

# Microexplosive Vaporization of Miscible Binary Fuel Droplets

Hojat Ghassemi<sup>†</sup>, Seung Wook Baek<sup>\*</sup>, and Qasim Sarwar Khan<sup>\*\*</sup>

## 미세폭발을 가진 혼화 이성분 연료 액적의 증발 현상

호젯 가세미, 백승욱, 카심 살월 칸

### Abstract

The evaporation 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. Heptane and Hexadecane are selected as two fuels with different evaporation rates and boiling temperatures. At the first step, the evaporation of single component droplet of both fuels has been examined separately. At the next step the evaporation of several blends of these two fuels, as a binary component droplet, has been studied. The temperature and pressure range is selected between 400 and 700 °C, and 0.1 and 2.5 MPa, respectively. High temperature environment has been provided by a falling electrical furnace. The initial diameter of droplet was in range of 1.1 and 1.3 mm. The evaporation process was recorded by a high speed CCD camera. The results of binary droplet evaporation show the three staged evaporation. In the the first stage the more volatile component evaporates. The droplet temperature rises after an almost non evaporating period and in the third stage a quasi linear evaporation takes place. The evaporation of the binary droplet at low pressure is accompanied with bubble formation and droplet fragmentation and leads to incomplete microexplosion. The component concentration affects the evaporation behavior of the first two stages. The bubble formation and droplet distortion does not appear at high environment pressure.

Nomenclature

**Keywords** : Liquid droplets, Multicomponent droplet, Droplet evaporation, Microexplosion

### 1. INTRODUCTION

Vaporization of a liquid fuel droplet at high pressure and high temperature environments is one of the basic mechanisms in spray combustion for various applications such as industrial furnaces, gas turbines, diesel engines, and liquid propellant rocket engines. The study of evaporation of a single droplet is necessary for characterizing and understanding the spray vaporization and combustion.

In many applications droplets consist of a mixture of two or more pure liquids. The multicomponent droplets may consist of several species with completely different physical and chemical properties. The degree of volatility, boiling temperature, evaporation latent heat, surface tension, and heat capacity of each component play an important role in the interior thermo fluid dynamic of droplet. There are various complications that occur during vaporization of multicomponent liquid droplet. Different components vaporize at different rates, creating concentration gradients within droplet and causing mass diffusion. Also evaporation of component with relatively low boiling temperature produces vapor and

<sup>†</sup> KAIST 연소기술센터

<sup>†</sup> 연락처자 : h\_ghassemi@kaist.ac.kr

<sup>\*</sup> KAIST 항공우주공학전공

<sup>\*\*</sup> KAIST 대학원, 항공우주공학전공

forms vapor bubbles and causing temperature and concentration gradient inside of droplet. In some cases pressure build up in bubbles leads to complete or incomplete explosion of droplet. The evaporation characteristics of multicomponent droplet have been studied (e.g. [1-4]) analytically and experimentally. Concentration and thermodynamic properties of species play very significant role in evaporation of binary or multicomponent droplets. 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 [5]. 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 [6]. The previous experimental results on two component fuels substantiate a three staged evaporation and combustion [7]. The three staged evaporation confirms that the diffusion is the dominant transport mechanism in droplet. They also have shown that the occurrence of microexplosion depends sensitively on mixture concentration. A good review on vaporization and combustion of droplet is presented in [8]. To study of some characteristics of binary droplet evaporation, several mixtures of normal Heptane and normal Hexadecane have been examined. The evaporation of each component has been studied at normal gravity condition and different environment pressures and temperatures as a single component fuel, separately. In this study, the environment pressure has varied from atmospheric pressure to 2.5 MPa. The environment temperature covers from 400 to 700 °C. Experiments are performed with an individual droplet suspended at the tip of quartz fiber. The initial diameter of droplets is ranged between 1.1 and 1.3 mm. The evaporation rate has been expressed as the time derivative of droplet squared diameter. This coefficient can be extracted from the

linear part of the evaporation history curve. The evaporation history is achieved by examination of temporal droplet diameters that are obtained from a high speed camera record.

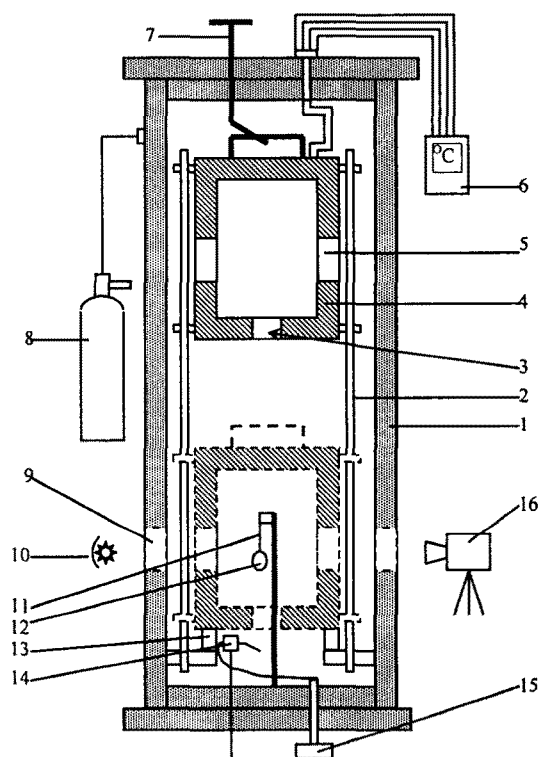


Fig. 1 A sketch of experimental setup. 1) Pressure vessel, 2) guide bar, 3) furnace entrance 4) electric furnace, 5) Quartz glass window on furnace, 6) temperature controller, 7) lever, 8) Nitrogen vessel, 9) Quartz glass window on pressure vessel, 10) backlight source, 11) Quartz fiber, 12) droplet,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

