行政院國家科學委員會專題研究計畫成果報告

可混合燃料之液滴碰撞燃燒特性的研究

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中文摘要

本實驗是針對尺寸約為320μm、不同混合比的雙組份自由下落液滴在高溫環境中燃燒特性的研究。液滴係由可混合的庚烷及十六烷經預混或碰撞方式形成。實驗結果顯示一些基本的燃燒特性，如點火延遲、火焰縮口、及燃燒速率等在不同的混合方式下並無明顯的差異。當庚烷含量增加時點火延遲減少而燃燒速率增加。然而，在高速碰撞及/或偏心碰撞下所形成的液滴在火焰梭口後往往會有微爆現象發生。同時，實驗中也觀察到在高速碰撞及/或偏心碰撞下有很高的比例有氣泡在所形成的液滴中。因此，實驗結果強烈指出碰撞中的氣泡是產生微爆的主要因素。而碰撞混合的非均勻特性則亦影響到混合組份的過熱極限。如同預混液滴一班，微爆僅發生在適當的混合比下，但，不同的是，碰撞混合液滴的微爆是發生在一區域內，而預混液滴微爆發生在一固定點上。而若有微爆發生，燃燒速率則大幅提昇。

關鍵詞：碰撞液滴、微爆

Abstract

The burning characteristics of freely falling bi-component droplets of ~320 μm size in a high temperature, oxidizing environment were experimentally determined as functions of the composition of droplets. Droplets were formed by either premixed or collide-coalescent of two mixable fuels, n-heptane and n-hexadecane. The results show that the burning characteristics, such as the ignition delay, flame shrinkage, and burning rate of different modes of droplet formation have no much difference. The ignition delay decreases and the burning rate increases with the increasing of n-heptane content. However, the coalescent droplets with high relative collision velocity and/or off-center distance between collision droplets may have micro-explosion after the flame shrinkage. Coincidently, the high relative collision velocity and/or off-center distance give a high probability to have air bubbles trapped within droplets. Thus the experimental results strongly suggest that the possible nucleon site - air bubble, generated during the droplet formation process, are the dominating factor to have the micro-explosion. The non-homogenized nature of collide-coalescent mixing influences the chemical nature of superheating is emphasized too.

Like the case in the premixed mixture, the micro-explosion occurs only with suitable concentrations; however, for a given size of the collision droplet, the explosion occurs within a region, instead a fixed point of that in the premixed droplet. And with the aid of micro-explosion, the burning rate increases sharply.

Keywords: collide-coalescent droplets, micro-explosion

Introduction

The study of multi-component droplet combustion is in practical interested, since the conventional liquid fuels are usually blends of many species with vastly different molecular structures and wide range of volatilities. While much previous study on droplet combustion has assumed a single component, such an approximation has become inadequate with the anticipated optimization of engine design and the relaxation of fuel specifications.

The multi-component nature of the liquid fuel introduces significant complexity and uncertainty, in describing the droplet combustion processes [1,2]. For a single-component droplet, the combustion phenomena only involve the gas-phase transport, while the droplet simply serving as a source of fuel vapor in most situations. However, for multi-component droplets, the liquid-phase heat and species mass transports as well as their coupling with the gas-phase processes at droplet interface need to be considered in an essential way.

Immediately after the droplet generate, it starts to gasify. However, the initial gasification of multi-component droplet is dominated by the more volatile component. For a bi-component droplet with very different volatility, the result suggested that the droplet ignition is controlled by the more volatile piece [3,4]. Within the period, the droplet temperature is low, being mostly controlled by the boiling point of the more volatile component. The less volatile component thus starts to accumulate, and the concentration of the volatile component in the surface layer is substantially reduced.

It is obvious that no matter how volatile a liquid component is, it cannot gasify unless it is exposed at the droplet surface either through the surface regression, or the species diffusion with/without the internal circulation. Since the liquid-phase species diffusion is

an extremely slow process, which is one to two orders slower than that of surface regression, it is reasonable to expect that the components in the core of the droplet will be trapped unless there is strong circular motion.

Due to the complexity, the combustion characteristics on multi-component droplet were thus be discussed in the two extreme rates of internal mixing, namely (a) a diffusion limit in which there is no motion within the droplet interior such that diffusion is the only active transport mode [5], and (b) a distillation limit in which it is assumed that mixing occurs so fast tihat the states within the droplet interior are uniformed [6]. Further analytic [7] and expermental [8] studies show that, even in the presence of infinitely fast internal circulatory motion, the liquid-phase diffusional resistance is still a dominating factor, part of the volatile components can still be trapped within the droplet interior.

Since the droplet surface sub-layer becomes more concentrated with the less volatile, higher boiling point component, which leads the surface temperature increase to sustain a steady burning. Moreover, the droplet interior temperature should more uniformly distribute, because of the higher rate of thermal diffusion, and which is close to the surface temperature.

