the evaporated water, which was affected by the initial water content, heating temperature, and the size of the dispersed droplets. The droplet heating and evaporation model of the oil-in-water emulsified fuel was studied, and the residual water in the droplet and the temperature distribution inside the droplet before the microexplosion, which determine the microexplosion intensity, were analyzed.

Antonov et al. believed that the main reason for the rupture of two-component droplets was the high gradient of convection velocity and temperature at the interface between the components. The threshold temperature in the interface (water−oil) was 100−120 °C, and the convective velocity threshold was 2.5−3 mm/s. These parameters characterized the local inhomogeneities and aggravated the transformation and destruction of the droplet surface. Recently, they filled the droplets with CO₂ gas in advance and stored them in a water core. Under the experimental conditions of high temperature and forced convection, they found that the threshold temperature range of droplet breakage was reduced by 10−15%. A certain number of secondary droplets surrounded by a liquid film in the gas vapor core formed the vapor cloud after the droplet ruptured. The data on the secondary droplets that could be captured by the image showed that the surface area of the liquid was increased by more than 10 times. The secondary droplets would interact with the adjacent original droplets and secondary droplets to form chain breaks, and the secondary droplets were ignited almost immediately after they were generated.

In the field of droplet combustion, Avedisian et al. focused on the combustion phenomenon caused by energy excitation at the core of the droplet. The combustion of isooctane droplets with an initial diameter of 0.5−5 mm was studied. They analyzed the effect on the combustion rate and flame extinction. The results showed that the combustion history of isooctane droplets in the standard atmosphere showed a significant dependence on the initial diameter. The combustion phenomenon of a heptane/isoctane mixture in a low gravity environment was studied. The numerical results showed that the prediction of the extinction diameter, droplet diameter, flame diameter, combustion rate, and flame emissivity was more accurate. They analyzed the evaporation and combustion of gasoline and ethanol containing seven substitutes by experimental and numerical studies and studied the effect of droplet diameter and radiation changes on combustion processes.

The purpose of this work was to study the evaporation characteristics of emulsified biodiesel by a high-temperature evaporation experiment and to explore the correlation between the original droplet and the secondary droplet in the evaporation process. The primary purpose is to examine the motion of the secondary droplets and their trajectories from a dynamic perspective based on the evaporation characteristics of the fuel (Sections 4.14.24.34.4), explain the critical conditions for the separation, and study the correlation between the secondary droplets and original droplets. The current results intended to shed some light on the potential contribution of secondary atomization of this fuel to improved spraying (Section 4.5).

2. EXPERIMENTAL APPARATUS AND PROCEDURES

Biodiesel is a multicomponent fuel whose chemical properties are affected by multiple components. The relevant information on biodiesel and ethanol involved in this study is summarized in Table 1.

Ethanol was used as an emulsifier to be blended into biodiesel in a large proportion, and the blending ratio was controlled to 30%. Microsyringes were used to add distilled water of different contents to the emulsified fuel, and an ultrasonic oscillator was used to mix the emulsified fuel uniformly to produce emulsified biodiesel with water contents of 0, 2, 4, and 6%, respectively, (volume percentage), which were labeled W0, W2, W4, and W6 in this study. Some properties of biodiesel and emulsified biodiesel are listed in Table 2. The density, kinematic viscosity, low heating value, and surface tension of emulsified biodiesel are lower than those of biodiesel. The oxygen content in the atmospheric environment was greatly improved. The overall physical and chemical properties changed greatly, which paved the way for the difference in evaporation characteristics.

An optical microscope (HIROX, lens MXB-2500REZ) was used to analyze the topography of the emulsion fuel, as shown in Figure 1. The diameter distribution range of the dispersed phase was 2.2−24.7 μm, appearing as spheroids.
Table 1. CAS Registry Number, Proportion, and Mass Fraction Purity of the Chemicals

| component                      | CAS reg. no. | proportion (%) | mass fraction (%) | suppliers                  |
|-------------------------------|--------------|----------------|-------------------|----------------------------|
| biodiesel^a                   | 57-10-3      | 13.9^b         | 99.5              | China Jinan Decheng Chemical Co., Ltd. |
| hexadecanoic acid             | 84675-68-3   | 42.1^b         |                   |                            |
| methyl 10-trans-hexadecenoate  | 2027-47-6    | 24.5^b         |                   |                            |
| 9-octadecenoic acid           | 593-40-8     | 9.7^b          |                   |                            |
| 6-octadecenoic acid           | 112-61-8     | 8.0^b          |                   |                            |
| ethanol                       | 64-17-5      | 99.9           |                   | Zhenjiang Huadong Chemical Co., Ltd. |

^aBiodiesel contained a total of more than 30 components, and only those components that account for more than 1% are listed. ^bAnalysis method was gas chromatography.