## 2. EXPERIMENTAL SETUP

A schematic of the experimental apparatus is shown in Fig. 1. A droplet hanging on a fine quartz fiber with 0.125 mm diameter was subjected to the hot environment by a freely falling furnace, thereby resulting in evaporation. This unit is enclosed within a high pressure vessel installed with glass windows which enabled us to observe the

evaporation process. The evaporation 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. It means the heat leakage from furnace to outside is negligible. Also, since a thin quartz fiber is used for droplet suspension, the heat transfer between droplet and fiber is minimized. The detailed description of the experimental setup, levels of accuracies, and procedure can be found in [9].

### 3. TEST MATRIX

To study of some characteristics of binary droplet evaporation, several blends of two pure hydrocarbons have been examined. Normal Heptane as a very high volatile fuel and normal Hexadecane as a very low volatile fuel have been selected with normal boiling temperature 98 °C and 287 °C, respectively. To find a clear picture of binary droplet evaporation, the evaporation of each main component has been studied as a single component droplet, separately. Droplet component concentrations for several mixtures of these fuels are shown in Table 1.

The critical pressures of normal Heptane and normal Hexadecane are 2.74 and 1.55 MPa, respectively. Also, the critical temperatures for these fuels are 276 and 451 °C, respectively. The pressure range includes critical pressure of Hexadecane. Therefore, in this study, evaporation of Heptane droplets takes place at subcritical condition. In other hand, the temperature range is beyond of critical temperature of Heptane.

Table 1. Droplet compositions (vol. %).

Mixture	Heptane	Hexadecane
1	100	0
2	70	30
3	50	50
4	30	70
5	0	100

### 4. DATA REDUCTION

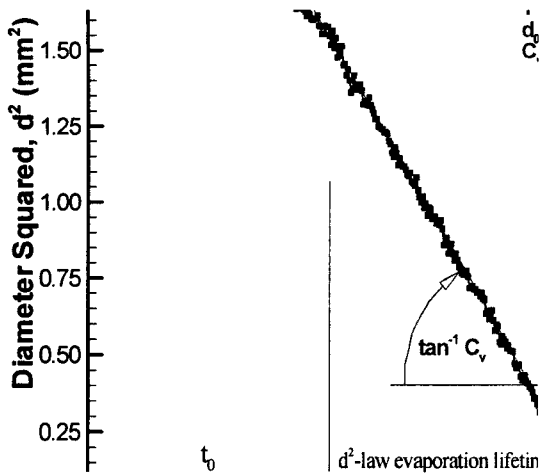
Figure 2 depicts a sample of droplet evaporation history. It shows the square of droplet diameter versus time for n Heptane droplet vaporization at 2.0 MPa and 700 °C. The initial diameter of droplet is 1.285 mm. This curve is composed of two completely different sequences. The first sequence shows a non linear behavior while the second one shows a linear regression in squared diameter. In the first or heat up period, the diameter of droplet increases and after some times starts to decrease. This behavior in droplet is due to its heat up by thermal conduction from gas and subsequent thermal expansion. As temperature of droplet surface increases and reaches its boiling temperature, evaporation starts. After that, a balance between thermal expansion and evaporation determines diameter of droplet. When the temperature inside the droplet reaches a quasi steady state, only evaporation is effective on the determination of droplet size. From this stage, the  $d^2$  law evaporation is valid. For the case shown in Fig. 2, the maximum increment of squared diameter,  $(\Delta d^2)_{max}$ , is about 6% in relation to initial squared diameter, which corresponds to 3% in diameter.

In Fig. 2, the lifetime of droplet has been divided into two parts;  $t_0$  indicates the nonlinear behavior part and the remainder is related to  $d^2$  law evaporation. For the purpose of evaporation study,  $t_0$  does not have importance, because the evaporation rate is determined by the second part of droplet behavior. For the study of ignition and combustion of droplets, however,  $t_0$  is an important characteristic of large liquid fuel droplet. The behavior of  $t_0$  is a function of initial droplet size, temperature of environment, and composition of droplet. Based on mass flux of the evaporating liquid droplet [10] for a small droplet, which heat up period is negligible,  $d^2$  law is expressed as

$$d^2 = d_0^2 - C_v t$$

where  $C_v$  is the evaporation rate (evaporation coefficient) and  $d_0$  is the initial droplet diameter. As indicated in Fig. 2, the evaporation rate can be expressed as the time derivative of droplet

