# Experimental Study on Microexplosive Burning of Binary Fuel Droplets

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## Abstract

*The combustion characteristics of binary component single droplets hanging at the tip of a quartz fiber are studied experimentally at different pressures and temperatures under normal gravity. Normal Heptane and Normal Hexadecane are selected as two fuels with high difference in boiling temperatures. A falling electrical furnace in a high-pressure vessel has provided high temperature environment. Nitrogen and air have formed the environment to study evaporation and combustion, respectively. The initial diameter of droplet was ranging from 1.1 to 1.3 mm. The evaporation and combustion processes were recorded by a high-speed digital camera. Some characteristics of droplet burning under different environment conditions and different droplet composition have been investigated. Microexplosion of droplet take place under atmospheric pressure. Bubble formation and its consequent result, incomplete droplet disintegration which presents in all binary compositions, do not appear at high pressure. The initiation of combustion, always takes place in the bottom of droplet due to buoyancy effect of relatively cold fuel vapor. Also, the burning of binary droplet produces soot when the pressure is high.*

## Introduction

The combustion of multicomponent droplet has been studied, analytically (e.g. Law 1978, Arias-Zugasti and Rosner 2003) and experimentally (e.g. Lasheras et al 1980 and Law et al 1982). It has been shown that the disruptive evaporation and combustion is a result of presence of different components with high difference in boiling temperature. The evaporation of the more volatile component, due to its lower boiling temperature, produces bubble within the droplet and leads to microexplosion. The disruptive boiling or microexplosion are possible since for certain regions of the droplet interior, the equilibrium vapor pressure of the more volatile component can exceed the ambient pressure (Sirignano 1999). The examinations of several n-paraffin fuels in a wide range of concentration as the binary fuel have shown that for occurrence of disruption a minimum difference in the normal boiling points of components as well as a certain initial concentration of the more volatile component must exist (Lasheras et al 1980). The previous experimental results on two component fuels substantiate a three-staged evaporation and combustion (Wang et al 1984 and Ghassemi et al 2005). The three-staged evaporation confirms that the diffusion is the dominant transport mechanism in droplet. They also show that the occurrence of microexplosion depends sensitively on mixture concentration.

In this paper a comprehensive study about the combustion of multicomponent fuel droplets has been carried out. Combustion characteristics of single and multicomponent droplets hanging at the tip of a quartz fiber are studied experimentally at the different environmental conditions under normal gravity. Normal Heptane and normal Hexadecane are selected as two fuels with different burning rates and boiling temperatures. At the first step, the combustion of single component droplet of both fuels has been examined separately. At the next step the combustion of three different mixtures of these two fuels, as binary component droplet, has been studied. The temperature and pressure range is selected between 400 and 700 $^{o}$C, and 0.1 and 2.0 MPa, respectively. The initial diameter of droplet was in range of 1.1 and 1.3 mm. Nitrogen and air have been used as environment for evaporation and combustion respectively. It is found out that the combustion also exhibits the three staged behavior. Droplet rupturing (partial microexplosion) has also been observed. The effects of component concentration, ambient temperature and pressure on the combustion and disruptive burning has also been examined.

## Experimental Setup

A schematic of the experimental apparatus is shown in Fig. 1. Berifely, a droplet hanging on a fine quartz fiber was subjected to the hot environment by a freely falling furnace, thereby resulting in evaporation and combustion. This unit is enclosed within a high pressure vessel installed with glass windows which enabled us to observe the evaporation and combustion processes. In the case of evaporation, the vessel is filed by Nitrogen while in the case of combustion, air is used. The evaporation or combustion process is observed using a high speed camera. Due to flexible feature of the furnace design the ambient gas temperature steps up from low to high stage in a short time. Also, since a thin quartz fiber (with 0.125 mm diameter) is used for droplet suspension, the heat transfer between droplet and fiber is minimized. Time histories of evaporation and combustion process are recorded on a computer. Several recording speeds were examined. For disruptive evaporation and combustion 3000 frames per second has been used as maximum recording rate while for non-disruptive cases 100 frames per second is used. A flexible image-processing program has been developed to extract the droplet shape and size. More details of experimental setup and data processing can be found in (Ghassemi et al 2005).