Table 2. Properties of Biodiesel and Emulsified Biodiesel

| properties                      | biodiesel    | emulsified biodiesel |
|---------------------------------|--------------|----------------------|
| density (40 °C, kg/m³)          | 0.883        | 0.847–0.861          |
| kinematic viscosity (40 °C, mm²/s) | 4.23        | 2.97–3.42            |
| low heating value (MJ/kg)       | 39.37        | 34.4–36.1            |
| oxygen content (%)              | 10.9         | 17.5–22.4            |
| surface tension (100 °C, mN/m)  | 30.2         | 23.1–27.3            |
| water content (%)               | 0.02         | 0–6                  |

Figure 1. Image of the emulsion fuel (W6) under an optical microscope (suspended matter was the dispersed phase, and the components were liquid ethanol and water).

Hoxie et al.\(^{40}\) preferred the method of suspending droplets off of a thermocouple bead. However, placing droplets on the cross section of two intersecting microfibers was a proven method for producing geometrically spherical droplets.\(^{41}\) Therefore, the quartz wire suspension method was used in the experiment.\(^{42}\) The experiment device was a self-designed high-temperature evaporator equipped with observation windows (3) on both sides, as shown in Figure 2. The temperature sensor (2) and the needle of the syringe (4) were arranged inside the evaporator, and the specially made ring-shaped needle carried two crossarranged quartz wires; the diameter of the quartz wires was 0.05 mm. The temperature sensor monitored the average temperature between the gas temperature near the droplet and the wall temperature. The droplet needle exposed to high temperatures was wrapped with a heat-resistant material to prevent the droplet from evaporating prematurely in the long and narrow needle. The inflation valve (5) was connected with a gas pump, and a high-pressure nitrogen gas cylinder was used to fill the inside of the evaporator with nitrogen and maintain the pressure. A small gear driven by a stepper motor (9) transmitted the controlled rotation angle to the large gear to realize rotation deceleration. The rotation of the large gear drove the internal thread to rotate and drove the push pin (8) to move up and down. The fuel in the syringe was pushed into the quartz wire quantitatively by the force of the propelling plug. The full fuel in the injector could meet the demand for more than 10,000 droplet-mounting times, so one type of fuel only needed to be filled once. The fuel could be changed by removing the push pin. The droplet-mounting control device could further improve the accuracy of each droplet entering the evaporator and reduce errors caused by manual operation by personnel. At the same time, the droplet backflow caused by the pressure inside the evaporator was effectively controlled by the irreversibility of the screw drive. In order to deal with the human measurement error and huge workload caused by repeated mounting of droplets, the embedded program quickly and conveniently controlled the stepper motor to mount the droplets accurately and repeatedly, which provided technical support for the large-scale collection of droplet evaporation data. The pulsed light source (1) and the high-speed camera (6, 7) formed an image acquisition system to record the evaporation process of the droplets.

Based on the actual physical conditions in the cylinder at the time of diesel injection (700–1200 K, ≥2 MPa),\(^{43}\) the temperature in the evaporator was set to 800, 900, and 1000 K, and the pressure was set to 2 MPa to approximate the environment when the fuel was injected. The forced turbulence in the diesel engine had a greater impact on the evaporation process of the droplets.\(^{44,45}\) In order to control a single variable, the turbulence conditions in the evaporator were simplified to natural convection in this study.

The temperature in the evaporator was raised by the heating wire, regulated by the temperature controller (REX-C900), and maintained within the set value range. The inert gas nitrogen was output from a high-pressure gas cylinder and was filled into the evaporator after passing through a pressure-regulated supercharger and an inflation valve, which caused the pressure in the container to stabilize at the preset pressure. By controlling the rotation angle of the stepper motor, the volume of the mounted droplet was precisely adjusted to 0.5 μL, and the droplet diameter was 0.90 ± 0.05 mm.

3. ERROR ANALYSIS

3.1. Suspended Droplet Configuration. First, 1000 K and 2 MPa were set as the test conditions, and the group test of the emulsion fuel W0 was carried out, the purpose of which was to verify whether the heat conduction of the quartz filament in this test will enhance the surface nucleation effect. After the quartz filament was removed, the pulse light source and high-speed camera were placed at the position where the droplets began to agglomerate and microexplose (in this case, moved down 21.8 and 38.5 cm, respectively). The change in the droplet’s microexplosion moment was observed under free-
fall conditions, as shown in Table 3. Compared with free fall, the suspended droplet configuration advanced the agglomeration and microexplosion of the droplets, and the systematic error was no more than 3%. Therefore, we considered that the influence of the suspended configuration of quartz filament on the destructive evaporation process of droplets was acceptable. The evaporation process of suspended droplets was accurately captured by the imaging system, while free-falling droplets required the dynamic image capture technology, and the shooting accuracy was not as good as that of the suspended droplets.

| parameter                  | suspension configuration (s) | free fall (s) |
|----------------------------|------------------------------|---------------|
| agglomeration timing (1000 K, 2 MPa) | 0.638–0.684                 | 0.655–0.690   |
| microexplosion timing (1000 K, 2 MPa) | 0.689–0.725                | 0.701–0.743   |

3.2. Morphological Processing, Consistency, and Reproducibility. This study refers to the static image processing scheme for the necessary morphological processing and quantitative analysis of the droplet image. Through the method of droplet projection area, the target area was cropped by Image-Pro Plus, the effective image was enhanced using the binarization method, the droplet projection area was obtained by calculating the number of pixels, and the equivalent diameter was finally calculated. The equivalent diameter and equivalent circle area were calculated and the error was less than 3%.