squared diameter,  $C_v = -d(d^2)/dt$



**Fig. 2** Temporal variation of the square of droplet diameter.

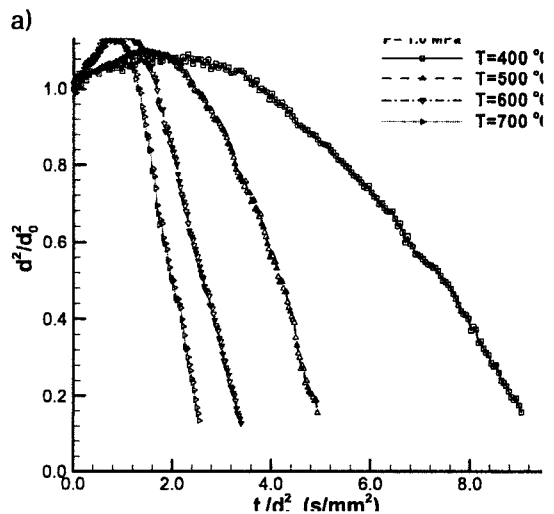
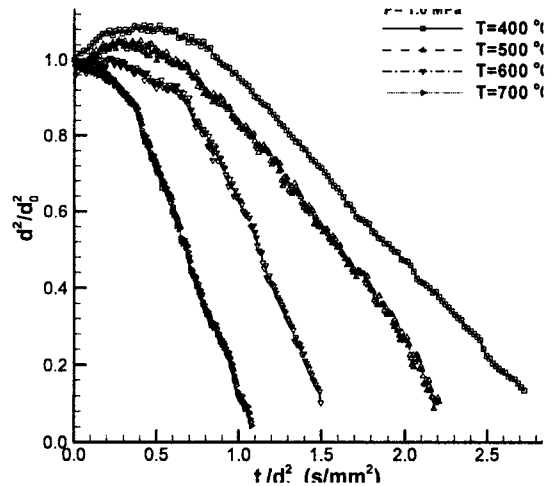
This coefficient can be extracted from the linear part of the evaporation history curve. The slope of this line, which is passing through the second part, is the minus of evaporation rate. The best fit straight line can be calculated using the least square regression.

## 5. RESULTS AND DISCUSSIONS

### 5.1 Single Component Droplet Evaporation

**General Behavior.** Figure 3 shows variations of normalized squared diameter with the normalized time for different environment temperatures and constant pressure 1.0 MPa for n-Heptane and n-Hexadecane. Each evaporation history follows the same general behavior. After a finite heating up period, the variation of square of droplet diameter becomes approximately linear with time while keeping  $d^2$  law at the last stage of evaporation. A little deviation from  $d^2$  law evaporation has been detected at lower temperature (400 °C) in Hexadecane evaporation. This general behavior has been also observed in evaporation at different environment pressures. As depicted in this fig.

increasing in ambient temperature decreases the total lifetime of droplet of Heptane and Hexadecane. Also, Heptane droplets show shorter lifetime than Hexadecane.



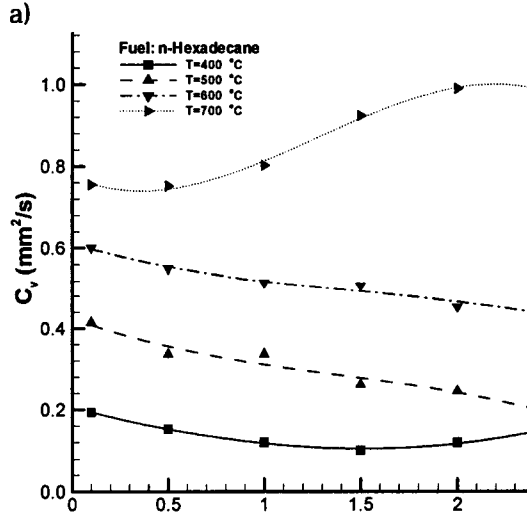
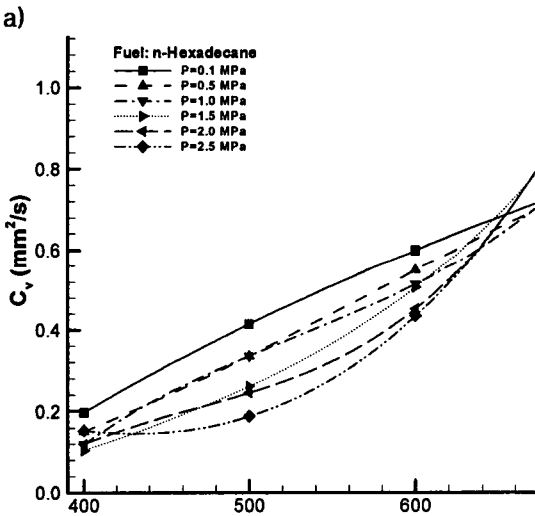
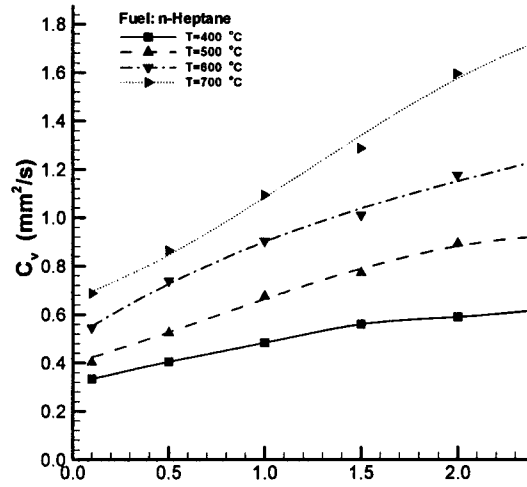
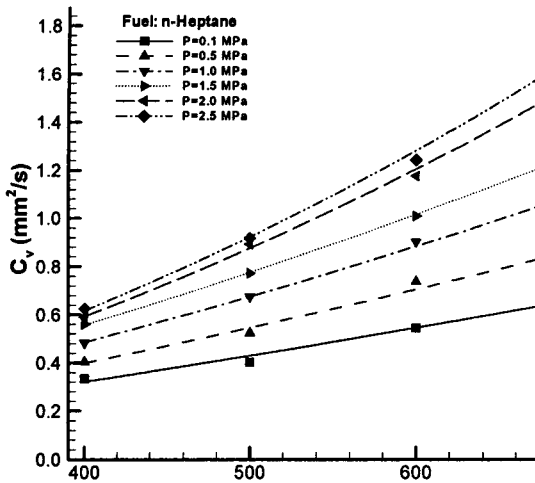
**Fig. 3** Variations of normalized diameter squared with the normalized time for several environment temperatures at 1.0 MPa for a) Heptane and b) Hexadecane.