It was first postulated by Law [5] that a miscible multi-component droplet may undergo internal superheating which subsequently leads to internal gasification and thereby violent rupturing of the droplet which termed micro-explosion, and this had since been shown to be possible by Lasheras et al. [9] with proper selection of the compositions in the mixture.

However, the result in Sangiovanni and Labowski [10] showed that droplet with the same compositions as it is in Lasheras et al. [9] undergoes a steady burning over its entire lifetime. In Wang et al. [11], the results further showed that the droplet may undergo either a steady burning or with micro-explosion, which more likely can be controlled by the mode of droplet generation. Mikami et al. [12] concluded that the micro-explosion probability depends largely on the initial droplet diameter. These will then further complex the problem that it looks already matured.

In the study, the burning behaviors of bi-component droplet formed by different mixing mechanisms - premixed and collide-coalescence - will then be investigated to get further insight information. The experimental aspects of the investigation will be given in the next section, which is followed by the presentation and discussion of the experimental results.

Experimental Apparatus and Test Procedures

The first crucial requirement is to generate spatially and temporally stable free droplets over extended periods of time. Modified ink-jet printing technique used in Wang et al. [3,4] is adopted in the present study, in which a circular piezoelectric crystal plate is used to squeeze out liquid fuel inside a closed fuel reservoir through a small glass nozzle to form droplets. Two such droplet generators, each with its own pulse width and amplitude, have the same pulse rates but with phase shift in between. And two stable droplet streams with different or equal droplet sizes at the same generation rate can thus be obtainable. The second crucial requirement is to have these fine droplets collide in a desired manner. By adjusting the trajectories of the two droplet streams on a same plane, varying the phase difference and/or the relative positions of the two generators, then the two streams of droplet can be collided properly. Seating the generation assembly on an extra 2-axes translator, the collide-coalescent droplets can be adjusted to fall through the small vertical channel that connect with the high temperature, oxidizing combustion environment and then get ignited. Figure 1 shows the schematic diagram of the collision device and the overall experimental setup, except the collision device, the rest of setup is similar to that used in previous study [4].

The high temperature furnace used nickel-chromium wire for heating, fire brick for wall insulation, and had a temperature range from room temperature to ~1300 K, was controlled by a thermostat and monitored by a thermocouple. Circulating water was used to separate the droplet generation device from the high temperature environment.

In the present study, the droplet sizes were varied in the range from 100 to 320 μm mainly by changing the size of the glass nozzles of the generators, and the composition of the collide-coalescent droplets was determined by the volume ratio of the two collision droplets. A strobe light synchronized with the droplet generator, with variable phase lags, was used to freeze the moving droplet for observation and photography of the droplet at various stages of the droplet lifetime. Enlarged droplet image was obtained by CCD camera and that attached with a Baush & Lomb Mono-zoom-7 long focus microscopic lens. The generated or collide-coalescent droplets after some settling period were basically spheroid, and the uncertainty in the determination of the size of droplets was about 2%, mainly from reading the boundary of the droplet images.

The burning characteristics of the droplets under this preliminary investigation included ignition delay, burning rates, micro-explosion phenomena, and some flame behaviors.

The ignition delay was defined as the time interval from the instant at which the droplet is exposed to the high-temperature environment to when a visible flame was observed. Experimental resolution of the time scale of the electric device was ~ 0.04 ms, which can be further improved by simply change some electric components within the control box; while the uncertainty to define the ignition point was estimated to be less than 1 ms. The selected droplet generation frequency was about 30 Hz, and droplets were

separated by over 100 diameters such that there was essentially no droplet interaction effect, as noted previously by Sangiovanni and Kesten [13]. Furthermore, ref. 13 also reported that while the ignition delay decreased with increasing the relative velocity between the droplet and the environment, but the effect was minor. Since the droplet falling velocities in the present experiment were not differed much, the influence of the relative velocity was not specifically checked.

Figure 2 shows the temperature profile along the center of the connection channel and furnace. It can be seen that there exists a certain distance during which the center temperature increases and eventually reaches the final temperature. For most test conditions droplet ignition actually took place within this transient region. Thus ignition delays obtained from studies of this nature are more of qualitative nature, showing the global, trend-wise behavior for the ambient temperature indicated.

N-heptane, n-hexadecane, and their premixed and collide-coalescent droplets were tested in the study. The pure fuels were all of technical grade with purity greater than 99%.