W0 was placed at a temperature of 800 K for multiple evaporations to evaluate the consistency and reproducibility of the evaporation experiment, and the normalized droplet diameter change is shown in Figure 3. At the beginning of the droplet evaporation, the curve showed some fluctuation, which was mainly due to the droplet entering the evaporator from the needle, and abrupt natural convection was applied to the droplet, causing the droplet to produce an irregular motion. When the droplet state was stable, the curve was maintained within the limited upper and lower regions, and the regression determination coefficients were $R^2 = 97.3$ and 98.6%, respectively. This showed that this mixed fuel can maintain certain consistency and reproducibility when evaporated at high temperatures.

3.3. Motion Accuracy. Taking the intersection of the quartz filaments as the origin of the coordinates, a reference system is established to analyze the dynamic parameters of the secondary droplets, as shown in Figure 4. The area of the original droplet was used as a reference standard to analyze the area of the secondary droplet.

The image accuracy when the secondary droplet was displaced mainly depends on the resolution, frame rate, and the shooting distance of the camera. The main parameters set by the high-speed camera in the test are listed in Table 4.
4. RESULTS AND DISCUSSION

4.1. Evaporation Process. Figure 7 shows a partial picture frame array of the details of the droplet evaporation process. The droplets of the mixed fuel basically underwent four processes during the evaporation process, including nucleation, agglomeration, puffing, and explosion.

The droplet explosion is divided into two categories in this study. A kind of explosion occurred when the liquid film was relatively thick and it usually occurs earlier. A thicker liquid film might mean that the probability of being destroyed was lower. At this time, the explosion was due to the higher pressure inside the bubble. During the explosion, the shape of the droplets changed dramatically. Another type of explosion occurred when the liquid film was thin and this occurs later. The thinner droplets lasted for a relatively long time in a high-temperature environment.

Both the agglomeration process and the explosion process of the droplets showed a sudden drop in the slope of the curve in the $D_\Delta$ graph, but the difference between the two was clearly judged by analyzing the droplet image. The normalized curves for the evaporation of the four groups of fuels at high temperatures are shown in Figure 8. The time range of droplet agglomeration and explosion was clearly delineated, where the time range of the explosion was denoted as $t_b$ and the time range of the agglomeration was denoted as $t_f$. The cases where only the agglomeration process occurred generally occur at 800 K, and they only experienced the puffing process in the later evaporation stage. This indicated that at 800 K, it was difficult to meet the requirements of pressure accumulation inside the bubble and tear the liquid film in a short time.

For determining whether the high-temperature evaporation characteristics of the mixed fuel met the classic $d^2$ law, we fitted 12 sets of data. However, the results showed that, except at 1000 K, when individual droplets (W0-1000K and W4-1000K) explode violently, the remaining droplets met the linear fit of the equilibrium evaporation stage, and other cases found it difficult to meet the $d^2$ law. This finding showed that the $d^2$ law was hardly used to study the evaporation characteristics of mixed fuels with large differences in physical and chemical properties.

4.2. Agglomeration, Explosion, and Droplet Lifetime. Figure 9 shows the normalized time for the agglomeration and explosion of the droplet bubbles. As the water content increased, the droplets gradually exhibited the process of agglomeration, and the normalization time experienced by agglomeration was gradually reduced, reflecting the reaccelerating integration process of the energy inside the bubble, which was also in line with the principle of energy minimization. At the same time, the time it took for the droplet to explode also shortened. As the temperature changed from 800 to 900 K and 1000 K, the normalized time of droplet agglomeration and explosion gradually decreased and tended to stabilize. This shows that while the high temperature shortened the time of droplet agglomeration and explosion, the violent degree of these two processes also correspondingly expanded, making the droplet area smaller in the reduced time range. This also
meant that the effect of droplet breakage was gradually getting better, which potentially optimized the combustion of droplets after atomization.