**Effects of Temperature.** The effects of ambient temperature on the evaporation rates of Heptane and Hexadecane have been investigated under different environmental pressures.

The variations of evaporation rates of Heptane

in terms of environmental temperature have been depicted in Fig. 4 a. As the ambient

than the critical pressure.



b) Fig. 4 Effects of ambient temperature on the evaporation rate; a) the evaporation rate of Heptane and b) Hexadecane at different ambient pressures.

b) Fig. 5 Variations of the evaporation rate versus ambient pressure at several ambient temperatures for a) Heptane and b) Hexadecane.

temperature is increased, the evaporation rate monotonically increases. This trend is held for different environment pressures. In Fig. 4 b the effects of temperature on evaporation rate are shown for different environmental pressures for Hexadecane. As indicated in this fig., the evaporation rate increases versus temperature, monotonically. The dependency of evaporation rate of Hexadecane on temperature is strong when the ambient pressure is higher

Effects of Pressure. Figure 5-a shows variation of the evaporation rate versus ambient pressure for Heptane droplets. The evaporation rate shows a monotonically manner at all environment temperature. This figure shows also the evaporation rate may take a maximum at pressure slightly greater than 2.5 MPa. As indicated in this figure, the ambient pressure at which the evaporation rate may reach to a maximum increases as the ambient temperature increases. Actually, the

critical pressure of Heptane is 2.74 MPa and according to the previous works (e.g. [11]) evaporation rate of Heptane takes a maximum around the critical pressure.

Figure 5-b shows the dependency of the evaporation rate to the ambient pressure at different temperatures for hexadecane. When the ambient temperature is low (400 °C) the evaporation coefficient decreases and reaches to a minimum, then increases with the ambient pressure. At the intermediate ambient temperatures (500 and 600 °C), where it is around the critical temperature of Hexadecane, the evaporation coefficient does not take a minimum. It decreases monotonously, at least in the working pressure. It may take a minimum at higher pressure. Actually, the evaporation rate at the above mentioned environment temperature does not change too much. When the ambient temperature is sufficiently above the critical temperature of Hexadecane, the evaporation rate increases with pressure and takes a maximum at pressure slightly greater than critical pressure.

## 5.2 Binary Component Droplet Evaporation

**General Behavior.** The general behavior of the binary droplet evaporation process is completely different from a single component droplet. fig. 6 represents two samples of normalized diameter squared histories for binary droplets. One curve shows the droplet history at atmospheric pressure while the other shows evaporation at elevated environment pressure. Both curves show three staged evaporation of a binary droplet. The evaporation of binary droplet at low pressure is accompanied with bubble formation within the droplet. This leads to highly distortion of droplet shape. But due to high external pressure, bubble formation or its demonstration does not take place.

The bubbles formation, distortion and partial rupture of droplet take place with different strengths at different ambient temperatures. When the temperature increases, the strength also increases. A comparison of droplet histories during vaporization for different environment temperatures is shown in Fig 7.

At low temperature, the droplet distortion is not too strong, but bubble formation and rupture take place several times. Before each rupture the droplet diameter increases due to bubble expansion inside.

Evaporation of Heptane, which is uniformly mixed in the droplet composition at the beginning, takes place at lower temperatures than the Hexadecane. When droplet senses high temperature 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.

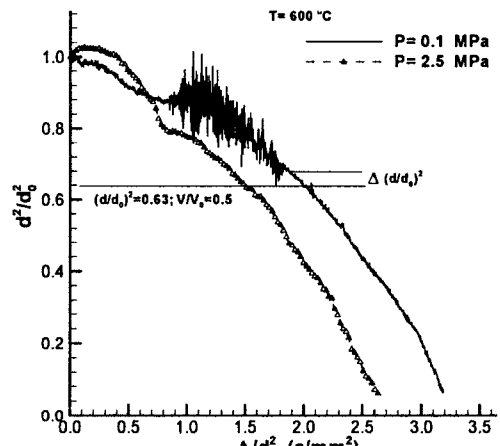


Fig. 6 The general binary droplet diameter squared history for evaporation at low and high pressure environments.

Heptane that are near to droplet surface, vaporize quickly and leave the droplet surface easily. 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 high to prevent the Heptane vapor escape. As Heptane evaporates more, the pressure inside of bubble builds up and causes the dilation of droplet. When the bubble pressure reaches to appropriate value, the bubble bursts and Heptane vapors leave the droplet. These local ruptures take place at the outer region of droplet, therefore the complete microexplosion does not appear.

