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EFFECTS OF WATERY VAPOR CONCENTRATION ON DROPLET EVAPORATION IN HOT ENVIRONMENT

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ABSTRACT–A study has been conducted to clarify the effect of watery vapor concentration in hot ambient on droplet evaporation. Droplets of water, ethanol, n-hexadecane and n-heptane were used in this experimental study. Ambient conditions are fixed at 470 K in temperature, 0.1 MPa in pressure and 2 m/s in velocity of ambient air. Watery vapor concentration was changed 0%~40% by 10% by add water to air. To obtain the time histories of droplet diameter after exposed in ambient, a suspended droplet in hot and humid ambient stream was synchronized with a back flash light, and enlarged droplet images were taken by a CCD camera. The evaporation rate constant of water droplet decreases slightly with the vapor concentration because diffusion velocity reduction of droplet vapor occurs on the surface. The values of ethanol and n-heptane droplet actively increase by effect that water from condensation of vapor flows into the droplet. The evaporation rate constant of n-hexadecane which has higher boiling point than water increases within around 30% of the concentration.

KEY WORDS : Droplet, Evaporation, Micro-explosion, Evaporation rate constant, Watery vapor, Condensation

1. INTRODUCTION

Many analytical and theoretical studies on evaporation of a liquid fuel droplet have been conducted over a long period of time to elucidate the mechanism of spray combustion (Kiyoshi, 1954; Agoston *et al.*, 1956; Seiichiro, 1952). As results of these studies, the effects of ambient temperature, pressure, and velocity on droplet evaporation have been reported in detail (Chung *et al.*, 1996; Chung *et al.*, 1995; Hiromitsu, 1997). On the other hand, since water or vapor is injected with liquid fuel into the combustion chamber of a diesel engine and a gas turbine to decrease NOx, not a little concentration of vapor is existed in combustion field of fuel spray. Generally, in a case of existence the vapor of same kind of evaporating fuel in combustion field, evaporation rate constant of droplet is regarded to decrease. But, when the watery vapor exists with practical fuel in combustion field, the watery vapor effecting evaporation is not clarified yet sufficiently, and it is important phenomena to analyze the mechanism of spray combustion. By an experimental result about diesel engine efficiency, there was a report that engine efficiency is elevated by the suction of watery vapor with air so as to burn the injected fuel. From the result, watery vapor could be considered as a factor influencing the evaporation of droplet.

In this study, the evaporation rate constant of single suspended droplet by quartz glass fiber in hot and humid environment are reported, aiming at showing the effect of vapor concentration. The CCD camera was provided so as to measure the droplet diameter variation concerned with elapsed time. Water and other liquid samples, i.e., ethanol, n-hexadecane, and n-heptane were selected for the test fuels. With the result obtained, the influence of watery vapor on evaporation rate constant was investigated regarding its relations to hydrophile and dehydrophile property and boiling point of each droplets. The boiling point of ethanol and n-heptane is lower than that of water, and that of n-hexadecane is 560 K.

2. EVAPORATION RATE CONSTANT

When a droplet is exposed to high temperature environment, it is heated and evaporation phenomenon is generated along on its surface. And then, if volume increase rate by heating is higher than volume decrease rate by evaporation, droplet diameter increases. As droplet temperature increases with time elapse, droplet diameter decreases since partial pressure of droplet vapor on its

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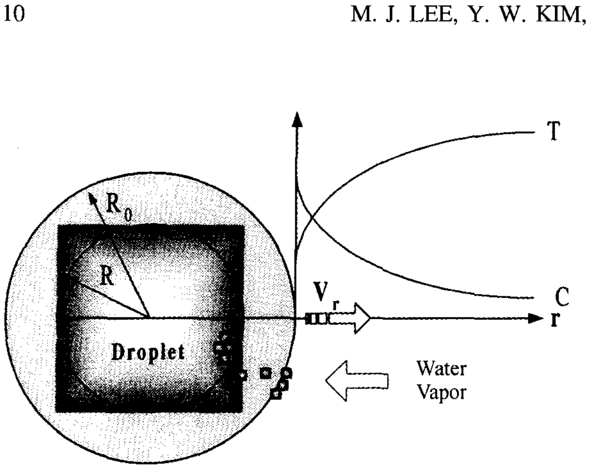