Results and Discussions

Behaviors of n-heptane and n-hexadecane collision

In all the previous collision studies [14-18], liquid of the two droplets were same, and with equal or unequal droplet size. For normal alkanes [16,17], the behaviors of collision could be approximately classified into five regimes, I to V, as shown in figure 3. On the figure, two important parameters, the collision Weber number, We, and impact number, B, which were respectively defined as $We = \dfrac{\rho(r_1 + r_2)U^2}{\sigma}$ and $B = \dfrac{\chi}{r_1 + r_2}$, where r_1 and r_2 were the radii of the colliding droplets, U the relative velocity at collision, ρ and σ respectively designated the density and surface tension of the liquid, and χ the projection of the separation distance between the droplet centers in the direction normal to that of U. And $B = 0$ and 1 respectively designated head-on and grazing collisions.

On the figure, I and III represented permanent coalescence regimes, the colliding two droplets merge and form a single droplet. The collision conditions as in the Regime II cause the collision droplets bounce off; and as in the regimes IV and V, the initial coalescence or contacted droplets separate into two main droplets with or without fine satellite droplets.

In the present study, the collision occurs between n-heptane and n-hexedacane droplets, and the behaviors of above regimes may still exist but have different corresponding values of We and B. Since the

goal of the present study is to clarify whether the uniformity of concentration within droplet will affect the burning behavior of two mixable fuels or not, the colliding behavior in the following is thus only focus on the regimes of I and III, permanent coalescent droplets. Some sequential photos of typical collision processes within the regimes are shown on figure 4 for the presentation.

From the visual observation of a steady generated pure or premixed droplet, since the uniformity of concentration within the droplet, the transmitted strobe light has the recorded images thus appeared more uniform. For collide-coalescent droplets, during the coalescent process, it induces mixing. Due to the non-uniformity of concentration, the transmitted light thus leads the images shadowed. Still, depended on the mixing strength, after several to tens ms, the shadowed appearance disappeared and the image was same as that in pure or premixed droplet. For head-on or almost head-on collisions, the increasing of the relative velocity U should increase the mixing strength, and thus had a shorter period with shadowed image. For off-center collisions, the increasing of the impact number B decreases the mixing strength, thus the time needed becomes longer. It is also noted that there is several mixing strips - represent different species, within the off-center collision droplet. Mass diffusion between the strips will then control the later mixing process, and that takes time.

Carefully analyze the images during the coalescent process, there were one or several black spots within the droplet in some photos, and they might still exist after the setting period. The phenomena was also be observed by Ashgriz and Poo [15] in their unequal size droplets collision, and they suggested that is air bubble trapped within the droplet. The photos in Jiang et al. [16] also showed that the phenomena appeared in the regimes I and III, for both of the head-on and the off-center collisions with equal-size droplets. Since this peculiar behavior will directly affect whether the coalescent droplets have micro-explosion or not, thus we then investigated into it with much further.

Immediately after the collision, several fine objects were observed within the coalescent droplets, and figure 5 gives some typical photos. And they appeared in (1) equal and unequal size, (2) head-on and off-center, and (3) the same or different species droplets collisions. However, the number density and the size distribution of the fine objects within the coalescent droplet are quite sensitive to the collision conditions. And after some period, about few to tens ms from the collision, some or all of those fine objects disappeared. The final collision results may then appear of only one, few, or even none objects within the coalescent droplet.

Due to the lack of strong evident, we may only guess the initial fine objects are small liquid droplets together with some tiny air bubbles. As the mixing

goes on, the fine liquid droplets dissolve into and mix with the nearby liquid, thus they disappeared within a very short time. The air bubbles are possibly to be expelled out if they can reach the surface through the interior liquid motion, or collapse with each other to form a few bigger bubbles. Compare with the liquid-liquid mixing, air bubbles are much harder to dissolve into liquid and have much the chance to sustain. For n-heptane and n-hexadecane droplets collisions, statistically, the observed results show that the probability to have air bubbles trapped within the droplet increases as the collision velocity and/or the off-center distance increases. In a fairly low relative collision velocity, fine objects may appear in the beginning collision stage, however, they disappeared afterward. For unequal size droplet collisions, it has no much effect on the probability of the exhibition of the air bubbles.

It needs to be emphasized that since the repeatability and stability of the droplet stream in the experiment, the observation results represent thousands of the coalescent droplets under almost the same collision condition, so as the data point in the following figures.

Burning Characteristics

Figure 6 plots the temporal variation of the normalized square of the droplet diameter $(d_s/d_0)^2$, for both the premixed and the collide-coalescent droplets, with the compositions of 34-66% and 66-34% n-heptane/-hexadecane. On the figure, within the experimental accuracy, the burning characteristics, such as the ignition delay, the time or size that occurring the flame shrinkage, and the temporal variation of the droplet diameter are all similar between the two mixing modes of droplet at these two represented compositions. And more complete results will then present in the following.