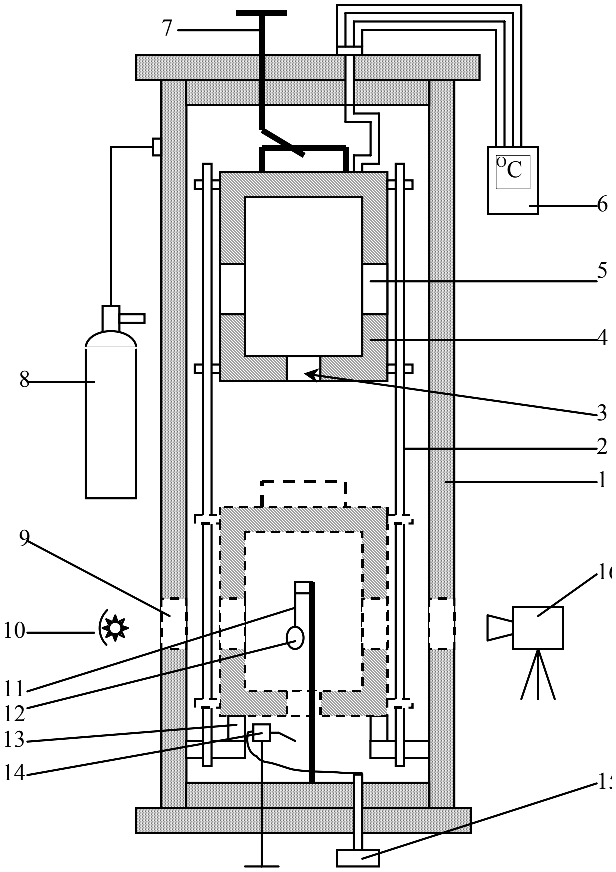

Figure 1 A sketch of experimental setup:
1) Pressure vessel, 2) guide bar, 3) furnace entrance 4) electric furnace, 5) Quartz glass window on furnace, 6) temperature controller, 7) lever, 8) Nitrogen/Air vessel, 9) Quartz glass window on pressure vessel, 10) backlight source, 11) Quartz fiber, 12) droplet, 13) shock absorber, 14) droplet maker, 15) plunger micro pump, 16) CCD camera

## Binary Droplet Evaporation

The general behavior of the multicomponent (binary) droplet is completely different from the single component droplet. Figure 2 comprises the normalized diameter squared histories for single and binary component droplets evaporation. Curve A shows the evaporation history of normal Heptane as a single component fuel. After a finite heating up period, which accompanies with small dilation in droplet size, the variation of square of droplet diameter becomes approximately linear with time while keeping $d^2$-law at the last stage of evaporation or combustion. This typical behavior of single component droplet shows a little deviation under very low or very high environment temperature.

Curves B and C show the evaporation history of the binary component droplet at the low (atmospheric) and elevated pressure, respectively. The evaporation or combustion of binary droplet shows two characteristics that distinguish it from single component fuel droplet; incomplete microexplosion and three-staged evaporation or combustion. These two features emerge when the normal boiling temperatures of each component differ highly. Normal boiling temperature of Heptane and Hexadecane are 98 $^{O}$C and 287 $^{O}$C, respectively. Evaporation of Heptane (as high volatile component), which is uniformly mixed in the droplet composition at the beginning, takes place at lower temperature than the Hexadecane. When droplet senses hot environment, the temperature within droplet reaches to the boiling temperature of Heptane. While at the same time, the temperature is lesser than the boiling temperature of Hexadecane. Look at the curve B in figure 2. Heptane that are near to droplet surface, vaporize quickly and leave the droplet surface easily. It results to approximately linear reduction in squared droplet diameter with low rate, as is shown in the beginning part of the curve B. The Heptane that are in region far from droplet surface, also reach to the boiling temperature but they cannot leave the droplet as easily as in the beginning. Because Hexadecane that is surrounding the droplet, does not evaporate yet and also its surface tension is enough to prevent the Heptane vapor escape. As Heptane evaporate more, the pressure inside the vapor bubble builds up and causes the dilation of droplet. When the bubble pressure reaches to the appropriate value to overcome the surface tension, the bubble bursts and Heptane vapors leave the droplet. The bubble formation and burst cause extreme change in droplet size and shape, which is shown in the curve B. After some time, most of Heptane leaves the droplet and this mechanism disappears gradually. In the case of 50 percent binary droplet evaporation, which is shown in curve B, when the all Heptane leave droplet completely, the normalized diameter should reach to 0.63, assuming no Hexadecane evaporation and thermal expansion. As indicated in the corresponding curve in figure 2, droplet distortion has disappeared before. A little difference, which is shown by $\Delta(d/d_0)^2$, may come from dead volume of quartz fiber and existence of a little part of Heptane in the droplet and thermal expansion of Hexadecane.