After linking the droplet lifetime and the explosion timing, as shown in Figure 10, we found that the evaporation lifetime of the mixed fuel droplets at three different temperatures tended to be stable. The droplet lifetimes at 800, 900, and 1000 K were 20, 4.2, and 2.1 s, respectively. When the fuel was mixed with water, the droplet lifetime increased greatly at 800 K and gradually decreased at 900 and 1000 K. The explosion timing also tended to be stable, and with the increase of the water content, the explosion timing gradually approached the lifetime of the droplet. We predict that when the water content reached more than 6%, the energy generated by the droplet in the explosion might bring most of the continuous phase into the high-temperature environment, the dispersed phase without the continuous phase package evaporated rapidly in the high-temperature environment, and the main structure of the droplet would be destroyed and disappear in the optical image.

Figure 7. Part of the detailed video frame of the droplet evaporation process (the suspended matter was bubbles, and components were ethanol and water vapor).
4.3. Bubble Generation. The influence of the number of nucleation on the droplet agglomeration and explosion was reported.\textsuperscript{48}−\textsuperscript{51} In order to quantify the expansion speed and scope of the bubble, a droplet bubble growth parameter $G_B$ was defined

$$G_B = \frac{S_B}{S_{B\text{-initial}}}$$  \hspace{1cm} (4)$$

where $S_B$ is the bubble area and $S_{B\text{-initial}}$ is the initial area of the bubble. Figure 11 shows the number of bubbles and bubble growth parameters under different water contents and temperature conditions.

As shown in Figure 11(a), in the process of droplet evaporation, the bubble growth parameters were all below 1.2. This result showed that the bubbles in the droplets hardly grew under the conditions of 800 K and 0% water content. Figure 11(b,c) shows that as the temperature increased, the peak value of the bubble growth parameters reached 20−30, and the maximum number of bubbles was 5 and 8, which were significantly higher than those shown in Figure 11(a). There were two obvious peaks observed in Figure 11(c), indicating that higher temperature promoted the rapid nucleation and agglomeration of the dispersed phase in a short period of time, combining the original two-stage bubble growth process into one and releasing energy concentratedly.

When water was added to the fuel mixture, the bubble growth parameters also showed a large-scale increase compared to those shown in Figure 11(a). As shown in Figure 11(d,g,i), the growth interval of the bubble was gradually compressed, and the time when the bubble expanded to the maximum was correspondingly advanced. This phenomenon was also reflected in other water-containing mixed fuels. Figure 11(e,h,k) shows that the peaks of the bubble growth parameters gradually appeared as more obvious double peaks, and the moments when the two peaks appeared gradually occurred. This showed that the dispersed phase of water in the fuel mixture accelerated the formation of the gas core, and the high-specific heat capacity of water could store more energy and the energy contained in the bubbles could be released in a concentrated manner.

The swelling of the droplet was measured under different pressures. In an environment of normal pressure and a pressure
of 1 MPa, the test results showed some characteristics that had been reported. Typical phenomena are listed in Table 5. The lower pressure caused the droplet to expand faster, and the degree of expansion was larger. We considered that a higher pressure would exert a normal force on the droplet from the outside of the droplet, which inhibited the expansion of the droplet, thus slowing down the expansion rate and constraining the droplet volume.

4.4. Motion of the Secondary Droplets. Under three experimental conditions (W0-1000K, W2-900K, and W6-1000K), typical secondary droplet images were obtained, as shown in Figures 4 and 12.
The energy analysis of droplet atomization has been reported in previous studies. Therefore, the dynamic parameters of typical secondary droplets should be quantitatively analyzed, as shown in Figure 13. Figure 13(a) shows that when the secondary droplet moved from 0.404 to 0.406 s, the droplet equivalent radius was reduced by 49%, and the displacement speed was increased by 140%. This meant that the bubbles agglomerated, exploded, or puffed, and the superheated steam inside pushed the droplets to move quickly. The dynamic energy of the secondary droplets had not changed significantly, indicating that in this very short period of time, part of the chemical energy and potential energy contained in the droplets was converted into dynamic energy, and the energy was generally conserved.

Figure 13(b,c) shows the parameters of the same original droplet generating two secondary droplets of different sizes. The parameters of the secondary droplets shown in Figure 13(b) were not much different from those shown in Figure 13(a). However, in the later stage of evaporation, the equivalent radius, displacement velocity, and dynamic energy of the secondary droplets had all decreased significantly. This showed that the liquid film of the secondary droplet and the main structure of the droplet were destroyed at the same time, resulting in the inability to capture the liquid phase using the high-speed camera. Similar phenomena are shown in Figure 13(c). However, it should be noted that the secondary droplets shown in Figure 13(c) underwent a process of droplet expansion in the early stage of evaporation, which meant that there was a certain amount of dispersed phase in the secondary droplets, and the dispersed phase absorbed heat and expanded under the wrapping action of the liquid film.