Ignition Delay

Figure 7 then shows the ignition delays of bi-component n-heptane/-hexadecane droplets with different compositions under fixed environmental condition and almost the same final droplet size of 320 μm, the results of the premixed and collide-coalescent droplets are shown on the same figure for the comparison. As it can be seen from the figure, the mixing processes seems have no much effect on the ignition delay, and they are pretty close for all the compositions. The ignition delay of the droplets decrease with the increasing of n-heptane concentration, as one would expect from the respective results of pure n-heptane and -hexadecane droplets, and which further confirm the previous results [3,4]. The reduction is most prominent for small amount of n-heptane addition, and is mostly accomplished when the volume fraction

of n-heptane exceeds 50%.

From the visual observation of the collide-coalescent droplet, according to our previous discussions, after the settling time periods, except the possible tiny air bubbles may trapped in the droplet, the outlook of droplets is similar to that of premixed droplets. Even the concentration may still not uniformly distributed over the surface and interior, but the ratios of n-heptane and n-hexadecane at surface or at each sub-layer should not deviate from that of premixed case too much. Thus it induces the ignition behavior of premixed and collide-coalescent droplets have almost the same results.

Fundamentally, for a heterogeneous ignition, such as in the present case of droplet ignition, the ignition delay can roughly be divided into two categories, physical and chemical delays. The physical delay is concerned with the physical properties of the fuel, such as droplet size, boiling point, latent heat, etc.; and the chemical delay is concerned with the chemical properties of the fuel, such as fuel structure, fuel flammability, activation energy, etc. However, these two delay times are not mutually exclusive but usually are overlapped considerably.

For pure fuel, on the figure, it shows that the ignition delay of n-hexadecane droplet is longer than that of n-heptane droplet. And the result is contrasted with the ignition delays of homogeneous mixtures of the homologous series of n-alkanes obtained from shock tube and flow reactor studies [19]. These homogeneous ignition results show that the ignition delay decreases with increasing the carbon numbers, and this is to be reasonable expected from their chemical structure. Thus the present heterogeneous ignition results show a completely opposite trend.

At the low introducing droplet temperature, according to the phase equilibrium relation, the liquid droplet almost does not vaporize. The temperature of the droplet will rise to a point that slightly below the boiling point of the droplet constitutes, only then, there is enough fuel vapor can diffuses into and mixes with the surrounding air. For the larger carbon number fuels, the higher boiling point lead the more time required for the heating. Since the ignition delay of n-hexadecane droplet is longer than that of n-heptane droplet, this manifests the droplet heating effect, and the additional physical delay causes the reversed trend in results.

Base on the gasification mechanisms of a bi-component droplet [2], for an ideal mixture, the total vapor pressure will follow the Raults' Law, which is the sum of the individual vapor pressure times its concentration. As the initiation of gasification, the gasification is dominated by that of the more volatile component within a thin layer next to the droplet surface. When the mixture consists of sufficient amount of the low boiling point - more volatile constituent, which is n-heptane in the present case, the

extent of droplet heating is minimal and is basically independent of the less volatile constituent, and the droplet heating and ignition processes only correspond to the volatile component. However, if only with a small amount of the volatile component, according to Roult's Law, the droplet will then undergo additional, intermediate heating, in order to have proper amount of fuel vapor to achieve the ignition condition, and the extent of which would depend on the mixture composition. This therefore explains the result for low n-heptane concentration, such that the ignition delay varies non-linear with the n-heptane addition and the variation is most sensitive with a small amount of n-heptane added into the mixture.

Flame Shrinkage

Figure 8 shows an integrated and an enlarged photo of flame of 80%-heptane and 20%-hexadecane by volume, visually, the flame color becomes fainter and the flame size becomes smaller at certain position. It was first noted and explained in Wang et al. [11], which was called flame shrinkage. The physical mechanism leads to the occurrence of this interesting flame shrinkage phenomenon should be contributed by the slow liquid-phase mass diffusion. For initial uniformly distributed fuel droplet, after it gets ignited, the amount of less volatile component vaporizes much less than it exists at the droplet surface and starts to accumulate. And the high volatile component is gradually reduced or even diminished at the droplet surface. Under such a relatively low droplet temperature, the burning droplet then tends to extinguish and the flame starts to diminish, the flame color and size thus becomes fainter and smaller. However, as the flame size decreases, the temperature gradient, so as the rate of heat transfer from the flame to the surface of droplet starts to increase. A large portion of this transferred heat is then used to intensely heat the droplet, sharply raises the droplet temperature, and consequently, the fuel vapor comes out and starts to burn normally. The flame, thus back to its normal burning size.

Figure 9 gives the relation of normalized flame shrinkage size d_{sf}/d_0 vs. %-heptane in the mixture. Both results of the premixed and the collide-coalescent droplets are presented for the comparison. And it can be seen from the figure that the occurrence of the flame shrinkage becomes late as the increasing of n-heptane in the mixture. Further consider the residue volume at the occurrence of the flame shrinkage, obviously, it is much larger than the given volume fraction of n-hexadecane, this indicates that there still is plenty of n-heptane contain within the droplet.