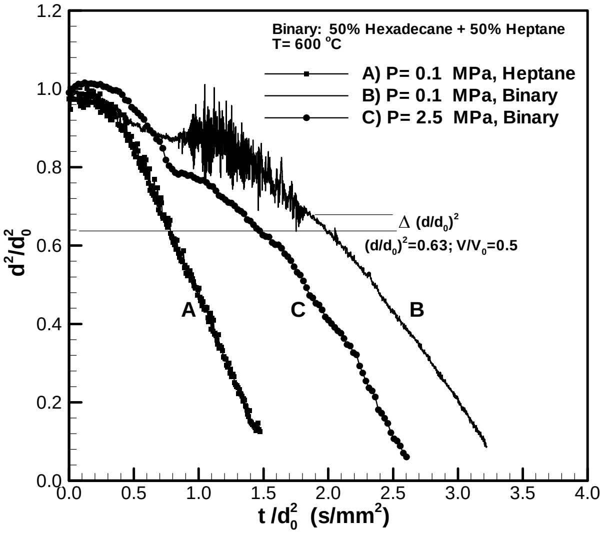

Figure 2. The general binary droplet diameter squared histories for evaporation.

Curve C in figure 2 shows a sample of binary droplet evaporation history at elevated pressure. Unlike of evaporation of binary component droplet at low pressure, escape of vapor from droplet does not lead to bubble formation and droplet rupture. Because as pressure increases, surface tension of Hexadecane decreases and allows vapor to leave the droplet.

Beside the incomplete microexplosion at the low ambient pressure, three-staged evaporation at all pressures and temperatures is another fact in evaporation of binary component droplet with high difference in boiling temperature of component. This feature is shown in curves B and C either at low or at high pressure. Generally, these evaporation histories consist of three stages; a fast reduction in droplet diameter in relatively short period, a nearly non-evaporating short period, and another period with diameter decay. In the first stage the droplet senses the temperature rise. The temperature of high volatile component (Heptane) reaches to its boiling temperature earlier than the low volatile component (Hexadecane). Heptane on and near droplet surface vaporizes, leaves the droplet and droplet shrinks.

In the beginning of the second stage, the Heptane, which was near the droplet surface, has vaporized resulting in a strong concentration gradient within the droplet. While, the Hexadecane is still in heating up period and does not start to evaporate. Therefore a mass diffusion mechanism handles Heptane to droplet surface. During mass diffusion, there is not considerable evaporation. Thus the droplet size remains almost constant. But the droplet temperature is going to increase and also Heptane is coming to droplet surface.

