An Experiment Study on the Laminar Burning Velocity and Markstein Length of Chlorella Oil/RP-3 Kerosene Blends

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ABSTRACT: Experiments have been carried out in a constant volume chamber to investigate the effects of Chlorella oil addition on the laminar burning velocity and Markstein length of Chlorella oil/RP-3 kerosene blends at an initial pressure of 0.1 MPa and temperature of 450 K over a wide equivalence ratio range from 0.8 to 1.4. The result shows that at equivalence ratios of 0.9 and 1.1, with the increase of Chlorella oil addition, no cellular structure is observed in the flame propagation images. It means that the Chlorella oil addition has little effect on the flame stability under these experimental conditions; however, at an equivalence ratio of 1.3, with the increase of Chlorella oil addition from 0 to 0.5, the flame tends to be stable. It is found that the Markstein length of Chlorella oil/RP-3 blend decreases with the increase of the equivalence ratio. The blend with 0.5 Chlorella oil addition has a more rapid decrease in Markstein length compared with that of the RP-3 between the equivalence ratio from 1.1 to 1.3. The peak laminar burning velocity of Chlorella oil/RP-3 kerosene blend is obtained at the equivalence ratio of 1.1, and with the increase of Chlorella oil addition from 0 to 0.5, the laminar burning velocity increases about 20%.

1. INTRODUCTION

With the rapid development of China’s civil aviation industry, the consumption of aviation kerosene has been accelerating. It is estimated that by the end of 2020, China’s oil and gas dependence on foreign countries will reach 67%.[1] At that time, China’s oil supply security issues will become very serious. In order to cope with climate change and reduce greenhouse gas emissions, the aviation industry has been taking various measures to reduce CO₂ emissions. IATA (International Air Transport Association) predicted that the only way to achieve zero growth in carbon emission in the aviation industry is to use renewable fuels.[2,3]

Biomass-derived jet fuels (bio-jet fuels) are a potential alternative to petroleum jet fuel, and nowadays, many technologies, which can convert biomass-based materials into bio-jet fuel, are available.[4,5] Because of the outstanding characteristics such as high oil content, fast growth, high yield, wide growth space, and strong purification effect, algae has become one of the most promising raw materials for bio-jet fuel.[4-6] At present, bio-jet fuel has already been produced from macroalgae and tested for flight. The testing results show that the algae bio-jet fuel has good adaptability to the existing aircraft. However, the incomplete understanding of ignition and combustion characteristics of algae bio-jet fuel also limits its application in aircraft engines greatly.[6-9]