Table 5. Expanding Phenomenon of Droplets under Different Pressures

| Time / s | W0 (Atmospheric pressure) | W0 (1MPa) | W0 (2MPa) |
|---------|---------------------------|-----------|-----------|
| 0.035   | ![Image](image1)           | ![Image](image2) | ![Image](image3) |
| 0.294   | ![Image](image4)           | ![Image](image5) | ![Image](image6) |
| 0.036   | ![Image](image7)           | ![Image](image8) | ![Image](image9) |
| 0.599   | ![Image](image10)          | ![Image](image11) | ![Image](image12) |
| 0.034   | ![Image](image13)          | ![Image](image14) | ![Image](image15) |
| 0.655   | ![Image](image16)          | ![Image](image17) | ![Image](image18) |

![Image](image19)

Figure 13. Dynamic parameters of typical secondary droplets under the condition of (a)W0-1000K, (b)W2-900K-droplet-a, (c)W2-900K-droplet-b, and (d)W6-1000K.
The liquid film of the secondary droplets cannot sustain this expansion process for a long time and was disintegrated at the later stage of evaporation.

The lifetime of the secondary droplets shown in Figure 13(d) was longer, which had a greater correlation with the water content of the original droplets. The higher the water content of the original droplet, the greater the possibility that the secondary droplet had more water content when it was removed from the original droplet. More water content supported the secondary droplets to remain in the high-temperature evaporation environment for a long time, which was similar to the evaporation law of the original droplets. This suggested that the secondary droplet was likely to evaporate in a scale-down space similar to the original droplet.

It was observed that the decrease of the equivalent radius of the secondary droplet is accompanied by the increase or decrease of the displacement velocity of the droplet, which indicated that the direction of the steam emitted might be the same as the motion direction, hindered the motion of the droplet, or it might be opposite to the motion direction, increasing the velocity of the droplet.

4.5. Relationship between Secondary and Original Droplets. The relationship between the original droplet and the secondary droplet was studied, and 12 × 50 groups of experiments were carried out in a targeted manner, and the experimental results are shown in Figure 14. Four original droplets with different water contents generated secondary droplets at 800, 900, and 1000 K, and the path with the highest probability in the matrix was plotted. The critical conditions for the generation of secondary droplets were reviewed. The data showed that the probability of secondary droplet formation increased significantly when the water content was within the range of 4−6% and the temperature was within the range of 800−900 K. This critical temperature was similar to the temperature in the cylinder at the time of diesel injection, which meant that this type of emulsified biodiesel generated a large number of secondary droplets when it was burned in the diesel engine.

Figure 15 shows the relationship between the area of the original droplet and the secondary droplet. The original droplet and the secondary droplet was generated and the equivalent radius of the secondary droplet. The original drop area that was most likely to generate secondary droplets was within the range of 0.6−0.7 mm², which also included the area at which the droplets began to evaporate, at the time $D_0/D_0^0 \approx 1$. Based on Figure 8, we believe that the droplet was in the explosion process when $(D_0/D_0^0)^2 \approx 1$, the energy release rate was faster, and the possibility of generating secondary droplets was also greater. When the area of the original droplet was small, it was generally in the late evaporation stage and the liquid film thickness was relatively thin, which could not support the main structure of the droplet. Once the secondary droplet was generated, it faced the risk of instantaneous rupture, so it was difficult to observe the secondary droplet. At the same time, the dispersed phase in the droplet was less, and even if a small amount of secondary droplets flew out, the equivalent radius was also small. When the area of the original droplet was large, the droplet was generally in the initial expansion stage of evaporation, the thickness of the liquid film was thick, and the interfacial tension was sufficient to wrap the dispersed phase, so it was difficult for the secondary droplet to fly away from the original droplet. Even if the secondary droplets could tear the liquid film, only a small part of the dispersed phase flew out, and the equivalent radius of the secondary droplets was small. When the area of the original droplet was in the range of 0.5−0.8 mm², the equivalent radius of the secondary droplet was larger, which might be due to the balance between the interfacial tension of the liquid film and the energy contained in the dispersed phase. When the droplet exploded, the bubble vibrated violently inside the droplet, and the thickness of the local liquid film was uneven and was in a critical state of being torn. The energy contained in the superheated gas in the bubble just reached the critical state and tore the liquid film. When the energy was released, due to the interfacial tension, the entrapped and fly-out liquid film closed again to form secondary droplets. The average equivalent diameter of the secondary droplets was in the range of 80−140 μm, which was reduced by 1−2 orders of magnitude compared with the original droplets. This had a positive effect on reducing the particle size distribution of the diesel spray droplets.