Figure 1. Modeling of evaporation of droplet in high temperature included water vapor.

surface increase and evaporation is in its act. During this evaporation, D^2 variation of pure fuel droplet is plotted linearly and evaporation rate constant of droplet is defined as following.

$$dD^2/dt = -\mathrm{Ke} \quad (1)$$
$$D_0^2 - D_1^2 = \mathrm{Ke}\ (t_1 - t_0) \quad (2)$$

where, D: droplet diameter (mm), t: time (s), Ke: evaporation rate constant (mm^2/s), D_0: droplet diameter at t_0 (mm), D_1: droplet diameter at t_1 (mm)

3. EXPERIMENTAL APPARATUS

The main experimental apparatuses are shown in Figure 2. They consisted of air compressor, air and water flow meter, electric heater, light source, CCD camera and computer for image capture and analysis. In order to make the droplet environment having hot and humid air stream, air and water preheated and fixed of mass flow rate were mixed in supply pipe and reheated to be desired temperature by electric heater before being sent to the droplet position. Ambient temperature around a suspended droplet was controlled by temperature controller operated by signal from thermo-couple settled around droplet. So as to expose the droplet in experimental ambient instantaneously, the enveloped droplet by steel tube operated by air cylinder was located in environment. The air cylinder was moved by a signal from a specially devised electronic controller, and then the exposed droplet images were taken by a CCD camera synchronized with air cylinder and light source.

In order to judge for entrainment of watery vapor into droplet, temperature variation of droplet center was measured by K-type thermo-couple of 50 μm in diameter. Tested liquids used in this study were water, ethanol of which boiling point is lower than that of water and hydrophile property, and n-hexadecane of which boiling point is higher than that of water and dehydrophile property. The kinds and properties of test liquids are shown in Table 1. The ambient temperature around droplet was constant as 473 K. The voluminal concentration of watery vapor in air was varied from 0% to 40% by 10%. Velocity of ambient flow of air and vapor was constant as 2 m/s.

Table 1. Kinds of tested liquids and the main properties.

Test liquids	Boiling point (K)	Latent heat (kJ/kg)
Distilled water	373.15	2676.0
Ethanol	351.7	854.8
n-heptane	371.6	320.1
n-hexadecane	560.0	284.6
n-heptane + n-hexadecane	371.6-560.0	undefind

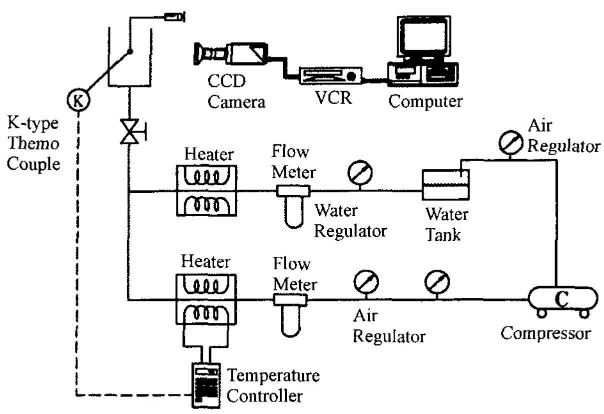

Figure 2. Schematic diagram of the experimental apparatus.

4. RESULTS AND DISCUSSION

4.1. Influence on Evaporation of Water Droplet by Watery Vapor

Figure 3 shows the evaporation histories of the squared diameter of water droplet in ambient temperature 473 K, voluminal concentration of watery vapor 0%~40%. Vertical axis shows squared droplet diameter, horizontal axis shows time taken from exposure of droplet in hot ambient flow. The squared droplet diameter decreases almost linearly as the time lapse. It is considered that watery vapor concentration has not effected significantly on evaporation of water droplet.