Result also shows that there is no much difference between the two different droplet formation modes.

It should also be noted, for collide-coalescent droplet, droplet will be either micro-exploded after some distance from the flame shrinkage or burned steady till the very end. However, the burning characteristics are similar before the occurrence of the micro-explosion.

Micro-explosions

The basic mechanism responsible for the occurrence of micro-explosion during mixable bi-component droplet combustion was postulated by Law [5] and will address in the following. Without strong internal circulation, the droplet temperature rapidly increases because of the increase in the concentration of the less volatile component on the droplet surface. However, the more volatile component remains trapped within the core due to the mass diffusional resistance; and in the mean time, the droplet temperature is more uniformly distributed due to the high thermal diffusion of liquid. Thus for suitable initial concentrations the volatile species trapped within the inner core can be heated to the state at which homogeneous nucleation is possible. The subsequent internal gasification then leads to violent droplet fragmentation, which has been termed micro-explosion. And suggested that the micro-explosion may occur if the volatilities of the components are sufficiently different and their concentrations lie within an optimal range.

Lasheras et al. [9] subsequently verified that micro-explosion does occur in their n-heptane/n-hexadecane droplets with proper initial concentrations. However, Sangiovonni and Labowsky [10] had a contradictory result - a smooth burning and quiet ending instead. Mikami et al. [12] had either with or without micro-explosion, which then concluded that the probability of the occurrence of micro-explosion depend largely on the initial diameter and compositions of the droplet. On the other hand, in Wang et al. [11], by varying the droplet generation modes, with and without satellite droplet absorbed by the main droplet, both of the micro-explosion and quite burning phenomena were obtainable. Thus the conditions for the occurrence of micro-explosion become ambiguously, which then need to be studied very carefully.

According to the theory by Law [5], that the mechanism of the occurring the micro-explosion is the local temperature exceeds the local superheat limit of the mixture. However, traditional, the superheat limit data were all determined from the liquid-in-liquid experiment [20], and with a clear liquid interface between the testing liquids. For a burning bi-component droplet, even though the concentration gradient does exist within the droplet, but there is no definite interface among the changing concentrations. Thus, it may not suitable to apply those experimental determined superheat limit data on the criterion of micro-explosion droplet, even though the concentration gradient does exist within the droplet, but there is of the

bi-component droplets. Therefore, in most of the cases, the micro-explosion did not occur.

After very carefully investigating the formation of the droplets, the above contradictory thus can be explained properly. And we believe, the peculiar phenomena during the droplet formation process, air bubble or bubbles trapped within the droplet, is the key factor to have the micro-explosion. The air bubble, serve as a nucleus, introduce an additional interface for the interior gasification of suitable mixture, which then cause the occurring of the explosion, and the explosion should then be termed with heterogeneous micro-explosion instead.

The results of the present collide-coalescent droplets, with a fairly low relative collision velocity, the burning may end with quite. But by increasing the relative velocity and/or the impact number B, the probability of the appearance of micro-explosion was increased. Which is coincident with that the probability of the occurrence and existence of air bubbles, and had been checked repeatedly.

By increasing the impact number of the two colliding droplets with the same premixed mixture, to simulate the droplet formation process of Lasheras et al. [9], have very high probability of the existence of air bubble trapped within the droplet, thus the micro-explosion. And this strongly suggest that during the droplet formation of Lasheras et al. [9], air bubbles should also be trapped within the droplets, which then caused their micro-explosion. Accompany with the absorption of the satellite droplet in Wang et al. [11], air bubbles should also be trapped during the satellite absorption process, and it had been duplicated and verified in the present study.

The micro-explosion, however, still has some fundamental difference between premixed and collide-coalescent droplets. For a given final composition, all explosions occurred after the flame shrinkage. However, in Wang et al. [11] or collide-coalescent droplets with premixed mixture, the micro-explosion occurred almost at a fixed location. But, for collide-coalescent droplets with different constituents, the micro-explosion occurred within a finite region.

In Lasheras et al. [9] and Wang et al. [11], the air bubble existed within a given premixed bi-component mixture, since the concentration is more systematically distributed, and thus leads the micro-explosion occurred at a fixed point. In the present mixture, formed by collide-coalescent of two different constituents, the interior concentrations should not so well distributed, and the condition to fulfill the criterion of micro-explosion is not fixed, thus leads the micro-explosion occurred within regions or no micro-explosion at all.

Compare the situation between the low and the high relative collision velocity, the low collision velocity gives the low mixing energy and should have poor mixing level, thus it should get the better chance

to have micro-explosion. However, the results gave an opposed in trend. For the situation at higher impact number, laminate was seen within the droplet and should have the poorer mixing, thus should have the better chance to have micro-explosion. And, they are indeed.