We found that the secondary droplets separated from the original droplets with a higher water content (4−6%) had the highest probability of appearing on the upper side, while the higher temperature (1000 K) made the secondary droplets appear most likely on the lower side. Based on these phenomena, it was determined that the superheated steam inside the droplets penetrated the surrounding environment of the droplets through the effects of puffing and explosion. The superheated steam reduced its own pressure through volume expansion, and the volumetric force of expansion acted on the secondary droplets, which had a lifting effect on it. The higher the water content meant the greater the possibility of lifting, which lead to the higher trajectory of this secondary droplet. Higher temperatures might cause natural convection in the evaporator, resulting in a downward air flow from the heating wall to the secondary droplets, which directly led to the downward movement of the secondary droplets. The experimental results of the trajectory gave a conclusion that...
the secondary droplets under the natural convection condition expanded the motion range (spray range) of the liquid phase by 20−40% (Figure 16).

Figure 16. Schematic diagram of the trajectory range of the secondary droplets.

4.6. Relationship between Secondary Droplets and Combustion. In a simulated air atmosphere (volume fraction ratio of nitrogen and oxygen = 78:22), the ignition delay and burnout time of emulsified fuel droplets were measured at different temperatures, as shown in Figure 17. W2 was taken as an example: ignition delay, 0.019 s (1000 K) and 0.028 s (900 K) and burnout time, 0.458 s (1000 K) and 0.523 s (900 K). This shows that the high temperature reduced the ignition delay and the burnout time.

The combustion phenomenon of microexplosion of droplets was measured. Typical images are shown in Table 6. Around 0.1 s, microexplosion occurred in the W6 mixed fuel droplets, and dozens of secondary droplets with diameters reduced by 1−2 orders of magnitude were formed. The secondary droplets were also in the ignition state and moved to the periphery, and the ignition area of the droplets was greater than W0.

The maximum area formed by the breakup of W6 droplets was about 1.32 times that of W0, and the maximum flame area was about 1.41 times that of W0. Compared with W0 (0.526 s), the burnout time of W6 (0.363 s) decreased by about 30%. This indicated that the ignition delay of W6 droplets was shorter and the combustion rate was faster.

5. CONCLUSIONS

The characteristics of evaporation, microexplosion of droplets, dynamics of secondary droplets, and the relationship between the original and secondary droplets for emulsified biodiesel were investigated to elucidate the feasibility of secondary atomization of this fuel and the promotion of fuel atomization under diesel engine-like conditions. Based on the results of measurement and statistics, the following conclusions were obtained.

1) The increase in temperature made the normalized time of droplet agglomeration and explosion gradually decrease and became stable, while the increase of water content drove the droplet explosion time to gradually approach close to the droplet lifetime. The water content of more than 6% would cause the emulsified biodiesel droplet to be completely broken. The larger pressure slowed down the expansion rate and degree of the droplet. The $d^2$ law could not be fully applied to analyze the evaporation characteristics of the emulsified biodiesel.

2) The evaporation process of the secondary droplets was similar to that of the original droplets in the reduced scale, including expansion, puffing, and microexplosions that released energy in random directions.

3) Under environmental conditions during diesel injection, emulsified biodiesel droplets generated a large number of secondary droplets. Secondary droplets were most likely to be produced when $(D_d/D_0)^2 \approx 1$. The average equivalent diameter of the droplets was in the range of 80−140 μm. The secondary atomization caused by the secondary droplets expanded the spray range by 20−40% in the diesel engine cylinder.

4) The high temperature shortened the ignition delay and the burnout time of the droplet. The increase of water content lengthened the ignition delay, but shortened the burnout time. The secondary droplets produced by the microexplosion were in the ignition state and extended the breaking range.

Table 6. Microexplosion and Combustion Images of W0 and W6 Mixed Fuel Droplets

| Time / s | W0  | W6  |
|---------|-----|-----|
|         | (1000K) | (1000K) |
| 0.099   | ![Image](https://example.com/image1) | ![Image](https://example.com/image2) |
| 0.156   | ![Image](https://example.com/image3) | ![Image](https://example.com/image4) |
| 0.231   | ![Image](https://example.com/image5) | ![Image](https://example.com/image6) |
| 0.472   | ![Image](https://example.com/image7) | ![Image](https://example.com/image8) |
| 0.102   | ![Image](https://example.com/image9) | ![Image](https://example.com/image10) |
| 0.158   | ![Image](https://example.com/image11) | ![Image](https://example.com/image12) |
| 0.229   | ![Image](https://example.com/image13) | ![Image](https://example.com/image14) |
| 0.352   | ![Image](https://example.com/image15) | ![Image](https://example.com/image16) |

Figure 17. Ignition delay and burnout time of emulsified fuel droplets.
Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.1c01091

Notes
The authors declare no competing financial interest.