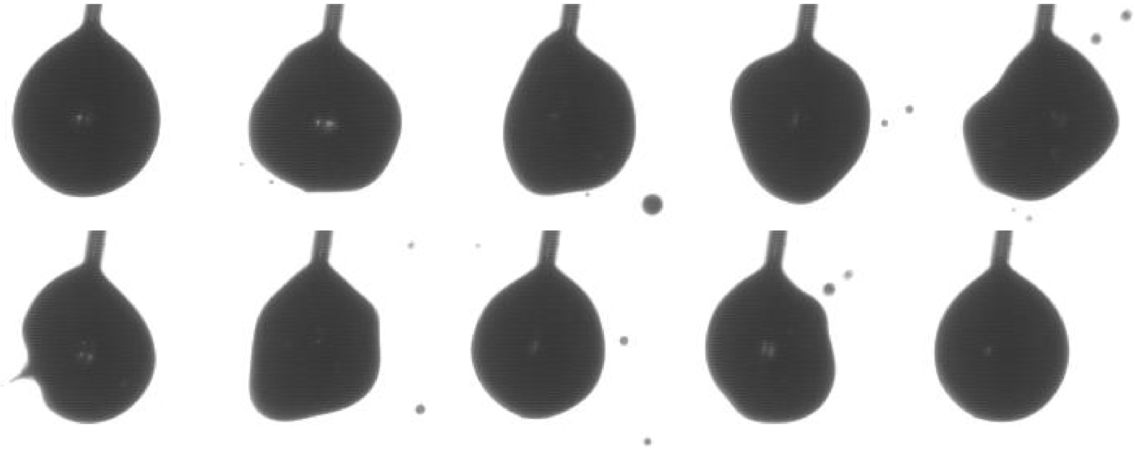

Figure 3. Some sequential photographs of droplet vaporization under low ambient pressure.

In the third stage, rest of the droplet vaporizes as the same manner as the first stage. The well mixed of Hexadecane and Heptane droplet with a completely different composition from the initial, vaporizes as a light mixture binary droplet. The evaporation of remainder Heptane takes place before the droplet reaches to the end of lifetime.

As it is shown in curve B, the evaporation binary droplet at low pressure is accompanying with bubble formation and strong droplet deformation. In figure 3, several frames of droplet photograph during evaporation at 600 $^{O}$C have been shown. The first photo (left-top) shows droplet at the beginning of explosive evaporation. The second one shows slightly distortion in droplet shape, which indicates the bubble formation inside the droplet. Other frames show very large deformation in droplet. They also show some fragments that leave the droplet. These tiny fragments consist of liquid Hexadecane and some Heptane vapor that is trapped in. The last frame (bottom-right) shows a photograph of droplet after irregular deformation has finished.

The effects of environment conditions and droplet composition on evaporation of binary droplet have been studied and can be found in (Ghassemi et al 2005). Briefly, evaporation at the atmospheric pressure leads to bubble formation within droplet and blasting of bubble causes incomplete disintegration of droplet. This phenomenon is called incomplete microexplosion. Evaporation at high pressure does not show droplet deformation or fragmentation.

Effect of environment temperature under atmospheric pressure causes changes in the strength of droplet deformation and microexplosion. At the higher environment temperature, incomplete droplet disintegration happens faster and it is seen in the movie that the number of fragments increases. But under high pressure, changes in the environment temperature, change the evaporation rats as well as the droplet lifetime.

Droplet composition affects the microexplosion strength and its onset. When the droplet contains more Heptane, its evaporation shows less fragmentation and week explosive behavior. The component concentration also affects the characteristics of three-staged evaporation. When the droplet contains more Heptane, duration of first stage increases.

## Binary Droplet Combustion

There is no essential difference between evaporation and combustion of binary component droplets. The incomplete microexplosion at low pressure and three-staged evaporation are happened in combustion in the same fashion as in evaporation. The differences are in the strength and onset time of the events. Figure 4 shows the comparison between evaporation and combustion histories for two similar cases. The ambient temperature is 700 $^{o}$C and the ambient pressure is one atmosphere.

In the case of evaporation, after an initial heating up period, the more volatile component evaporates with a constant rate in the first stage. The second stage should be a non-evaporating stage as are mentioned in the previous section as well as the literatures (e.g. Wang et al 1984).

In the case of combustion, the first stage is exactly same as evaporation, i.e. the more volatile component evaporates. The difference appears in second stage whose onset time is earlier than in the case of evaporation. The second stage in combustion also accompanies with fragmentation. The third stage is the combustion with constant rate.

In evaporation, volatile component vaporizes quickly from the outer periphery of the droplet. Then the components of volatile liquid inside the droplet start vaporizing while the non-volatile components are still in their heating up period. At this point the vaporization of volatile component inside the droplet follows the temperature gradient inside the droplet. That is why the bubble formation due to volatile component vaporization takes place near the droplet surface and not in the center. This bubble formation causes a pressure build up and an expansion in the droplet. This is the reason of increasing droplet size during the second stage of vaporization. And when the pressure in the bubble exceeds the ambient pressure, it bursts up resulting in a partial microexplosion and a sharp reduction in the droplet size. This expansion and rupturing continues till the end of the second stage until approximately the entire volatile component evaporates.