Base on the above results, it can conclude that the air bubble is the dominating factor to cause the explosion and the mixing strength may not be important.

Figure 10 gives two photos of the flame behaviors with and without micro-explosion at the same droplet composition and size. Figure 11 then plots the size ratios d_{exp}/d_0 at micro-explosion of collide-coalescent droplets with different fraction of n-heptane contents. Similar to the results in Lasheras et al. [9] and Wang et al. [11], there is a certain range of concentrations that the occurrence of the explosion, and the optimum concentration or the maximum strength of explosion lie on ~ 0.5 volume faction of n-heptane. And it should be noted that for collide-coalescent droplets, the point that the occurrence of the micro-explosion is no longer fixed, so as the size. Figure 11 simply shows the maximum possible explosion size at that composition.

Burning Rates

Since the temporal variation of square of the droplet diameter were little curved, it is practically useful to define some global burning rates which account for the processes of ignition, steady burning, and micro-explosion. Based on the measured values of the initial droplet diameter d_0, the burning time t_b for the droplet be ignited till burned out, and the overall burning time t_{ob} for droplet be first exposed to the hot environment till burned out, we then defined an average burning rate K_{ab} and an overall average burning rate K_{ob} as follows: $K_{ab} = d_0^2/t_b$ and $K_{ob} = d_0^2/t_{ob}$. Figures 12, 13 then respectively give the burning times and the burning rates of the two different mixing modes at different compositions, and the droplets are about $320\,\mu m$ in size. Similarly, all the results show that the two different modes of mixing almost have the same values. Thus, it can conclude that with the same compositions, without micro-explosion, droplets formed by different mixing modes have the same burning characteristics, and the concentration uniformity within droplet has very little effect.

For steady burning droplets, the average burning rate only increased a little as n-heptane concentration increased. However, if we include the effect of ignition delay, then the effect become little more pronounced, as it can be seen from figure 13.

Once the occurrence of micro-explosion, the ruptured droplets were burned out within a very short

6

time (and since it is almost impossible to determine, in here, we only can consider it as zero time) after the explosion. Therefore, the burning time t_b is much less than that of the regular burning case, this gives the burning rate increases sharply. The results of the burning time and the burning rate that with micro-explosion then are also plot on figure 12, 13 for the comparison. And the optimum concentration is about with the equal fraction of the components, which then gives more than doubled the regular burning rate. And it should be addressed once more that the occurrence of the micro-explosion is not a fixed point for collide-coalescent droplets, so as the burning time and the deduced burning rate, figure 13 then only shows the maximum possible burning rate at that composition.

Conclusion Remarks

The present study can yield the following conclusions:
1. The burning characteristics between premixed and collide-coalescent bi-component droplets do not differ too much, thus the uniformity within the droplet interior play no much effect in the burning.
2. Te ignition delay of the droplets decrease with the increasing of n-heptane concentration, and the reduction is most prominent for small amount of n-heptane addition. Thus by adding a suitable amount of volatile component should improve the ignitability of the mixture.
3. The mixing strength does not play an important role on the occurrence of the micro-explosion. Air bubble plays a major role to have micro-explosion in the bi-component droplet, no matter what it is premixed or collide-mixed. The air bubble severs as a nucleus to cause the heterogeneous superheat of the mixture, and thus the heterogeneous micro-explosion. And air bubble should exist in Lasheras et al. [9] and Wang et al. [11], which then caused the micro-explosion in their premixed mixtures.
4. The probability to have air bubble trapped within a collide-coalescent droplet increases with the increasing of collision velocity and off-center distance, thus the probability to have micro-explosion increases too. The micro-explosion occurs at a fixed point for the premixed droplet, but within a finite region for the collide-coalescent droplet.
5. For steady burning droplets, the average burning rates increase with the increasing of n-heptane concentration. With the aid of micro-explosion, the burning rate increases sharply. Thus by proper select the collision strategy, one may then obtain an optimum burning result.

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Figures
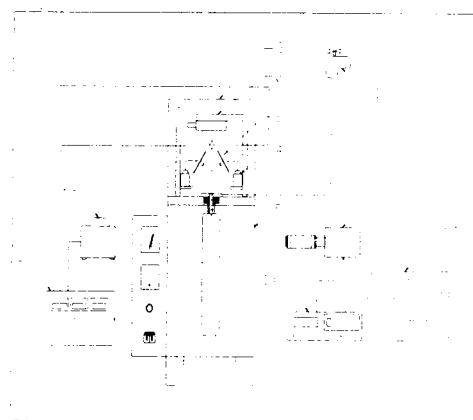
1. droplet generators 2. collision device 3. air tight chamber 4. fuel reservoirs 5. combustion chamber 6. stroboscope 7. electronic controller 8.CCD Camera 9. monitor 10. recorder 11. circulating cooling water