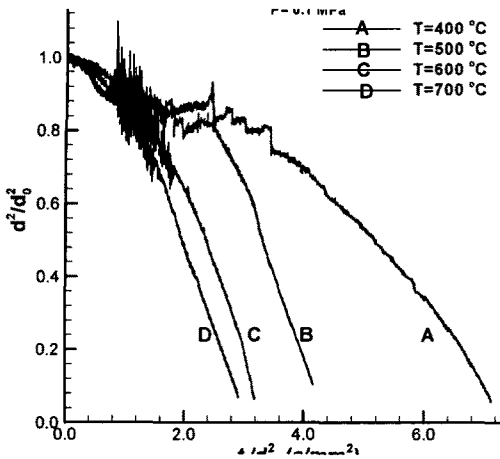


Fig. 7 Comparison of binary droplet evaporation histories at low pressure and different environment temperatures.

At the higher environment temperature, heat diffusion into droplet is faster than the lower one. Therefore the inside droplet temperature, quickly, reaches to the boiling temperature of Heptane. It leads to fast vapor formation inside of droplet, while the Hexadecane starts to evaporate. Therefore, the Heptane vapors leave

along with tiny fragments of Hexadecane easily.

The outward motion of bubbles makes a very strong internal flow inside droplet. This fact has been observed by high frame rate photography. The movie shows a rotational dislocation of bubbles with high frequency. The break open of bubbles is accompanied with incomplete fragmentation of droplet.

After some time, most of Heptane leaves the droplet and this dynamism disappears gradually. It is important to note that when Heptane completely leaves droplet, the normalized diameter squared should reach to 0.63. As indicated in Fig. 6, droplet distortion has disappeared before. A little difference, which is shown by  $\Delta(d^2/d_0^2)$ , may come from dead volume of quartz fiber and its tip bead.

In Fig. 8, several frames of droplet photograph during evaporation at atmospheric pressure and 600 °C have been shown. The first photo (top left) shows droplet at the beginning of 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

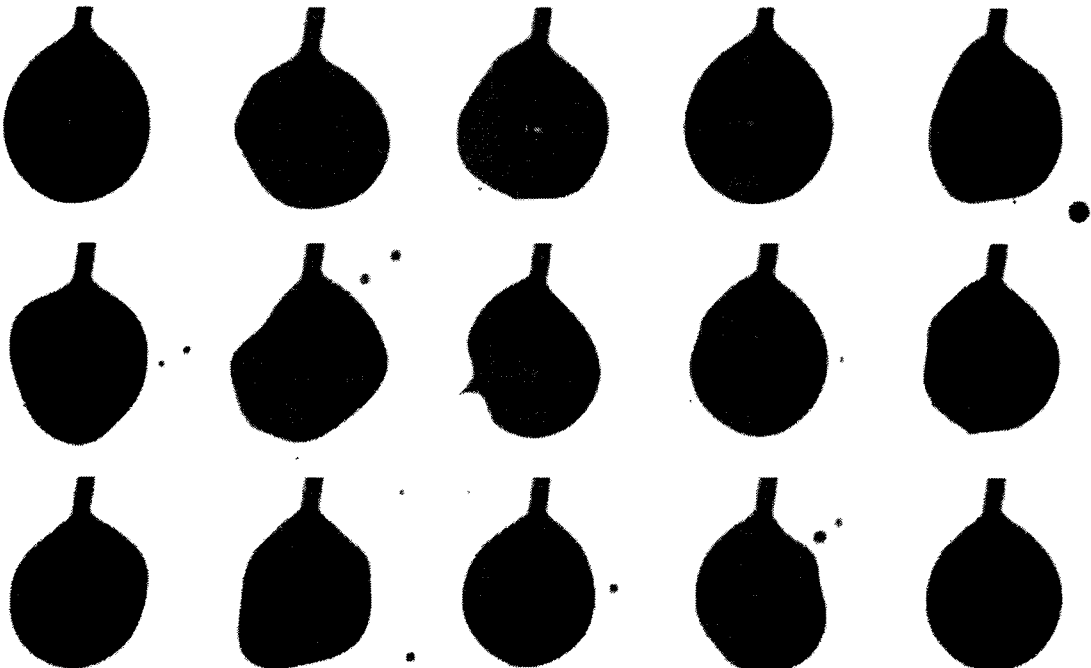


Fig. 8 Some sequential photographs of droplet vaporization under low ambient pressure.

droplet. These 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 been finished.

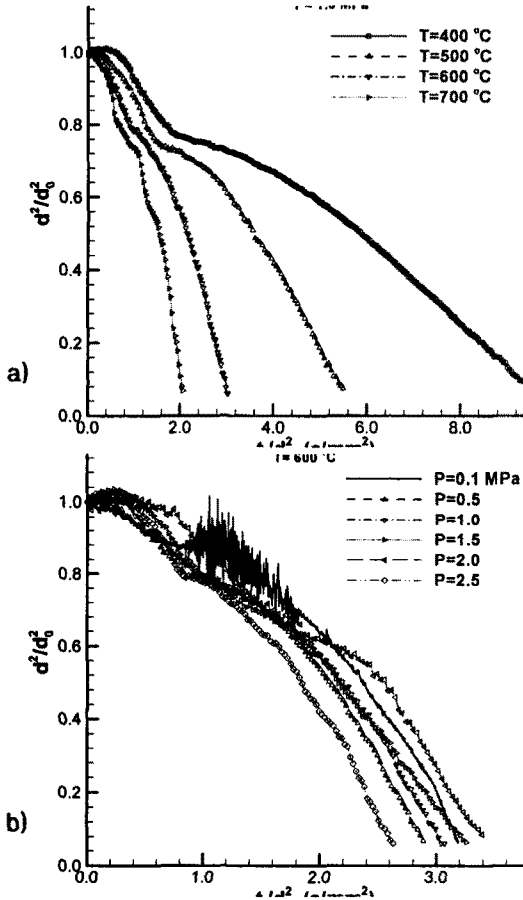


Fig. 9 Temporal variation of diameter squared of droplet for binary fuel at a) different temperatures and constant pressure, b) different pressures and constant temperatures.