At present, a number of studies have measured the fundamental combustion characteristics of bio-jet fuels, as shown in Table 1. Allen et al.[10] measured the auto-ignition delay time of JP-8 and camelina hydro-processed renewable jet (CHRJ) fuel using a heated rapid compression machine (RCM) in a low temperature range of 625−730 K at pressures of 5, 10, and 20 atm. It is found that the ignition delay measurements using CHRJ fuel are shorter than measured for JP-8 under identical conditions. Zhu et al.[11] measured the ignition delay times of JP-8, HRJ-Tallow, HRJ-Camelina, and other alternative aviation fuels in the temperature range of 1047−1520 K over a wide equivalence ratio range from 0.25 to 2.2 with two pressure and mixture regimes. It is pointed out that the HRJ-Tallow is most reactive at 6 atm, and the ignition delay of JP-8 and other alternative fuels are similar. Valco et al.[12] measured the ignition delay times of JP-5, JP-8, two HRJ (HRJ-8 and HRJ-5), and two Fischer−Tropsch (F-T) fuels (Shell and Sasol) in an RCM and shock tube in the temperature range of 1047−1520 K over a wide equivalence ratio range from 0.25 to 2.2 with two pressure and mixture regimes. It is pointed out that the HRJ-Tallow is most reactive at 6 atm, and the ignition delay of JP-8 and other alternative fuels are similar. Valco et al.[12] measured the ignition delay times of JP-5, JP-8, two HRJ (HRJ-8 and HRJ-5), and two Fischer−Tropsch (F-T) fuels (Shell and Sasol) in an RCM and shock tube in the temperature range of 1047−1520 K over a wide equivalence ratio range from 0.25 to 2.2 with two pressure and mixture regimes. It is pointed out that the HRJ-Tallow is most reactive at 6 atm, and the ignition delay of JP-8 and other alternative fuels are similar. Valco et al.[12] measured the ignition delay times of JP-5, JP-8, two HRJ (HRJ-8 and HRJ-5), and two Fischer−Tropsch (F-T) fuels (Shell and Sasol) in an RCM and shock tube in the temperature range of 1047−1520 K over a wide equivalence ratio range from 0.25 to 2.2 with two pressure and mixture regimes. It is pointed out that the HRJ-Tallow is most reactive at 6 atm, and the ignition delay of JP-8 and other alternative fuels are similar. Valco et al.[12] measured the ignition delay times of JP-5, JP-8, two HRJ (HRJ-8 and HRJ-5), and two Fischer−Tropsch (F-T) fuels (Shell and Sasol) in an RCM and shock tube in the temperature range of 1047−1520 K over a wide equivalence ratio range from 0.25 to 2.2 with two pressure and mixture regimes. It is pointed out that the HRJ-Tallow is most reactive at 6 atm, and the ignition delay of JP-8 and other alternative fuels are similar. Valco et al.[12] measured the ignition delay times of JP-5, JP-8, two HRJ (HRJ-8 and HRJ-5), and two Fischer−Tropsch (F-T) fuels (Shell and Sasol) in an RCM and shock tube in the temperature range of 1047−1520 K over a wide equivalence ratio range from 0.25 to 2.2 with two pressure and mixture regimes. It is pointed out that the HRJ-Tallow is most reactive at 6 atm, and the ignition delay of JP-8 and other alternative fuels are similar. Valco et al.[12] measured the ignition delay times of JP-5, JP-8, two HRJ (HRJ-8 and HRJ-5), and two Fischer−Tropsch (F-T) fuels (Shell and Sasol) in an RCM and shock tube in the temperature range of 1047−1520 K over a wide equivalence ratio range from 0.25 to 2.2 with two pressure and mixture regimes. It is pointed out that the HRJ-Tallow is most reactive at 6 atm, and the ignition delay of JP-8 and other alternative fuels are similar. Valco et al.[12] measured the ignition delay times of JP-5, JP-8, two HRJ (HRJ-8 and HRJ-5), and two Fischer−Tropsch (F-T) fuels (Shell and Sasol) in an RCM and shock tube in the temperature range of 1047−1520 K over a wide equivalence ratio range from 0.25 to 2.2 with two pressure and mixture regimes. It is pointed out that the HRJ-Tallow is most reactive at 6 atm, and the ignition delay of JP-8 and other alternative fuels are similar.
on the ignition behavior was inferred. Han et al.\textsuperscript{13} measured the ignition delay time and sooting index of kerosene blended with a bio-jet fuel for a comparative study with general aviation fuels by a shock tube over a wide range of temperature from 700 to 1200 K at 20 atm. It is found that the blended fuel has a shorter ignition delay time at a low temperature below 900 K. In terms of sooting index, blends with a bio-jet fuel reduce the propensity remarkably. Flora et al.\textsuperscript{14} measured the ignition delay time and sooting index for four bio-jet fuels derived from corn grain, canola, and soya with two single-pulse shock tubes. Their experimental conditions covered a pre-ignition temperature range of approximately 980–1800 K at a pressure of 16 ± 0.8 atm and an equivalence ratio of 0.5. Won et al.\textsuperscript{15} measured and compared the DCN, global oxidative reactivity profiles, extinction strain rate, and laminar burning velocity of HRJ Camelina, HRJ Tallow, and their blends with JP-8 with three initial temperatures exploiting the cone angle method with the equivalence ratios of 1.0–1.4. In an explosion vessel, Vukadinovic et al.\textsuperscript{19} investigated the laminar burning velocity and Markstein number of kerosene Jet A-1, GTL, and GEL blend with 20% aromatics at three different initial temperatures of 100, 150, and 200 °C, and three different initial pressures of 1, 2, and 4 bar and a wide range of equivalence ratios of 0.66–1.66. Hui et al.\textsuperscript{20} has experimentally investigated the fundamental combustion characteristics in terms of the derived cetane number (DCN), ignition delay time, laminar burning velocity, and extinction stretch rate for Jet-A and six alternative jet fuels, including three F-T synthetic paraffinic kerosene (SPK) fuels and three HRJ fuels. Furthermore, Hui and Sung\textsuperscript{21} reported the laminar burning velocities of an alternative jet fuel S-8 with initial temperature of 400 K and pressures of 1–3 atm. Munzar et al.\textsuperscript{22,23} measured the laminar burning velocities and extinction stretch rates of several blends of Jet A-1 and HRJ fuels at an initial temperature of 400 K and atmospheric pressure. It is found that Jet A-1, 20/80 Camelina HRJ/Jet A-1, and 50/50 Camelina HRJ/Jet A-1 have very similar flame speeds across the range of equivalence ratios in which the results for laminar flame speed indicate that the 20/80 Camelina HRJ/Jet A-1 blend is very similar to Jet A-1. The fundamental combustion characteristics include ignition delay time, laminar burning velocity, and extinction stretch rate of jet fuels.
fuels are directly linked to the engine performances such as blowout, altitude relight, combustion efficiency, and emissions, which are all very sensitive to the fuel compositions and molecular structures. Chlorella is a typical algal species and its main components are C16:0 saturated fatty acids, C16:3 (n-3), and C18:3 (n-3) unsaturated fatty acids. The Chlorella oil, mainly composed of C14, C16, and C18 straight-chain alkanes, is derived from Chlorella through hydroprocessing. As the HRJ fuel, it is regulated that Chlorella oil can be mixed with RP-3 in a certain proportion, but the mixing proportion should not be higher than 50% (in weight) according to the requirements of American Society for Testing and Materials (ASTM). To our knowledge, there is no flame speed data available in the literature for algae bio-jet fuel or its blend with conventional jet fuel. In order to fully understand the combustion characteristics of RP-3 kerosene blended with Chlorella oil, experiments have been carried out and the effect of Chlorella oil addition on the laminar burning velocity and Markstein length of RP-3 will be analyzed. This study will provide theoretical basis for the application of algae bio-jet fuel in aircraft engines.