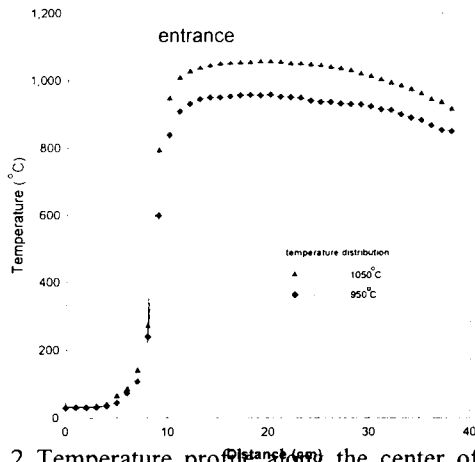Figure 1 Schematic of the experimental setup

Figure 2 Temperature profile along the center of the connection channel and furnace
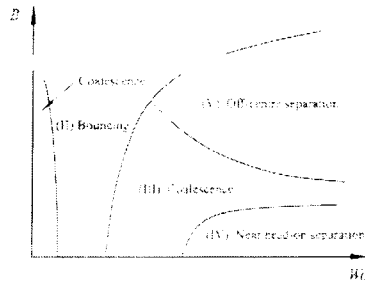

Figure 3 Schematic of the various boundaries for coalescence and separation of n-Alkane fuel [16]
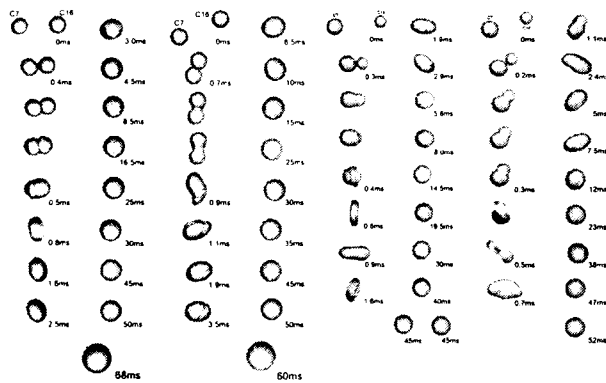

Figure 4 Sequential photos of the formation of collide-coalescent droplets
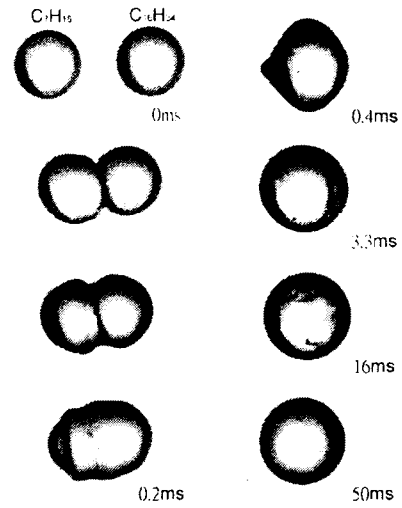

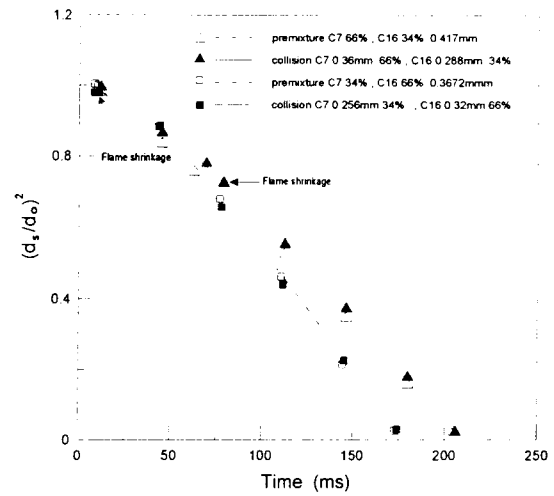Figure 5 Typical photos that show the air bubbles trap in the droplet

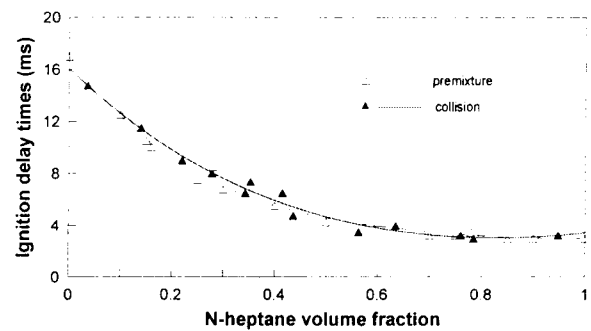Figure 6 Temporal variation of the normalized square of the droplet diameter $(d_s / d_0)^2$