Figure 4 shows the variation of evaporation rate constant of water droplet from the results of Figure 3. In Figure 4, the evaporation rate constant of water droplet is decreased a little as the ambient concentration of watery vapor increases, and the tendency agrees with the results

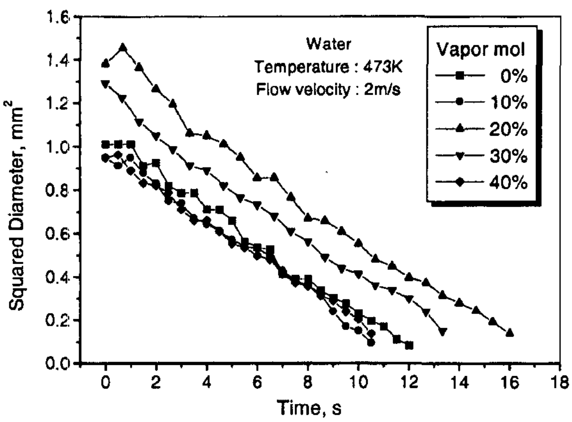

Figure 3. D^2 variation of water droplets.

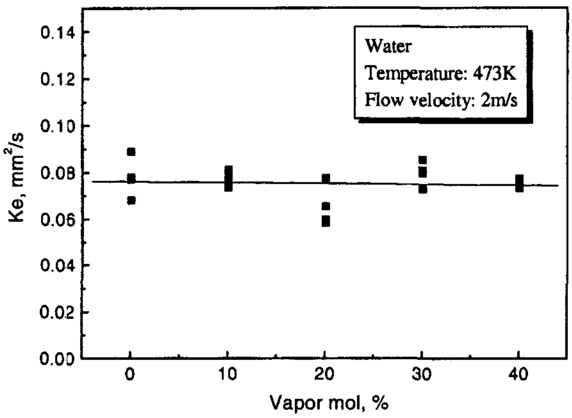

Figure 4. Evaporation rate constant of water droplet in each vapor mole.

by Hiromitsu (1997). It is considered that evaporation rate constant of water droplet decreases with watery vapor because the diffusion velocity of the vapor from droplet decreases if concentration of watery vapor is the same in environment as droplet evaporates. In addition to these, because the heat-transfer coefficient estimated by the thermal properties calculation method, in case of 2 m/s in ambient velocity and 2 mm in droplet diameter, is decreased a little at 40% in vapor concentration than at 0% in it, it affects on evaporation decrease.

When watery vapor concentration of ambient is increased, diffusion velocity of watery vapor from surface of water droplet decreases. In that case, the droplet surface temperature rises up to the point, at which the vapor concentration necessary for the diffusion of the vapor equivalent to the heat received from the ambient becomes a saturated one. Therefore, evaporation of droplet slows down when watery vapor concentration increases, because temperature gradient between ambient and droplet surface decreases. On the other hand, when

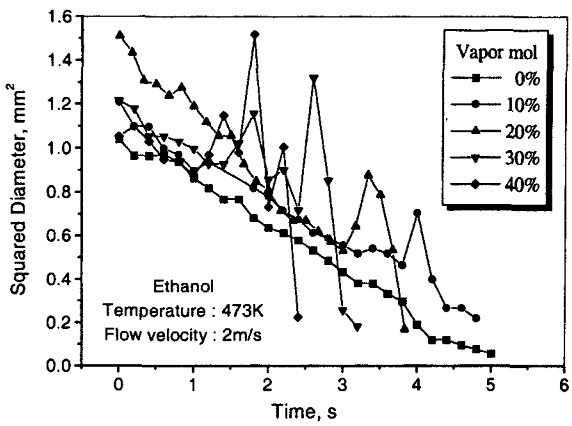

Figure 5. D^2 variation of ethanol droplets.

surface temperature of droplet is lower than saturation temperature of watery vapor concentration in the environment, vapor condenses on surface of droplet. The condensed water is mixed with droplet and the condensation heat is used for evaporation of droplet. Because water entered into droplet obtains heat again from environment and evaporates, it is not considered that the condensation of the vapor has influenced on total evaporation.