2. EXPERIMENT

2.1. Experimental Setup. The experimental setup is composed of a constant-volume container, intake and outlet system, temperature controlling device, central spark ignition facility, Schlieren optical system, and high-speed camera, as shown in Figure 1. Figure 2 shows the cross-section view of the constant-volume container, which is made of stainless steel, and the internal shape of the container is a cylinder with a radius of 90 mm and a height of 180 mm. The container employs two circular glass windows on the opposite side wall to make the ignition point and flame travel process visible. The inlet system includes valves and pipes connecting to the high-pressure tanks of O2 (99.99%) and N2 (99.99%), and a special valve above the container is used to inject liquid fuels of RP-3 or Chlorella oil/RP-3 blend. A vacuum pump is connected to the container to evacuate exhaust gases after combustion. The central spark ignition facility is used to ignite premixed fuel−air mixture as well as to provide a signal to trigger the high-speed camera. In addition, a high-speed camera (Phantom V611) is used to photograph the image of flame at constant velocity of 10,000 frames per second.

In the experiment process, a K-type thermocouple is used to measure the initial temperature of the Chlorella oil/RP-3/air.
mixture and a pressure transmitter (RoseMount 3051TA2A2-B21AB4MS) is used to measure the initial pressure. To make sure that the mixture is homogeneous and quiescent enough for different fuel conditions and different equivalence ratios by the time of ignition, 6 min (according to experience, generally 3 min for gaseous fuel and 6 min for liquid fuel) is needed after injecting all components. Because of the large C numbers, the partial pressure of RP-3 or Chlorella oil/RP-3 blend in the mixture is quite small. Therefore, very precise control of the partial pressures of RP-3 or Chlorella oil/RP-3 blend, O₂, and N₂ is essential. In our study, the amount of N₂ and O₂ to be filled into the constant-volume container is calculated according to the actual partial pressure of the injected RP-3 or Chlorella oil/RP-3 blend, which can eliminate the influence of incomplete evaporation, saturated vapor pressure, and other factors on the equivalence ratio. Because the precision of the pressure transmitter used in this study is 0.075% in the measuring range, the uncertainties of the equivalence ratio are estimated to be within 1–3%. In order to reduce the measurement error, each experimental condition needs to be repeated at least three times. In this paper, 3σ criterion is used to eliminate the careless error. The laminar burning velocity can be calculated by

\[ u_l = \frac{1}{n} \sum_{i=1}^{n} u_i \]  

(1)

The standard deviation is calculated by

\[ S^2 = \frac{1}{n-1} \sum_{i=1}^{n} (u_i - u_l)^2 \]  