In the case of combustion, when the evaporated volatile component in the first stage reaches to its ignitable limit, combustion takes place. The extra heat flux from the flame surface enhances the evaporation of volatile component inside the droplet, which results in the onset of partial microexplosion earlier. One important conclusion can be derived from the figure 4 is that due to flame, the rate of heat transfer to the droplet is too much enhanced that the non-volatile component also starts vaporizing during the second stage of combustion. This fact can be seen from the figure, which shows that the surface regression rate during the second and third stage is same. The only difference is that the second stage accompanies with rupturing phenomenon due to quick vaporization and escape of volatile liquid near the droplet surface.

Therefore, the difference in evaporation and combustion is that the onset time of second stage is earlier in the combustion case. And in the evaporation case the vaporization of most of the less volatile component occurs in the third stage while in the combustion case, most of the less volatile component vaporizes in second stage and the remaining in the third stage.

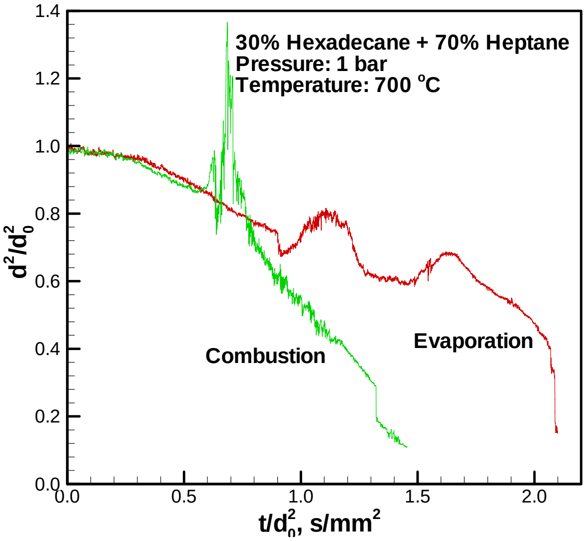

Figure 4. The general binary droplet diameter squared history for evaporation and combustion.

Figure 5 shows some photographs of droplet combustion. The first photo (left-top) shows droplet just before auto ignition. The second one shows initiation of burning. It is important to mention that the ignition starts from the some point under the droplet. May be it is the gravity effect due to which relatively cold vapor of fuel penetrates more downward rather than symmetrically around the droplet. Also, it is important to note that despite presence of incomplete droplet fragmentation in the beginning of combustion, the fragments and distorted droplet shape are not clear in these photographs. Using side light instead of backlight makes image contrast inadequate to see the tiny fragments. The bubble formation and its movement within the droplet can be seen in these photos.

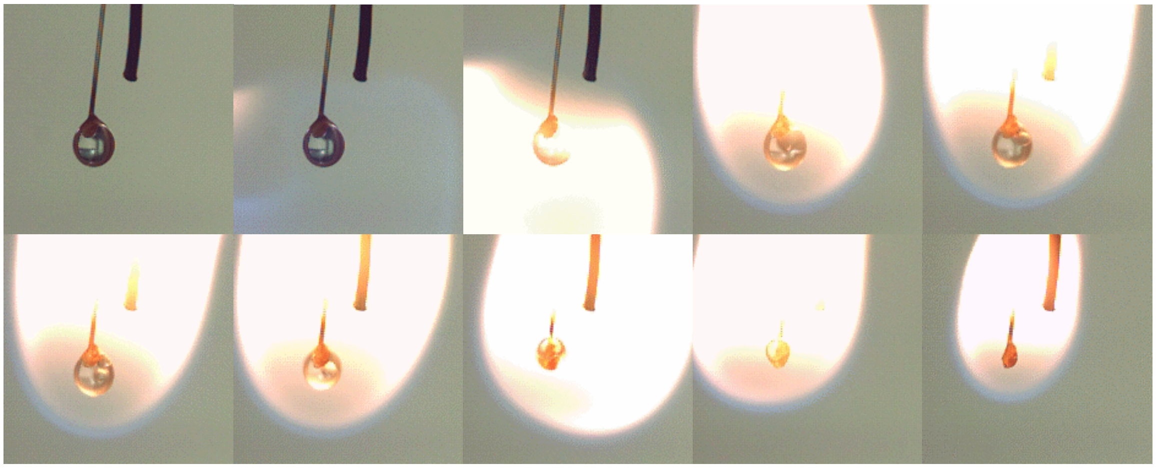

Figure 5. Some photographs of droplet combustion under low ambient pressure. P=1 bar, T=700 OC, Fuel: 50% Hexadecane + 50% Heptane.