4.2. Influence on Evaporation of Ethanol Droplet by Watery Vapor

Figure 5 shows D^2 variation of ethanol droplet that has hydrophile property with time in high temperature and humid flow. In this figure, the evaporation tendency of ethanol droplet is different from that of water droplet significantly. That is, watery vapor has not effected on evaporation of droplet significantly in early evaporation process. In watery vapor 0%, the gradient of D^2-t decreases constantly. In case of vapor addition, however, rapid expansion and reduction of droplet are shown partially.

Figure 6, in watery vapor concentration 40%, shows images that droplet has rapid expansion and reduction of droplet on a time. After occurring micro-explosion phenomenon, diameter of droplet decreased rapidly. The reason for the phenomenon is that watery vapor in

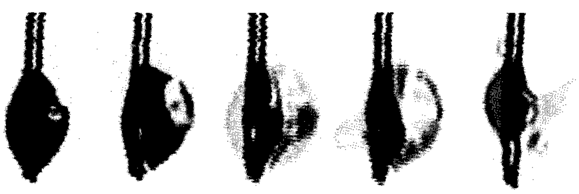

Figure 6. Explosion of Ethanol (Vapor mole 40%).

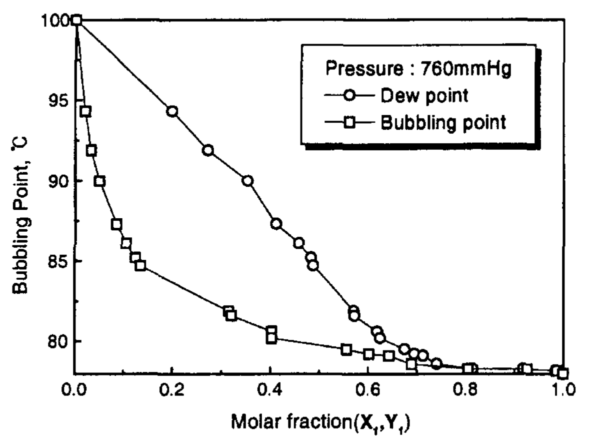

Figure 7. Vapour-liquid equilibrium diagram of water-ethanol fuel.

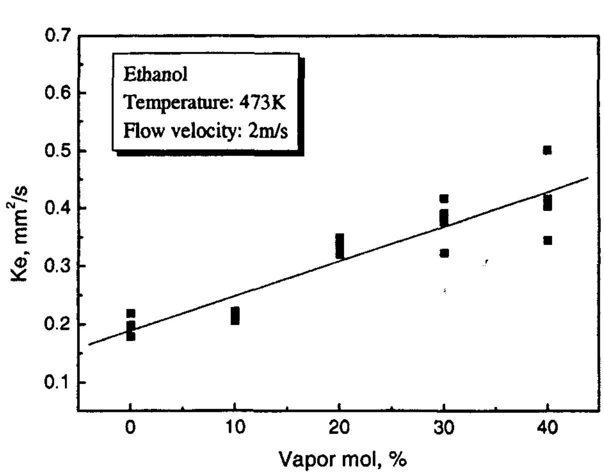

Figure 9. Evaporation rate of ethanol droplet in each vapor mole.

environment condenses on droplet surface and enters into the droplet. These can be described by gas-liquid equilibrium diagram of mixed fuel with ethanol and water and inner temperature of droplet.

Figure 7 shows, in the case of mixing ethanol with water, bubbling point and ingredient of ethanol (Y1) in gas phase for mole fraction of ethanol (X1) (Boom *et al.*, 1961). In the figure, lower curve is bubbling point and upper curve is dew point. As mixing fraction of water with pure ethanol increases, it shows that bubbling point becomes close to boiling point of water gradually. Therefore, Figure 7 shows that temperature of ethanol droplet becomes close to boiling point of water gradually as ethanol droplet with water evaporates, and evaporated quantity of ethanol is larger than that of water relatively.