(2)

According to the foregoing analyses, the total uncertainty of the laminar burning velocity is 1–4.5 cm/s in this study.²⁶

2.2. Spherical Flame Analysis. Based on Bradley’s theory,²⁷ the laminar burning velocity can be acquired by means of the observed flame propagation photos. For an outwardly propagating spherical flame, the stretched flame speed \( S_n \) represents the observed flame velocity and it is the derivative value of the flame radius \( r \) to time \( t \).

\[ S_n = \frac{dr}{dt} \]  

(3)

The flame stretch rate \( \alpha \) represents the effects of strain on combustion flame, and it is the derivative value of the area’s natural logarithm to time

\[ \alpha = \frac{d(\ln A)}{dt} = \frac{dA}{A dt} \]  

(4)

where \( A \) refers to the area of flame front. Because of the nearly spherical shape of the combustion flame in the constant-volume container, \( \alpha \) can be written as

\[ \alpha = \frac{2dr}{r dt} = 2S_n/r \]  

(5)

The unstretched flame speed \( S_l \) is a specific value of \( S_n \) which has eliminated the effects of \( \alpha \) on flame travel. \( S_l \) can be extracted from \( S_n = \alpha \) curves by linear or nonlinear methods.

The linear method (L model) given by Wu and Law et al.²⁸ in 1985 is

\[ S_n = S_l - L_\alpha \]  

(6)

and the nonlinear method (NL1 Model) proposed by Markstein²⁹ in 1951 and with the theoretical deduction and proof by Frankel and Sivashinsky³⁰ in 1983 and Chen³¹ in 2011 is

\[ S_n = S_l - \frac{2S_l L_\alpha}{r} \]  

(7)

Another nonlinear method (NL2 model) proposed by Kelley and Law et al.¹³ in 2009 is

\[ \frac{S_l^2}{S_n} \left( \frac{S_l}{S_n} \right)^2 = \frac{2L_\alpha}{S_n} \]  

(8)

where \( L_\alpha \) refers to the Markstein length. Among these linear and nonlinear methods, the L model is widely used in the measurement of laminar burning velocity. However, the linear method is based on the assumption of weak flame stretch, so it is not suitable for the flame with strong stretch or unequal diffusion. Because the error of the linear method is large, studies have shown that the relationship between the flame speed and flame stretch rate is essentially nonlinear, so in this study, the NL1 model is used.

Since the pressure rise is very small except near the end of flame travel, the relation between \( u_l \) and \( S_l \) can be determined be means of

\[ A_l u_l = \rho_b S_l \]  

(9)

where \( u_l \) refers to the laminar burning velocity of combustion flame. \( \rho_u \) and \( \rho_b \) are the density of unburned and burned gases, respectively.

2.3. Experimental Procedure. Chinese RP-3 kerosene is widely used in China. It consists of 92.1% (in mass) saturated hydrocarbons and 7.9% aromatic hydrocarbons. The detailed compositions are listed in Table 2. In our previous studies, the main physicochemical properties of RP-3 were obtained as shown in Table 3. Some blend fractions, fuel composition, and physical properties of Chlorella oil/RP-3 blends have been measured by GC-MS, as shown in Table 4. According to the hydrocarbon ratio, the average molecular formula of each blend can be obtained. In this paper, the Chlorella oil addition rate is defined as

\[ R_{Chl} = \frac{m_{Chlorella}}{m_{Chlorella} + m_{RP-3}} \]  

(10)

where \( m_{Chlorella} \) and \( m_{RP-3} \) represent the mass of Chlorella oil and RP-3, respectively. The equivalence ratio \( \phi \) of Chlorella oil/RP-3/air mixture is

\[ \phi = \frac{F/A}{(F/A)_e} \]  

(11)

where \( F/A \) is the real fuel-air ratio and \( (F/A)_e \) is the fuel-air ratio of the chemically correct Chlorella oil/RP-3/air mixture.
2.4. Image Processing. The laminar burning velocity and combustion stability of Chlorella oil/RP-3 blends will be discussed at an initial temperature of 450 K, initial pressure of 0.1 MPa, Chlorella additions of 0, 0.1, 0.3, and 0.5, and under equivalence ratios from 0.8 to 1.4. The measurement of flame radius was accomplished by a self-developed software. According to the research of Huang et al.33 and Burke et al.34, the spark ignition interference and the wall confinement have a negligible effect on flame velocity within a flame radius from 6 to 25 mm. A more stringent criterion of flame radius from 8 to 18 mm was selected to process and obtain flame velocity.