**Effect of Ambient Conditions and Droplet Composition**

The effects of ambient conditions on combustion of binary droplet, several temperatures and pressure have been examined. The temperature ranges from 500 to 800 $^{O}$C and pressure ranges from atmospheric pressure up to 20 bar. Generally speaking, the pressure and temperature have monotone effects on combustion characteristics in the range of current study. As temperature increases, the droplet lifetime decreases. Also in low-pressure environment, the strength of droplet distortion and bubble formation increases. Combustion of binary component droplet is accompanied with soot formation at high-pressure environment. As ambient pressure increases the soot formation also increases. Due to soot formation it is very difficult, and in some cases is impossible to see the droplet through the soot.

Figure 6 presents some sequential photographs of combustion under 5 bar and 700 $^{O}$C. In this figure the sequence of photographs are from first row left to right and then other rows. The first photograph (top-left) shows the droplet just before the ignition. The ignition has been shown in the next picture. Similar to low-pressure combustion (figure 4) ignition has started below the droplet and then grows in a bell shell form. This shell quickly expands (third and fourth pictures) and gradually turns upward (from fifth to eleventh pictures). After that a relatively steady shape has establish till the lifetime of droplet. The last three pictures show the extinguishing flam just before droplet lifetime. The shell, which is seen, is not the flame surface. It is a shell that has formed by the soot in the fuel rich zone. Photographs of higher-pressure combustion show the darker surface around the droplet that confirms the shell is formed by soot.

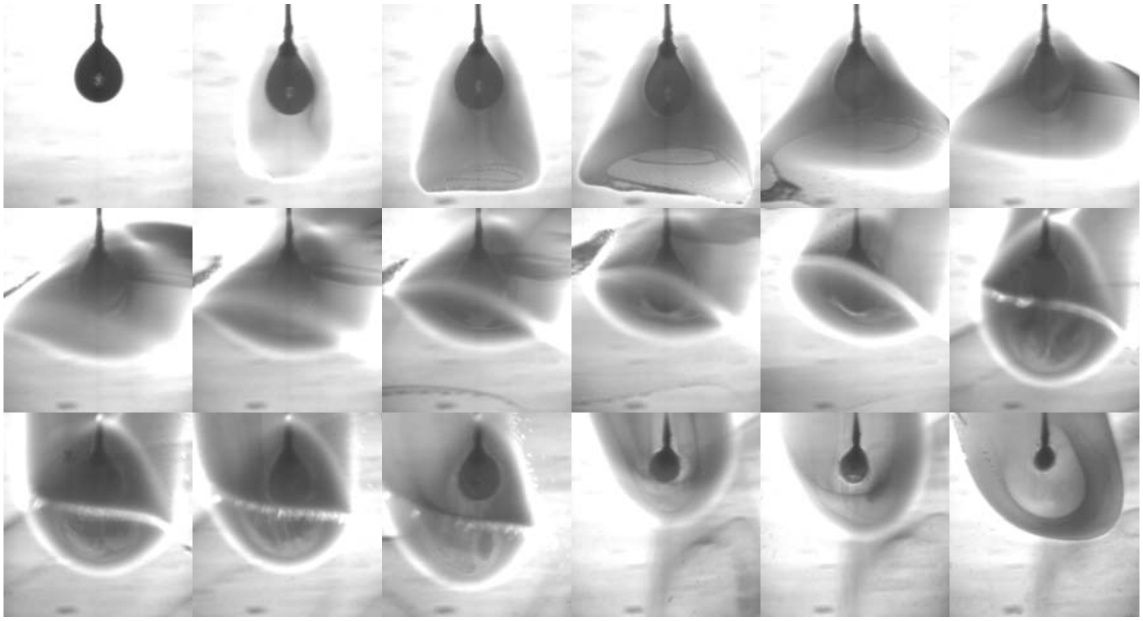

Figure 6. Some photographs of droplet combustion under high ambient pressure. P=5 bar, T=700 $^{O}$C, Fuel: 70% Hexadecane + 30% Heptane.