Figure 8 shows inner temperature of ethanol droplet in watery vapor concentration 0%, 20%, and 40%. The figure indicates that droplet temperature is higher at the

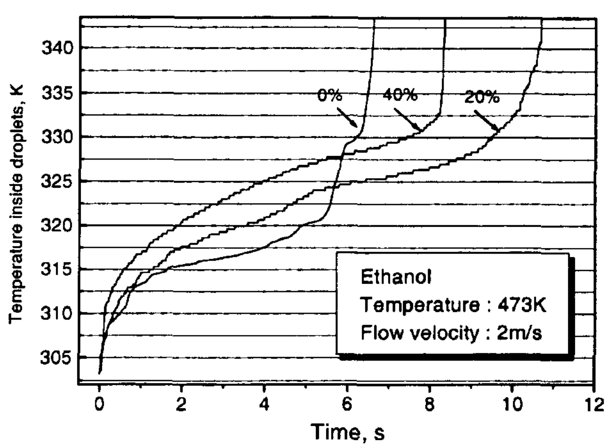

Figure 8. Central temperature of ethanol droplet.

evaporation of 20% and 40% than that of 0%. Because watery vapor condenses on surface of ethanol droplet and enters into it, a pure ethanol droplet has characteristics of mixture gradually. As watery vapor concentration of droplet surroundings increases, mole fraction of ethanol decreases relatively. As shown in gas-liquid equilibrium of Figure 7, therefore, it is considered that the final temperature of droplet increases. It can be explained by Figure 8 obtained through the experiment.

Figure 9 shows mean value of results of Figure 4 obtained through many experiments. In evaporation rate constant, the diameter of excessively expanded droplet was excluded from calculation. Hiromitsu (1997) reported that the quantity of watery vapor entering into ethanol droplet is no more than about 0.1 mm^2 in D^2 although a case of vapor concentration 40%. Therefore, it is possible that the result of Figure 9 shows evaporation rate constant of only ethanol. Figure 9 shows that evaporation rate constant almost increases linearly with increasing of watery vapor in environment. it is almost twice higher at 40% than at 0%. It is considered that ethanol droplet in a state of saturation at high temperature vaporized rapidly by condensation heat of watery vapor and micro-explosion, so that evaporation rate constant increases. Figure 5 shows tendency that rapid expansion time of droplet was advanced with watery vapor concentration. It is considered as a factor that is promoting evaporation of ethanol droplet.

4.3. Influence on Evaporation of *n*-hexadecane Droplet by Watery Vapor

In case of evaporation of n-hexadecane droplet, it is considered that watery vapor is condensed and entered into droplet like the evaporation of ethanol droplet. Standard boiling point of *n*-hexadecane, however, is 560 K

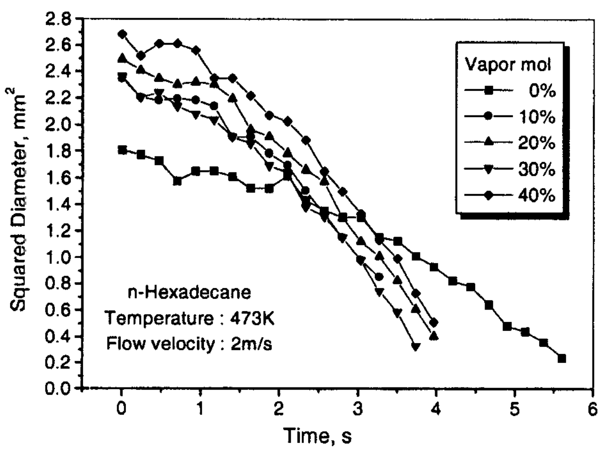

Figure 10. D^2 variation of *n*-hexadecane.

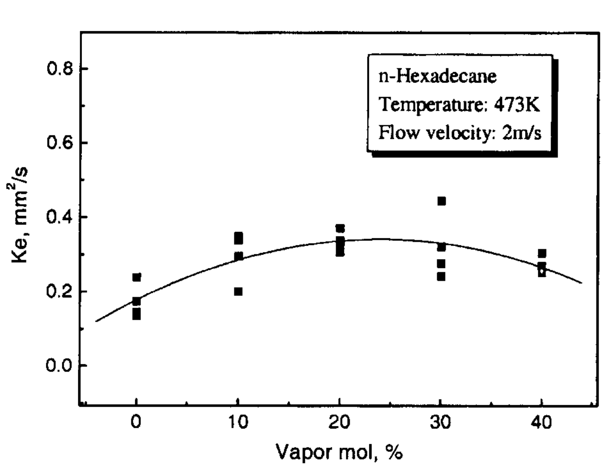

Figure 12. Evaporation rate constant of *n*-hexadecane droplet.

and higher than that of water. So, it is expected that evaporation tendency is different from that of ethanol droplet.