For validating the measured laminar burning velocity, comparison of current experimental data with the previous literature is needed. The laminar burning velocity of S-8, Jet A, and Jet A-1 under similar conditions in the previous literature was adopted to validate our current experimental data. As shown in Figure 3, it is observed that our experimental data has agreed well with those of Kumar et al., Hui et al., and Vukadinovic et al.16,20,35

3. RESULTS AND DISCUSSIONS

3.1. Effects of Chlorella Oil Addition on Flame Propagation Characteristics. Figure 4 shows the flame propagation images of Chlorella oil/RP-3 blends with Chlorella oil addition from 0 to 0.5 at the given equivalence ratios of 0.9, 1.1, and 1.3. As shown in Figure 4, at equivalence ratios of 0.9 and 1.1, all the images have definite spherical flame boundaries. With the increase of Chlorella oil addition, no obvious cellular structure in flame is observed, which means that the combustion flame keeps stable with the increase of Chlorella oil addition. However, it is observed that at the equivalence ratio of 1.3, the initially formed flame front of RP-3 without Chlorella oil addition is not smooth, and with its propagation, the situation becomes worse. The flame surface is with many bulges, folds, and cracks, and when the flame propagates near the combustion chamber wall, dense wrinkling structure appears on the flame front, which means that the flame of RP-3 at the equivalence ratio of 1.3 is quite unstable. However, with the increase of Chlorella oil addition from 0 to 0.5, the flame of Chlorella oil/RP-3 blend tends to be stable again, which means that the Chlorella oil addition has the effect to make the flame stable.

As shown in Figure 4, the elapsing time after ignition is given, and the comparison of the elapsing time at the same flame radius indicates the effect of Chlorella oil addition on the flame propagation speed. It is shown that at the given equivalence ratios of 0.9, 1.1, and 1.3, with the increase of Chlorella oil addition from 0 to 0.5, the flame propagation speed increases slightly.

Figure 5 shows the flame radius versus time under experimental conditions. The horizontal axis represents the elapsing time after ignition, and the vertical axis represents the flame radius. As shown, an obvious near-linear relationship between time and flame radius is observed, and the slope keeps quite similar with the increase of Chlorella oil addition under all equivalence ratio conditions. As mentioned above, the flame radius is measured from 8 to 18 mm. It is noted that in Figure 5, the elapsing times from ignition to the appearance of flame with 8 mm radius are different from different Chlorella oil additions. As shown in Figure 5a, the time decreases with the increase of Chlorella oil addition, which means the formation of flame becomes faster with more Chlorella oil addition. A similar phenomenon is also observed with an equivalence ratio of 1.3 in Figure 5c, although the differences are not evident with the increase of Chlorella oil addition from 0 to 0.3. In Figure 5b, with the increase of Chlorella oil addition, the same trend is also observed, but the effect is not as obvious as Figure 5a, c. It is concluded from Figure 5 that with the increase of Chlorella oil addition, the formation of flame tends to be faster.

In order to explain the characteristic of the flame propagation in detail, the stretched flame speed $S_f$ is obtained by formula 3, and the data of $S_f$ versus flame radius were plotted in Figure 6. As shown in Figure 6, $S_f$ is not constant within the flame radius from 8 to 18 mm. With the propagation of flame, the stretched flame speed increases, which might be due to the decrease of the stretch rate. In addition, it is also
observed that $S_n$ increases with the increase of Chlorella oil addition for 0.9 and 1.3 equivalence ratios, which means that the Chlorella oil has the potential to accelerate the stretched flame speed.

Figure 7 shows the relation between $S_n$ and stretch rate $\alpha$ under experimental conditions, which can explain the effect of stretch on the flame propagation. As shown in Figure 7, the $S_n$ increases with the decrease of $\alpha$ for all conditions. For the outward propagating flame, the effect of flame stretch on the

Figure 4. Effect of Chlorella oil addition on flame propagation characteristics ($P = 0.1$ MPa, $T = 450$ K).

Figure 5. Effect of Chlorella oil addition on flame radius versus time.
flame speed is inevitable unless the flame propagates so far that the flame surface can be regarded as infinite.