In Fig. 9 the normalized time histories of squared diameter of droplet at different ambient conditions have been shown. Fig. 9 a presents evaporation history at ambient pressure 1.0 MPa and different temperatures. The lifetime and evaporation rate of droplet extremely vary at different temperature. In other hand, as shown in Fig. 9 b, the effect of pressure on evaporation process is not too strong. This figure emphasizes that the bubble formation and probably explosion of droplet is suppressed

when environment pressure increases. But previous experimental study of binary droplet explosions with different component confirms the enhancement of the occurrence of microexplosion with increasing environment pressure [12].

The evaporation history consists 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 sense the temperature rise and the temperature of high volatile component (Heptane) reaches to its boiling temperature earlier than low volatile component (Hexadecane). Heptane on and near droplet surface vaporizes, leaves the droplet and droplet shrinks.

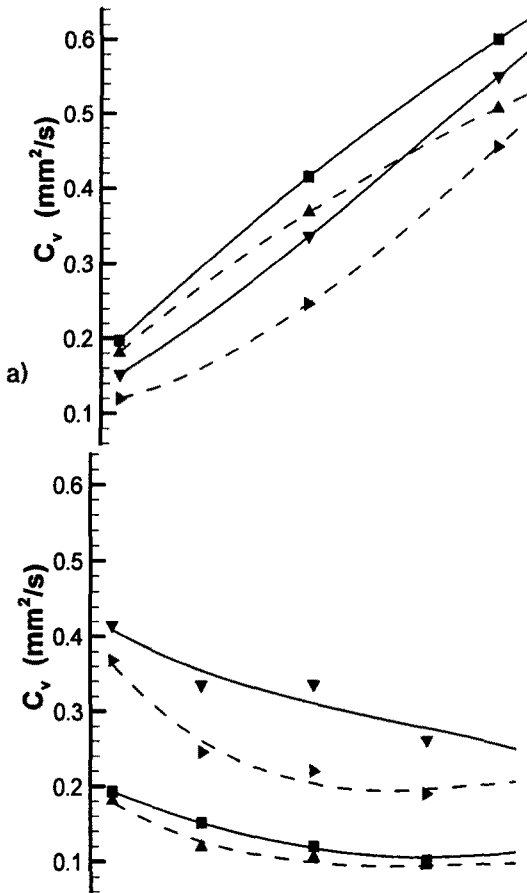
In the beginning of the second stage, the Heptane, which was near the droplet surface, has vaporized resulting in a strong concentration gradient with in the droplet. While, the Hexadecane is still in heating up period and does not start to evaporate. Therefore a mass diffusion mechanism handles Heptane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

At the third stage, remainder of 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 end of lifetime. Actually, when the evaporation rate is too slow, at the end period of the third stage, the droplet almost contains Hexadecane.

As shown in Fig. 9 a and b, when the evaporation rate is relatively high, like at high temperature, the difference between two stages is not too clear. Especially at 700 °C and above 1.0 MPa pressure, the first and third stages merge to each other and it is not possible to distinguish three staged evaporation. In other words, the duration of the second stage diminishes. The three staged



evaporation has been also addressed by other researcher (e.g. [7]). They have mentioned the relative durations of these three stages must depend on the concentrations of component. The effects of component concentration have been discussed in the following section.



b)  
Fig. 10 Comparison between the evaporation rate of Hexadecane and the binary fuel; a) Effect of temperature and b) Effect of pressure.

As mentioned above, the three staged evaporation of binary droplet at low environment pressure is accompanied with bubble formation and its consequent phenomena. Unlike of evaporation at low pressure, escape of vapor from droplet does not lead to bubble formation or droplet rupture. Because as pressure increases, surface tension of Hexadecane decreases and allows vapor to leave the droplet. The vaporization of lighter

component absorbs heat and increases the total heat transfer resistance within droplet. These lead a delay for rising of droplet temperature. Approximately two thirds of Heptane vaporizes and leaves the droplet in the first stage. This amount is calculated base on the diameter squared at the end of this stage.

Effects of Temperature and Pressure. The evaporation rates of binary droplet have been extracted from the linear part of the third stage evaporation history curves. Base on the above discussion, the evaporation rate of binary droplet should follow the Hexadecane. In Fig. 10, a comparison between evaporation rate of Hexadecane and binary fuel has been presented. Figure 10-a shows the effect of environment temperature on evaporation of Hexadecane and binary fuel at two low environment pressures. The evaporation trend of the binary fuel is same as Hexadecane but the lower rates. In Fig. 10-b the effect of environment pressure on evaporation rates of two fuels is compared. This figure also emphasizes that the effect of pressure on evaporation rates of two fuels, follows the same manner. The evaporation rate of binary fuel is almost lesser than Hexadecane evaporation rate. It is due to occupation of droplet atmosphere by vapors of more volatile fuel (Heptane). The temperature of Heptane vapors is lower than Hexadecane. This relatively cold gas decreases the total heat transfer from environment to the droplet. Consequently, evaporation of droplet takes place at slower rate than pure Hexadecane.