Figure 10 shows the result of evaporation of *n*-hexadecane droplet measured. D^2-t curve has corn shape in 0%, however, considering experimental error, it can be thought evaporating of a fuel droplet. In case of more than 20%, the corn is higher, especially, because its tendency is different before and after one second after exposure, it is considered that watery vapor has an effect on evaporation of *n*-hexadecane droplet. Until one second after exposure of droplet, although entrainment of watery vapor, since the condensation watery vapor on droplet surface increases temperature of droplet rapidly, droplet diameter is reduced. The pure *n*-hexadecane droplet is changed to mixture of water and *n*-hexadecane in this period. Watery vapor is condensed until temperature of droplet surface reaches to dew point of watery vapor, and the dew point will be 60, 70, and 75 each at vapor concentration of 20%, 30%, and 40% respectively. Considering difference of boiling points between water and *n*-hexadecane, it is considered that the last evaporating ingredient would be *n*-hexadecane.

The entrainment of watery vapor is shown by Figure 11. In this figure, it is observed generating of bubbles from droplet for 13 seconds, and weaker than that of ethanol droplet. These phenomenon is not shown in the case of pure fuel droplet, and generated by evaporating of the condensation water entered into droplet in early period when temperature of droplet is low. It is considered that bubbles exist as an excessively small particle in inner droplet each.

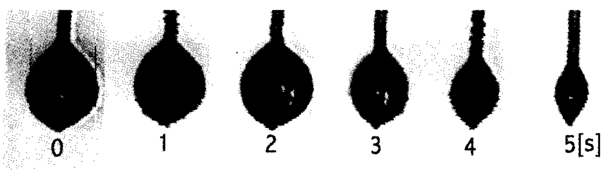

Figure 11. Progress of evaporation of *n*-hexadecane (Vapor mole 40%).

Figure 12 shows evaporation rate constant of *n*-hexadecane for watery vapor such as experiment of Figure 10. Although Evaporation rate constant of *n*-hexadecane increases with watery vapor, it decreases after concentration of 30%. In this study, assuming that the heat value for inflow of the vapor is equal to that of vapor outflow, the watery vapor of ambient flow reduces convection heat transfer coefficient and evaporation velocity of droplet. Factors increasing evaporation velocity are enlargement of receiving heat area due to expasion of droplet surface by condensation and inflow of watery vapor, and outflow of n-hexadecane with water. It is considered that decreasing of evaporation rate constant after 30% is caused by diffusion velocity of water with watery vapor concentration.

4.4. Influence on Evaporation of n-heptane Droplet by Watery Vapor

Figure 13 shows the evaporation rate constant of *n*-heptane as dehydrophile fuel with vapor concentration. In this figure, in case of vapor concentration is 10%, absolute value of initial D^2-t gradient of droplet is larger than that of 0% vapor concentration, and the gradient is gentle at the final stage of evaporation. It is considered that the inflow of condensed vapor onto droplet surface of low temperature promotes increasing of droplet temperature and evaporation because latent heat of water is higher than that of *n*-heptane and water evaporates with time partially. Although the end point of *n*-heptane

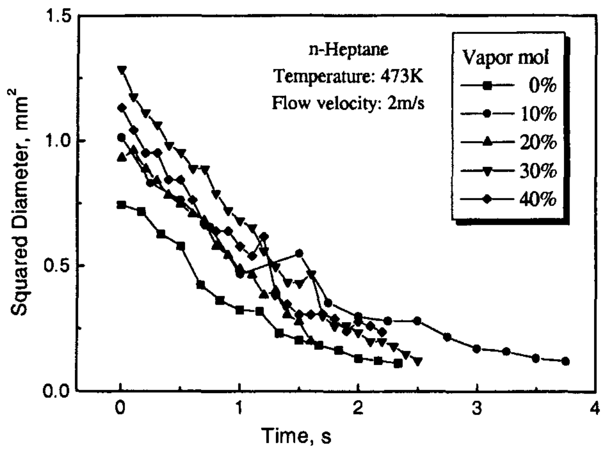

Figure 13. D^2 variation of *n*-heptane.