In this paper, the nonlinear method is used to fit the experimental data. Figure 7 shows the fitting curves of $S_n$. In Figure 7 the intersection value of each fitting curve and vertical axis is $S_n$, which is called unstretched flame speed. In addition, the Markstein length, which indicates the stability of combustion flame, can also be obtained by formula 7.

3.2. Effects of Chlorella Oil Addition on Flame Stability. Flame stability is an important characteristic of combustion flame that affects the combustion efficiency and engine performance. Ma et al.\textsuperscript{36} told us that the Markstein number (Ma) and Markstein length ($L_b$) are primary parameters to reflect the flame stability. The positive value of $L_b$ indicates that the flame has the ability to restrain the protuberances of the flame front and makes the flame stable. The larger the $L_b$ value is, the more stable the flame can be. The negative value of $L_b$, however, indicates that the flame tends to promote the protuberances of the flame front and makes the flame unstable.

Figure 6. Effect of Chlorella oil addition on $S_n$ versus the flame radius.

Figure 7. Effect of Chlorella oil addition on $S_n$ versus the stretch rate.
According to the recommendation by Chen et al.,\textsuperscript{31,37} $L_b$ can be expressed as

$$L_b = \delta \sigma \left( \frac{1}{2} Ze (Le - 1) \gamma_1 + \gamma_2 \right)$$ \hspace{1cm} (12)

It proposes the correlation for $L_b$ as a function of $Le$, $Ze$, $\delta$, and $\sigma$ where $Le$ is the Lewis number, $Ze$ is the Zeldovich number, $\delta$ is the flame thickness, and $\sigma$ is the density ratio,

$$\gamma_1 = 2\sigma/(1 + \sqrt{\sigma}), \ \gamma_2 = \frac{\sigma}{\sigma - 1} \left[ \sqrt{\sigma} - 1 - \ln \left( \frac{\sqrt{\sigma} + 1}{\sigma - 1} \right) \right].$$

All these parameters, which represent the physical and chemical properties of fuels, have great effect on $L_b$.

In this paper, the $L_b$ will be obtained directly by an experimental method through fitting the experiment data of stretched flame speed using formula 7. Figure 8 shows the

Markstein length of Chlorella oil/RP-3 blends versus the equivalence ratio under experimental conditions. Figure 8 shows that there are large error bars for the measured Markstein lengths. Some studies pointed out that the relative Markstein lengths measured by different researchers can even be larger than 300\%,\textsuperscript{31} which means that the uncertainty of Markstein length must be large. In this study, the trend that the Markstein length of Chlorella oil/RP-3 blend decreases with the increase of the equivalence ratio can be observed. In addition, it is observed in Figure 8 that the blend with 0.5 Chlorella oil addition has a more rapid decrease in Markstein length compared with that of RP-3 between the equivalence ratio 1.1 to 1.3. At the equivalence ratio of 0.8, the Markstein length of blend with Chlorella oil addition is larger than that of RP-3, while at the equivalence ratio of 1.3, the Markstein length of RP-3 is larger than that of blend with Chlorella oil addition. However, because the large uncertainty of Markstein length, it is difficult to analyze the effect of Chlorella oil addition on the flame stability of Chlorella oil/RP-3 blend only by the Markstein length obtained by the experimental method.

3.3. Effects of Chlorella Oil Addition on Laminar Burning Velocity. Figure 9 shows the unstretched flame speed $S_l$ versus the equivalence ratio. As shown, with the increase of the equivalence ratio from 0.8 to 1.4, the unstretched flame speed increases at first and then decreases. The peak values of the unstretched flame speed are observed at the equivalence ratio of 1.1, which is consistent with the relative theory. Moreover, at each given equivalence ratio, the unstretched flame speed of blend with 0.5 Chlorella oil addition is larger than the others, which means that the Chlorella oil addition can increase the unstretched flame speed of RP-3.

To further explain the effect of Chlorella oil addition on flame speed, the laminar burning velocity versus the equivalence ratio with error bars is plotted in Figure 10. It is shown that all the errors are less than 4.5 cm/s, which means that the measurement error has been controlled in a reasonable range. The laminar burning velocity $u_l$ is one of the most important parameters of the fuel. It is defined as the velocity of a steady, one-dimensional, laminar propagation of a planar, adiabatic combustion wave into a uniform fuel/oxidizer mixture. Figure 10 shows the laminar burning velocity $u_l$ versus equivalence ratio. Same with $S_l$, $u_l$ reaches its peak value at the equivalence ratio of 1.1, and with the increase of Chlorella oil addition, the laminar burning velocity increases. From the experimental data, the $u_l$ of RP-3 and its blends with Chlorella oil are 72.28, 78.72, 82.81, and 86.97 cm/s, respectively. The $u_l$ of blend with 0.5 Chlorella oil addition increases by 20.32% compared with that of RP-3.