Figure 7 Ignition delays of pre-mixed and collide-coalescent heptane/hexadecane droplets

8

(b)
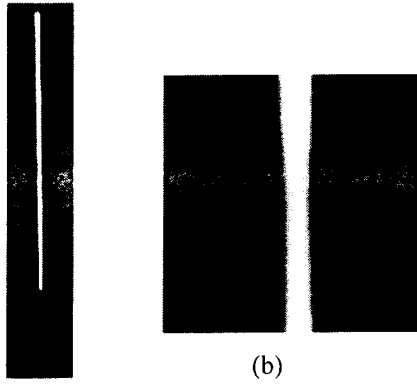
Figure 8 (a) Integrated and (b) enlarged photos of flame of 80% n-heptane and 20% hexadecane at flame shrinkage
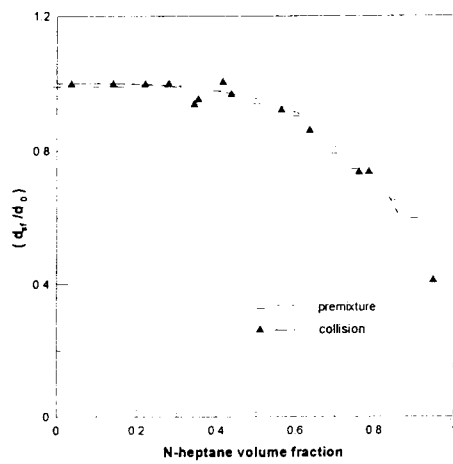
Figure 9 Size ratios at the occurrence of flame shrinkage of collide-coalescent heptane/ hexadecane droplets
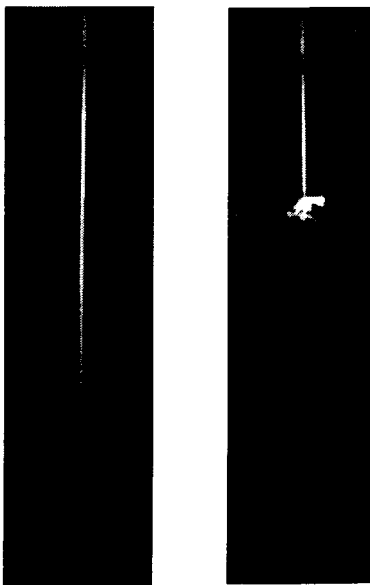

Figure 10 Photos of the flame behaviors with and without micro-explosion
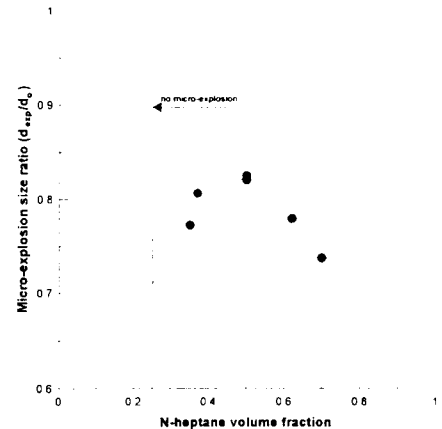

Figure 11 Size ratios at the occurrence of micro-explosion of collide-coalescent heptane/ hexadecane droplets
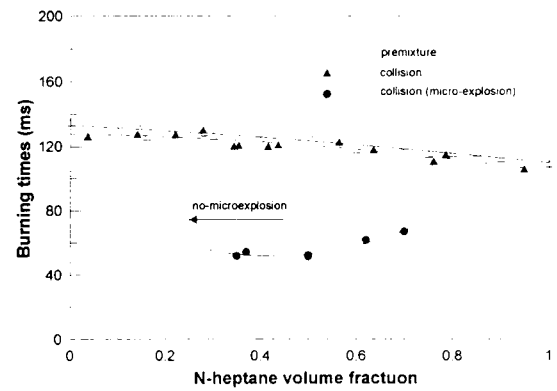

Figure 12 Burning times of pre-mixed and collide-coalescent heptane/-hexadecane droplets
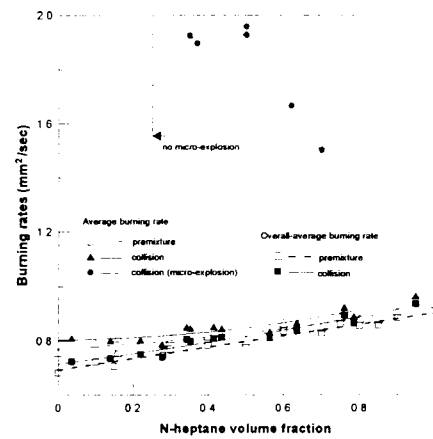

Figure 13 Burning rates of pre-mixed and collide-coalescent heptane/hexadecane droplets

9