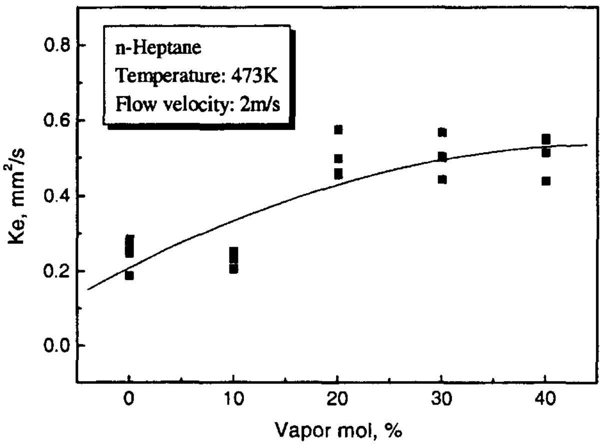

Figure 14. Evaporation rate constant of *n*-heptane droplet.

evaporation is not able to discriminate between standard boiling points of both ingredient, it is considered that most n-heptane evaporates in less than 1.5 seconds and the D^2-t gradient begins showing its gentle shape and water almost evaporates after then.

Figure 14 shows evaporation rate constant of *n*-heptane for watery vapor using results of Figure 13 experiment. In this figure, the evaporation rate constant increases along with watery vapor. It is considered that condensation heat of watery vapor promotes heat transfer, due to the increase of concentration of watery vapor in the environment.

4.5. Critical Evaporation Rate

When ambient air of droplet flows, the evaporation rate constant of droplet is influenced by the air velocity. The influence of the velocity for the evaporation rate of droplet is expressed in function with the diameter of

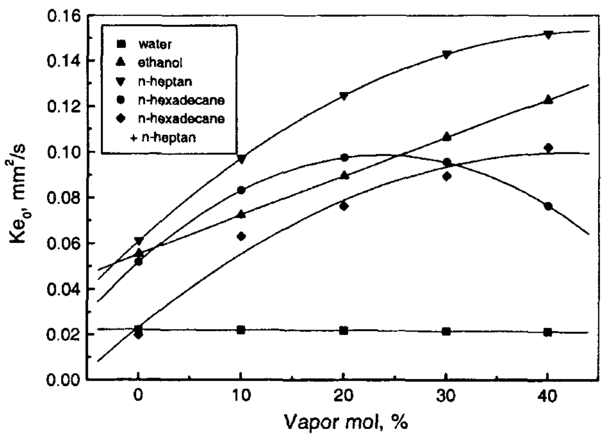

Figure 15. Critical evaporation rate of each fuels for vapor concentration.

droplet and physical amount of the air. Figure 15 shows critical evaporation rate of water, ethanol, *n*-hexadecane, and *n*-heptane using Ranz-Marshall's equation (Ranz *et al.*, 1952).

$$Ke = Ke_0\ (1+0.3Re^{1/2}\ Pr^{1/3}) \tag{3}$$

Ke_0: Critical evaporation rate [mm^2/s]
Re : Reynolds number [–]
Pr : Prandtl number [–]

5. CONCLUSIONS

(1) The evaporation rate constant of water droplet decreases with increasing of watery vapor in environment.
(2) In ethanol droplet which has hydrophile property, the watery vapor increases the evaporation of the droplet after entering into the droplet, and promotes evaporation velocity with occasional micro-explosion. As the standard boiling point of droplet is lower than that of water, the phenomenon of micro-explosion is intense.
(3) In case of *n*-hexadecane droplet with dehydrophile property and boiling point higher than that of water, evaporation is promoted gradually in low concentration of watery vapor, but decreased in high concentration of watery vapor.
(4) The evaporation rate constant of *n*-heptane droplet with dehydrophile property tends to be promoted by increasing of condensation heat as increasing of watery vapor concentration.

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