According to the method of Moffat,\textsuperscript{38} the relationship between the laminar burning velocity and influence factors such as the equivalence ratio, Chlorella oil addition rate, initial
temperature, and pressure can be obtained through the equation as follows:

\[ u_i = u_i(\phi) \left( \frac{R}{R_0} \right)^\gamma_i(\phi) \left( \frac{P}{P_0} \right)^{\alpha_i(\phi)} \left( \frac{T}{T_0} \right)^{\beta_i(\phi)} \]  

(13)

where \( u_i(\phi) \) is \( u_i \) under the reference condition, \( R \) is \( R_{\text{ref}} \), \( \alpha_i(\phi) \), \( \beta_i(\phi) \), and \( \gamma_i(\phi) \) are the Chlorella oil addition rate, initial pressure, and temperature exponents, respectively. In this equation \( R_0 \), \( P_0 \), and \( T_0 \) are 0.1, 0.1 MPa and 450 K, respectively.

By the fitting with the experimental data, the following result is obtained

\[ u_i = 10^4(-1.53 + 7.21\phi_i^4 - 13.45\phi_i^2 + 12.47\phi_i^3 - 5.74\phi_i^4 + 1.05\phi_i^5) \left( \frac{R}{R_0} \right)^{(4.48 - 11.94\phi_i^4 + 10.58\phi_i^3 - 3.08\phi_i^4)} \]  

(14)

Li et al.\(^3^9\) measured the laminar burning velocities of mixtures of air with \( n-C_{16}H_{34}, n-C_{10}H_{22} \), and \( n-C_{14}H_{30} \) a petroleum-derived JP-5 jet fuel, a camelina-derived hydrotreated renewable JP-5 jet fuel, a petroleum-derived F-76 diesel fuel, and an algae-derived hydrotreated renewable F-76 diesel fuel in the counterflow twin-flame configuration. It was found that the laminar burning velocities of the other four fuels are lower than those of \( n-C_{14}H_{30} \) and \( n-C_{16}H_{34} \) due to the presence of aromatic hydrocarbons and branched alkanes in fuel composition; laminar burning velocities are lower than those of alternative fuels due to more aromatic hydrocarbons in petroleum-based fuels (JP-5 and F-76). As we know, the chemical components of Chlorella oil are mainly composed of straight-chain alkanes and Chlorella oil contains less cycloparaffins and aromatics compared with RP-3. It is inferred that the difference in laminar burning velocity of Chlorella oil/RP-3 blends is attributed to the small fraction of cyclo-paraffins and negligible aromatics in the composition of Chlorella oil, which is consistent with the results of Li et al.\(^3^9\).

4. CONCLUSIONS

In this study, the effects of Chlorella oil addition on laminar burning velocity and flame stability of Chlorella oil/RP-3 blend were investigated. The flame propagation images of Chlorella oil/RP-3 blends indicate that at an equivalence ratio of 1.3, with the increase of Chlorella oil addition, the flame tends to be stable. For all equivalence ratios, with the increase of Chlorella oil addition, the flame propagation speed increases slightly. The near-linear relationship between time and flame radius is observed. With the increase of Chlorella oil addition, the formation of flame with an 8 mm radius tends to be faster. In addition, the Chlorella oil also has the effect to accelerate the stretched flame speed \( S_f \). The Markstein length of Chlorella oil/RP-3 blend decreases with the increase of the equivalence ratio. It is observed that the blend with 0.5 Chlorella oil addition has a more rapid decrease in Markstein length compared with that of RP-3 between the equivalence ratio from 1.1 to 1.3. The peak laminar burning velocity \( u_i \) of the Chlorella oil/RP-3 blend is observed at the equivalence ratio of 1.1. With the increase of Chlorella oil addition, \( u_i \) increases. The peak \( u_i \) of the blend with 0.5 Chlorella oil addition increases about 20% compared with that of RP-3.

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**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

The authors appreciate the financial supports from the National Natural Science Foundation of China (51606129, S1676132).

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