Effects of Component Concentration. In the previous sections, the evaporation of a 50% mixture of Heptane and Hexadecane as a binary component droplet is described. According to Table 1, three combinations of these fuels are selected to study the effects of component concentration on evaporation of binary droplets. To achieve a clear description, evaporation of single component droplet (pure Heptane and pure Hexadecane) as two extremes of binary component is taken into account. Since vaporization of the binary component droplets follows the three staged behavior, the component concentration affects the characteristics of the evaporation stages.

fig. 11 shows the normalized time histories of squared diameter of droplet at 600 °C for different component concentrations. Figure 11-a shows the evaporation histories under atmospheric pressure, which is accompanied with fragmentation of binary droplets. As it mentioned above, fragmentation of the binary droplet under high pressure does not appear. Figure 11-b shows the evaporation histories of binary droplets in high pressure ambient.

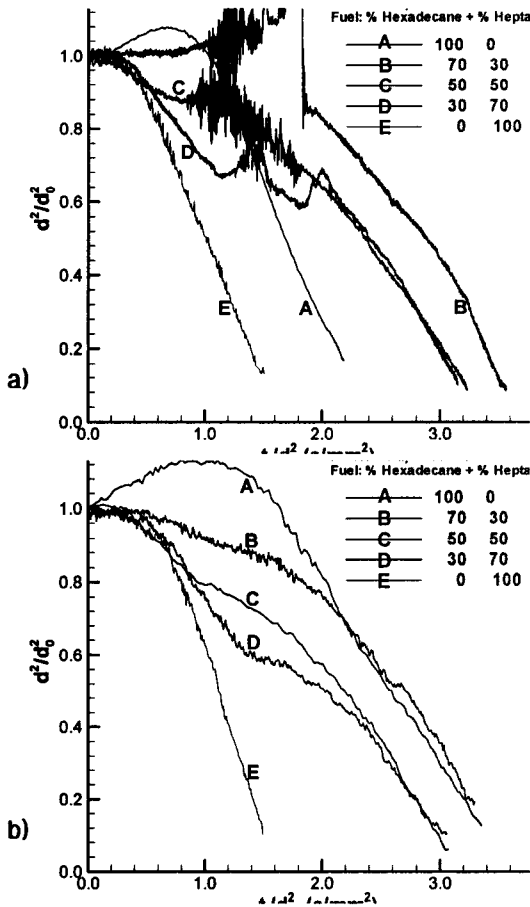


Fig. 11 Temporal variation of diameter squared of droplet for different binary fuels at a) low and b) high pressure temperatures.

In Fig. 11-a, curves A and E show the evaporation histories of pure Hexadecane and pure Heptane droplets, respectively. During the first stage of evaporation of binary droplet, two simultaneous events take place. The first one is the evaporation of more volatile

component (Heptane) causing reduction in droplet size and the other is heating of less volatile component (Hexadecane) resulting in thermal expansion of droplet. For the droplets containing more volatile component in minor proportion, like case B in Fig. 11-a, heating and evaporation of Heptane and heating of Hexadecane consume the incoming heat. In competition between droplet size reduction due to evaporation of Heptane and thermal expansion of Hexadecane, the droplet diameter does not change significantly. In the case of pure Hexadecane droplet, curve A, all incoming heat, just heats the droplet and expands its diameter. That is why in the case B, the droplet diameter remains nearly constant and droplet life time is longer than case A. As heat penetrates more into droplet, more Heptane evaporates and forms bubble inside the droplet. The bubble break open causes the droplet fragmentation, as shown in case B in Fig. 11-a. In high ambient pressure and in contrast with the atmospheric pressure, the droplet size reduction due to evaporation of Heptane overcomes to the thermal expansion of Hexadecane. As depicted in Fig. 11-b, curve B does not show a plateau in evaporation history. It is due to higher evaporation rate of Heptane under high pressure (See Fig. 4-a or Fig. 5-a). In the third stage, when almost of Heptane has vaporized and left the droplet, remainder histories show a linear behavior. The remainder fuel at this stage is almost less volatile component (Hexadecane). The rate of evaporation in this stage is lesser than the evaporation rate of pure Hexadecane droplet at the same ambient.

For the droplets containing more volatile component in major proportion, like case D in Fig. 11, the evaporation of Heptane is the dominant phenomenon at the first stage. The initial dilation of droplet due to thermal expansion does not appear and the first stage evaporation follows the linear behavior in atmospheric and higher ambient pressure. In case D, as shown in Fig. 11-a, the bubble formation and incomplete explosion exists with weak strength relative to cases B and C. After droplet fragmentation, the reminder of evaporation process goes linear. The evaporation rates in the first and third stages

are lesser than the evaporation rate of pure Heptane droplet (case E) and pure Hexadecane droplet (case A), respectively. This is true in both low and high pressure. In the first stage, the evaporation rate of binary droplet (cases C and D) is lesser than the evaporation rate of pure Heptane, because of heat absorption by Hexadecane within droplet. In the third stage it is due to lower heat transfer rate to droplet from ambient. In this case, the relatively cold vapor of Heptane, which surrounded the droplet, acts as an inhibitor.

A simple comparison between Figs. 11 a and 11 b shows that if the bubble formation does not occur, the lifetime of binary droplets, regardless to the composition, is shorter than the lifetime of less volatile component. It confirms the bubble formation increases the total heat resistance within droplet. It means, the incoming heat into the droplet from outside regardless to its initial composition, cannot penetrate into the inner part of droplet. The bubble not only increases heat transfer resistance due to its very low heat conductivity, but also absorbs heat. This heat absorption superheats vapor inside the bubble.