As there is no combustion history available after ignition in the case of high-pressure condition, so the results and discussions about pressure, temperature, and composition effects are limited before ignition. Figure 7 shows the normalized droplet diameter squared histories for combustion of a 50 percent binary droplet at 700 $^{O}$C at two different pressures. In the case low-pressure combustion, the rupturing period and ignition time are marked in the figure for simplicity. In the case of high-pressure combustion, the history shows droplet diameter just before ignition. The ignition delay in the case of low pressure is smaller as compared to high-pressure ignition delay, which is contrary to the findings in the case of pure components where ignition delay in the case of higher ambient pressures is always less than ambient pressure. The one and only difference in the history of the two curves is the presence and the absence of microexplosion. So it would be quite rational if we try to find the reduction in the ignition delay for low-pressure case in the light of microexplosive behavior. During microexplosion or fragmentation period, the volatile fuel near the surface and in the core of droplet vaporizes, builds up pressure inside the droplet and finally leaves the droplet along with tiny fragments of non-volatile fuel. This fragmentation effects are twofold:

The first is the optimum availability of fuel vapors ready for ignition and the other is the tiny fragments of nonvolatile fuel, which also vaporizes quickly due to increase in surface area available for evaporation. In other words, in the case of microexplosive behavior, the minimum need of fuel vapors required for ignition fulfills quickly hence affecting the total ignition delay by reducing the physical ignition delay time.

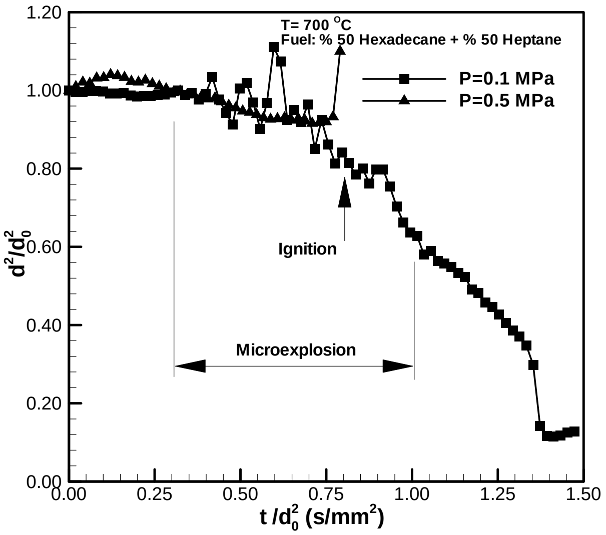

Figure 7. The droplet diameter squared history for combustion at different pressure.

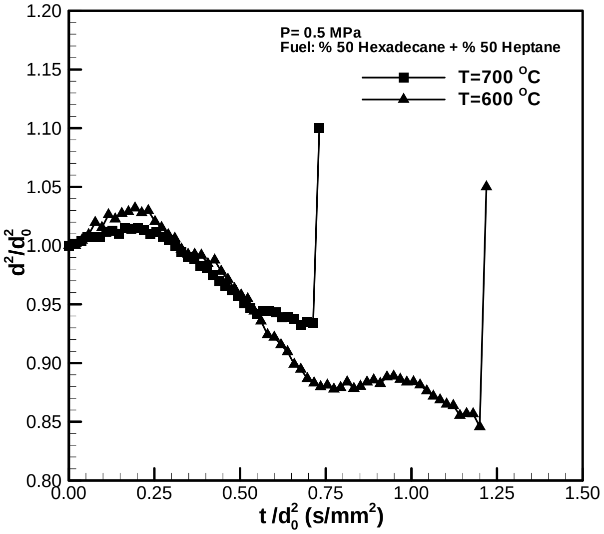

Figure 8. The droplet diameter squared history for combustion at different temperatures.