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■ REFERENCES

(1) Brady, R. N., Internal Combustion (Gasoline and Diesel) Engines. In Encyclopedia of Energy, Cleveland, C. J., Ed. Elsevier: New York, 2004; S15–528.
(2) Feng, Z.; Zhan, C.; Tang, C.; Yang, K.; Huang, Z. Experimental investigation on spray and atomization characteristics of diesel/gasoline/ethanol blends in high pressure common rail injection system. Energy 2016, 112, 549–561.
(3) Mukhtar, M. N. A.; Hagos, F. Y.; Noor, M. M.; Mamat, R.; Abdullah, A. A.; Abd Aziz, A. R. Tri-fuel emulsion with secondary atomization attributes for greener diesel engine. Energy Convers. Manage. 2013, 64, 438–453.
(4) Law, C. K. A Model for the Combustion of Oil/Water Emulsion Droplets. Combust. Sci. Technol. 1977, 17, 29–38.
(5) Wang, C. H.; Liu, X. Q.; Law, C. K. Combustion and micro-explosion of freely falling multicomponent droplets. Combust. Flame 1984, 56, 175–197.
(6) Kim, H.; Won, J.; Baek, S. W. Evaporation of a single emulsion droplet in elevated temperature and pressure conditions. Fuel 2018, 226, 172–180.
(7) Zhang, Y.; Huang, Y.; Huang, R.; Huang, S.; Ma, Y.; Xu, S.; Wang, Z. A new puffing model for a droplet of butanol-hexadecane blends. Appl. Therm. Eng. 2018, 133, 633–644.
(8) Meng, K.; Bao, L.; Li, F.; Wang, C.; Lin, Q. Experimental study on the electrospay and combustion characteristics of biodiesel-ethanol blends in a meso-scale combustor. Energy 2019, 179, 843–849.
(9) Manigandran, S.; Gunasekar, P.; Devipriya, J.; Nithya, S. Emission and injection characteristics of corn biodiesel blends in diesel engine. Fuel 2019, 235, 723–735.
(10) Avedisian, C. J.; Andres, R. P. Bubble nucleation in superheated liquid—liquid emulsions. J. Colloid Interface Sci. 1978, 64, 438–453.
(11) Law, C. K. A Model for the Combustion of Oil/Water Emulsion Droplets. Combust. Sci. Technol. 1977, 17, 29–38.
(12) Wang, C. H.; Liu, X. Q.; Law, C. K. Combustion and micro-explosion of freely falling multicomponent droplets. Combust. Flame 1984, 56, 175–197.
(13) Kim, H.; Won, J.; Baek, S. W. Evaporation of a single emulsion droplet in elevated temperature and pressure conditions. Fuel 2018, 226, 172–180.
(14) Zhang, Y.; Huang, Y.; Huang, R.; Huang, S.; Ma, Y.; Xu, S.; Wang, Z. A new puffing model for a droplet of butanol-hexadecane blends. Appl. Therm. Eng. 2018, 133, 633–644.
(15) Meng, K.; Bao, L.; Li, F.; Wang, C.; Lin, Q. Experimental understanding on combustion and micro-explosion characteristics of mixed droplets of aviation fuel, biodiesel and ethanol. J. Energy Inst. 2021, 169.
(16) Antonov, D. V.; Kuznetsov, G. V.; Fedorenko, R. M.; Strizhak, P. A. Micro-explosion of a two-component droplet: How the initial temperature of the water core affects the breakup conditions and outcomes. Powder Technol. 2021, 382, 378–387.
(17) Antonov, D. V.; Strizhak, P. A.; Fedorenko, R. M.;Nissar, Z.; Sazhin, S. S. Puffing/micro-explosion in raepseed oil/water droplets: The effects of coal micro-particles in water. Fuel 2021, 289, No. 119814.
(18) Strizhak, P. A.; Volkov, R. S.; Castanet, G.; Lemoine, F.; Rybydijova, O.; Sazhin, S. S. Heating and evaporation of suspended water droplets: Experimental studies and modelling. Int. J. Heat Mass Transfer 2018, 127, 92–106.
(19) Strizhak, P.; Volkov, R.; Moussa, O.; Tarlet, D.; Bellettre, J. Child droplets from micro-explosion of emulsion and immiscible two-component droplets. Int. J. Heat Mass Transfer 2021, 169, No. 120931.
(20) Sazhin, S. S.; Rybydijova, O.; Crua, C.; Heikal, M.; Ismael, M. A.; Nissar, Z.; Ariz, A. R. B. A. A simple model for puffing/micro-explosions in water-fuel emulsion droplets. Int. J. Heat Mass Transfer 2019, 133, 815–821.
(21) Sazhin, S. S.; Bar-Kohany, T.; Nissar, Z.; Antonov, D.; Strizhak, P. A.; Rybydijova, O. D. A new approach to modelling micro-explosions in composite droplets. Int. J. Heat Mass Transfer 2020, 161, No. 120238.
(22) Meng, K.; Fu, W.; Lei, Y.; Zhao, D.; Lin, Q.; Wang, G. Study on micro-explosion intensity characteristics of biodiesel, RP-3 and ethanol mixed droplets. Fuel 2019, 256, No. 115942.