The general behavior of the evaporation of binary droplets with different initial compositions at different ambient temperatures and pressures are similar to that are discussed here. A detailed study on the effects of component concentration on evaporation of binary droplets can be found in [13]. A comparison between the evaporation histories of binary droplets under atmospheric pressure and different temperatures has been done. It is found that the bubble formation and droplet fragmentation occurs when the droplet reach to a new composition. As indicated in cases C and D in Fig. 11 a, the fragmentation happens when some part of more volatile component (Heptane) vaporizes and leaves the droplet. At this time, the droplet diameter is known and assuming no Hexadecane vaporization, it is not too difficult to find the new composition of each component in the droplet.

## 6. CONCLUSION

The focus of this work was on the study of evaporation of a binary component droplet. Normal Heptane and normal Hexadecane were selected as high and low volatile fuel, respectively. These fuels have very different boiling temperature. The evaporation rates of each component have been investigated under different environment pressures and temperatures, individually.

Three different blends of Heptane and Hexadecane were examined as binary fuels. This study has provided a useful insight to evaporation of binary droplets at different environmental conditions. The specific results are following.

The evaporation of the binary droplet at very low ambient pressure leads to extremely distortion and incomplete fragmentation of droplet. This phenomenon takes place due to vaporization of fuel with very less boiling temperature. Bubble formation within droplet and its blasting causes droplet fragmentation. At higher environment pressure, where it overcomes to bubble pressure and the surface tension of Hexadecane decreases, droplet explosion does not appear.

Regarding to high difference between the boiling temperatures of two components, there is a very strong internal motion inside of droplet. It emphasizes the droplet is encountered with a quick internal mixing.

The evaporation history of the binary droplet consists of two main stages with two nearly linear rates. These two stages are separated with an almost non evaporating period. An appreciable amount of component with lower boiling temperature evaporates quickly in the first stage. It means the gas liquid mass diffusion is the dominant mechanism in vaporization of the binary droplet at first the stage.

The evaporation rate of the binary droplet at the third stage is lesser than the evaporation rate of less volatile single component droplet.

The component concentration affects the characteristics of three staged evaporation. It also controls the lifetime of the droplets.

The bubble formation at atmospheric pressure increases the total heat transfer resistance within droplet and absorbs additional heat, which superheats the vapor inside.

Total binary droplet lifetime is longer than the lifetime of single component droplet at low pressure.

### Acknowledgment

The present work was supported by the Combustion Engineering Research Center at the Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, which is funded by the Korea Science and Engineering Foundation.

### References

- [1] Law, C.K. (1978) Internal Boiling and Superheating in Vaporizing Multicomponent Droplet. *AICHE Journal*, Vol. 24, No. 4, pp. 626 633.
- [2] Randolph, A.L., Makino, A., and Law, C.K. (1986) Liquid phase Diffusion Resistance in Multicomponent Droplet Gasification. *Proc. Combust. Instit.* 21, 601.
- [3] Arias Zugasti, M., and Rosner, D.E. (2003) Multicomponent Fuel Droplet Vaporization and Combustion Using Spectral Theory for a Continuous Mixture. *Combustion and Flame*, Vol. 135, pp. 271 284.
- [4] Morin, C., Chauveau, C., Dagat, P., Gokalp I., and Cathonnet, M. (2004) Vaporization and Oxidation of Liquid Fuel Droplets at High Temperature and Pressure: Application to n Alkanes and Vegetable Oil Methyl Esters. *Combustion Science and Technology*, Vol. 176, pp. 499 524.
- [5] Sirignano, W.A. (1999) *Fluid Dynamics and Transport of Droplets and Spray*. Cambridge University Press, UK, Chap. 3.
- [6] Lasheras, J.C., Fernandez Pello, A.C., and Dryer, F.L. (1980) Experimental Observations on the Disruptive Combustion of Free Droplets of Multicomponent Fuels. *Combustion Science and Technology*, Vol. 22, pp. 195 209.
- [7] Wang, C.H., Liu, X.Q., and Law, C.K. (1984) Combustion and Microexplosion of Freely Falling Multicomponent Droplets. *Combustion and Flame*, Vol. 56, pp. 175 197.
- [8] Law, C.K. (1982) Recent Advances in Droplet Vaporization and Combustion. *Progress in Energy and Combustion*, Vol. 8, pp. 171 201.
- [9] Ghassemi, H., Baek, S.W. and Khan, Q.S. (2005) Evaporation of Binary Droplets at Elevated Pressure and Temperature. *AIAA Paper 2005 353*, 43rd Aerospace Sciences Meeting and Exhibit, Reno, Nevada.
- [10] Forhan, A. and Roth, N. (2000) Dynamics of droplets. *Springer*, Chaps. 3, 6.
- [11] Sato, J. (1993) Studies on Droplet Evaporation and Combustion in High Pressures. *AIAA Paper 93 0813*, 31st Aerospace Sciences Meeting & Exhibit, Reno, Nevada.
- [12] Wang, C.H., and Law, C.K. (1985) Microexplosion of Fuel Droplets under High Pressure. *Combustion and Flame*, Vol. 59, pp. 53 62.
- [13] Khan, Q.S., Baek, S.W., and Ghassemi, H. (2005) Effect of Component Concentration on the Evaporation and Microexplosive Behavior of Multicomponent Fuel Droplets. 6th world conference on experimental heat transfer, fluid mechanics, and thermodynamics, April 17 21, 2005, Matsushima, Miyagi, Japan.