Figure 8 shows the normalized droplet diameter squared histories for combustion of a 50 percent binary droplet at 5 bar pressure and two different environment temperatures. The ignition happens sooner in the higher temperature. The temperature has direct effect on heat flux. Therefore in the case of higher temperature, the heat flux from ambient to droplet increases. Also, it seems that the combustion has started in the second stage of evaporation at low temperature, while at high temperature it has started in the first stage.

Figure 9 shows normalized diameter squared histories of two different composition binary droplets under high pressure. Since there is no microexplosive behavior at high pressure the volatile component concentration on the surface of the droplet is the only parameter on which we can discuss the ignition delay and the droplet diameter depletion behavior. In the case of 70% Heptane, minimum amount of fuel needed for the ignition is readily available from the surface of the droplet and this is the reason for quick depletion of droplet diameter that results in the quick evaporation of volatile fuel from the surface. In the case of 30 % Heptane, there is no sufficient amount of Heptane available for evaporation, and droplets needs to wait for Hexadecane to be evaporated. The hexadecane first heat up and thermally expands and enlarges the droplet diameter (this is the reason that the droplet diameter doesn't seem to be decreased although the Heptane from the surface is already evaporated). The case of 50% Heptane is the intermediate behavior between the above-mentioned two extremes.

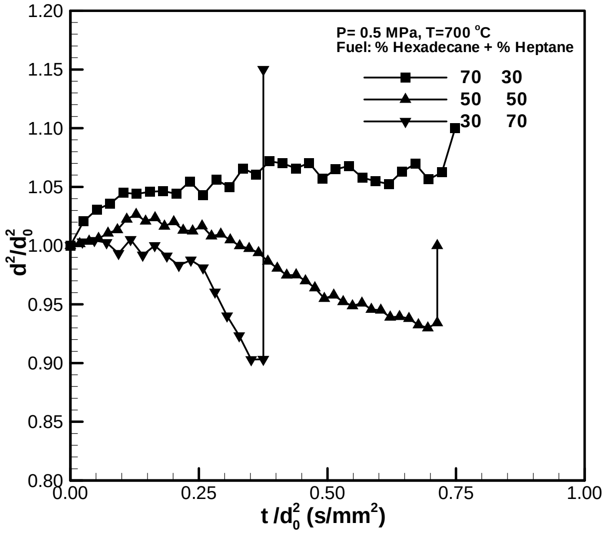

Figure 9. The combustion histories for three droplets with different compositions.

## Conclusion

A comprehensive experimental study has been carried out to investigate the microexplosive behavior of binary component single droplets. The experiments were conducted using the Hexadecane and Heptane as less and more volatile components in a binary droplet, respectively. Because evaporation is the main controlling mechanism in combustion, first the evaporation of binary droplet has been examined. Different environment conditions were used to find the effects of pressure and temperature on the combustion. Also, to investigate the effect of composition, three different blends of Heptane and Hexadecane were used. The highlighted results can be summarized as following.

- The evaporation and combustion of binary component droplet at low (atmospheric) pressure leads to incomplete disintegration of droplet. Bubble formation within droplet and its blasting cause droplet fragmentation.
- At the high pressure, the evaporation and combustion do not show the explosive behavior. High environment pressure overcomes to pressure build up within droplet and lower surface tension of Hexadecane in high pressure allows the Heptane vapor to leave the droplet freely.
- The three staged evaporation and combustion is one of the main features in the binary component burning.
- The combustion follows same fashions of evaporation. Generally, the effect of combustion on the rest of the droplet is same as introducing a hotter environment for evaporation. The flame shell around the droplet introduces more heat flux and enhances the processes.

- At higher environment temperatures droplet lifetime decrease and strength of microexplosive vaporization at low pressure increases.
- The ignition delay of binary droplet at the atmospheric pressure, which is accompanying with microexplosion is lesser than the single component droplet. It is due to enhanced penetration of more volatile fuel vapor in to the surrounding by the microexplosion.
- As concentration of more volatile fuel in the droplet increases, the auto ignition dealy of droplet decreases.
- The ignition always starts from the bottom of droplet and a flame shell turns up and finally envelops the droplet.
- Combustion of binary droplet at high pressure is accompanying with soot. In the case of Hexadecane-Heptane binary droplet, when the pressure increases, the soot formation also increases.

## Acknowledgment

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