(28) Li, T.; Zhang, X-Q; Wang, B.; Guo, T.; Shi, Q.; Zheng, M. Characteristics of non-evaporating, evaporating and burning sprays of hydrous ethanol diesel emulsified fuel. Fuel 2017, 191, 251–265.
(29) Shen, S.; Sun, K.; Che, Z.; Wang, T.; Jia, M.; Cai, J. An experimental investigation of the heating behaviors of droplets of emulsified fuels at high temperature. Appl. Therm. Eng. 2019, 161, No. 114599.
(30) Shen, S.; Che, Z.; Wang, T.; Yue, Z.; Sun, K.; Som, S. A model for droplet heating and evaporation of water-in-oil emulsified fuel. Fuel 2020, 266, No. 116710.
(31) Antonov, D. V.; Kuznetsov, G. V.; Misyura, S. Y.; Strizhak, P. A. Temperature and convection velocities in two-component liquid droplet until micro-explosion. Exp. Therm. Fluid Sci. 2019, 109, No. 109862.
(32) Antonov, D. V.; Shlegel, N. E.; Strizhak, P. A. Secondary atomization of gas-saturated liquid droplets as a result of their collisions and micro-explosion. Chem. Eng. Res. Des. 2020, 162, 200–211.
(33) Antonov, D. V.; Fedorenko, R. M.; Strizhak, P. A. Micro-explosion and puffing of a group of two-component droplets. Appl. Therm. Eng. 2020, 181, No. 116023.
(34) Xu, Y.; Hicks, M. C.; Avedisian, C. T. The combustion of iso-octane droplets with initial diameters from 0.5 to 5 mm: Effects on burning rate and flame extinction. Proc. Combust. Inst. 2017, 36, 2541–2548.
(35) Xu, Y.; Farouk, T. I.; Hicks, M. C.; Avedisian, C. T. Initial diameter effects on combustion of unsupported equi-volume n-heptane/iso-octane mixture droplets and the transition to cool flame behaviour: Experimental observations and detailed numerical modeling. Combust. Flame 2020, 220, 82–91.
(36) Cuoci, A.; Avedisian, C. T.; Brunson, J. D.; Guo, S.; Dalili, A.; Wang, Y.; Mehl, M.; Frassoldati, A.; Seshadri, K.; Dec, J. E.; Lopez-Pintor, D. Simulating combustion of a seven-component surrogate for a gasoline/ethanol blend including soot formation and comparison with experiments. Fuel 2021, 288, No. 119451.
(37) Xing-cai, L.; Jian-guang, Y.; Wu-gao, Z.; Zhen, H. Effect of cetane number improver on heat release rate and emissions of high speed diesel engine fuelled with ethanol–diesel blend fuel. Fuel 2004, 83, 2013–2020.
(38) Ithnin, A. M.; Ahmad, M. A.; Bakar, M. A. A.; Rajoo, S.; Yahya, W. J. Combustion performance and emission analysis of diesel engine fuelled with water-in-diesel emulsion fuel made from low-grade diesel fuel. Energy Convers. Manage. 2015, 90, 375–382.
(39) Danilov, I. N.; Danilova, R. A. Properties of water-emulsion fuels. Chem. Tech. Fuels Oil 1977, 13, 862–865.
(40) Hoxie, A.; Schoo, R.; Braden, J. Microexplosive combustion behavior of blended soybean oil and butanol droplets. Fuel 2014, 120, 22–29.
(41) Avedisian, C. T.; Glassman, I. Superheating and boiling of water in hydrocarbons at high pressures. Int. J. Heat Mass Transfer 1981, 24, 695–706.
(42) Chauveau, C.; Birouk, M.; Halter, F.; Gokalp, I. An analysis of the droplet support fiber effect on the evaporation process. Int. J. Heat Mass Transfer 2019, 128, 885–891.
(43) Li, R.; Wang, Z.; Ni, P.; Zhao, Y.; Li, M.; Li, L. Effects of cetane number improvers on the performance of diesel engine fuelled with methanol/biodiesel blend. Fuel 2014, 128, 180–187.
(44) Sazhin, S. S. Modelling of fuel droplet heating and evaporation: Recent results and unsolved problems. Fuel 2017, 196, 69–101.
(45) Elbadawy, I.; Gaskell, P. H.; Lawes, M.; Thompson, H. M. Numerical investigation of the effect of ambient turbulence on pressure swirl spray characteristics. Int. J. Multiphase Flow 2015, 77, 271–284.
(46) Wang, J.; Qiao, X.; Ju, D.; Wang, L.; Sun, C. Experimental study on the evaporation and micro-explosion characteristics of nanofuel droplet at dilute concentrations. Energy 2019, 183, 149–159.
(47) Dai, M.; Wang, J.; Wei, N.; Wang, X.; Xu, C. Experimental study on evaporation characteristics of diesel/cerium oxide nanofluid fuel droplets. Fuel 2019, 254, No. 115633.