# Effects of Suspender Diameter and Natural Convection on Measured Evaporation Constant of a Fuel Droplet

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Thermal effect of a suspender and effect of natural convection on fuel droplet evaporation were estimated experimentally with varying suspender diameter and initial droplet diameter widely. An individual suspended droplet of n-heptane was employed for experiments. It was found that the relationship between evaporation constant $k$ and suspender diameter $d_S$ for a fixed value of initial droplet diameter was expressed as $k = c_1 + c_2 d_S^2$, where $c_1$ and $c_2$ are constants dependent on ambient temperature and initial droplet diameter. The evaporation constant was corrected by this function to eliminate thermal effect of a suspender. The elimination of the thermal effect of a suspender from the evaporation constant made the effect of natural convection on droplet evaporation clear. The natural convection effect on droplet evaporation was expressed as $k_0 \propto 1+0.36\mathrm{Ra}^{0.26}$, where $k_0$ is the evaporation constant free from heat transfer though a suspender and Ra is the Rayleigh number.

## 1. Introduction

Spray combustion is widely applied to combustors such as diesel engines, jet engines and industrial furnaces. Droplet evaporation lifetime is one of the important parameters to design spray combustors, because the evaporation lifetime of the largest droplet in a spray determines the residence time required for the complete droplet evaporation in the combustion chamber. Many experimental studies have been carried out to examine droplet evaporation [1-13]. Most of them used a suspended droplet or a porous sphere around or more than 1 mm in diameter as an object of experiment. On the other hand, fuel droplets in spray combustors are free droplets and, since they are so fine, the influences of both natural and forced convections on droplet evaporation are negligible. Evaporation experiments of a free droplet in a non-convective field are proper to obtain useful data for estimation of droplet lifetime in spray combustion and for verification of theoretical and numerical models. However, there is no such report on free droplet evaporation because of the difficulty of experiment. Some researchers included the effect of a suspender into their numerical simulation models of droplet evaporation and compared the calculated results with the experimental data of suspended-droplet evaporation to verify the numerical model [14-17].

The purpose of this work is to evaluate the influences of a suspender and natural convection on droplet evaporation experimentally and to estimate the true evaporation rate from the results of evaporation experiments with a suspended droplet in a natural convection field. Kumagai and Isoda [18] tried to estimate the influence of suspender on droplet combustion. They found that suspender diameter and heat conductivity of the suspender material strongly affect burning rate constant but initial droplet diameter has little effect on the burning rate constant. In the case of droplet evaporation, dependence of evaporation constant on initial droplet diameter changes drastically when suspender diameter is varied. It can be explained by two contrary effects. One is the effect of natural convection which increases evaporation constant with the increase of initial droplet diameter. The other is the effect of heat transfer though a suspender which increases evaporation constant with the decrease of the ratio of initial droplet diameter to suspender diameter. To evaluate these two effects separately, evaporation experiments of a suspended droplet were carried out with varying suspender diameter and initial droplet diameter widely.

## 2. Experimental apparatus and procedure

Evaporation experiments were performed within a chamber (inner diameter: 100 mm; inner height: 318 mm). Figure 1 shows the suspended-droplet experiment module, which was installed into the chamber. This module consists of an electric furnace, a droplet generator and a droplet elevator. A droplet was generated at the tip of a glass fiber and inserted into the electric furnace just before observation. The fiber was horizontally fixed to a movable arm of the droplet elevator and the tip of the fiber was shaped like a ball to prevent a droplet from falling down during the insertion. Suspender diameter $d_S$ and initial droplet diameter $d_0$ were varied from 25 to 125 μm and from 0.15 to 1.2 mm, respectively. Initial droplet temperature was room temperature. A linear slider crank mechanism was applied to the droplet elevator to reduce the impact on the suspended droplet during droplet insert process. The time required to the droplet insert process was 0.16 seconds. Ambient temperature $T_a$ was measured at the distance of 4 mm horizontally from the test position with a chromel-alumel thermocouple. Nitrogen gas was used as an ambient gas and n-heptane was used as a fuel. The ambient temperature was varied from 400 to 800 K.
Backlit photography was employed to observe a droplet. Evaporation process of a droplet was recorded with a CCD camera and a digital video recorder. Droplet diameter, which was defined as the diameter of the equivalent volume sphere, was measured with a computer-aided image analyzer. The detail of the droplet diameter measurement was described in Ref. 13.

## 3. Results and discussion

Evaporation constant is a measure of evaporation rate. For all cases in this work, the latter half of $d^2$-$t$ curve can be regarded as a straight line. Based on this fact, evaporation constant $k$ was defined as the absolute value of slop of the $d^2$-$t$ curve in the range of $d^2 < d_0^2/2$. Linear approximation by the least squares method was applied to calculate the slope of the $d^2$-$t$ curve. Figure

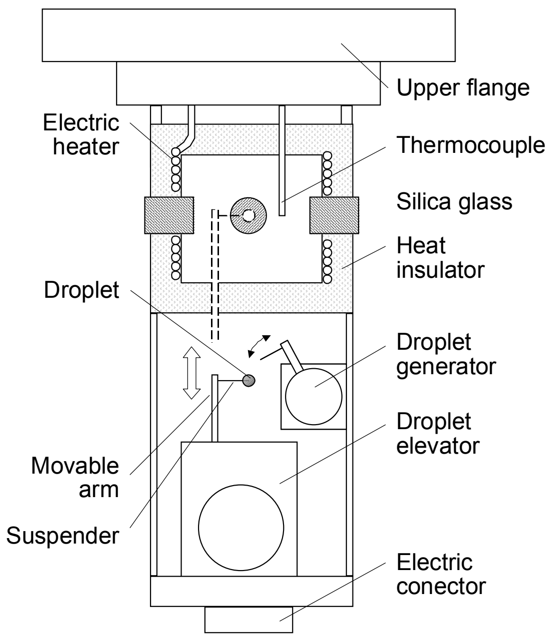


**Fig.1** Suspended-droplet experiment module.

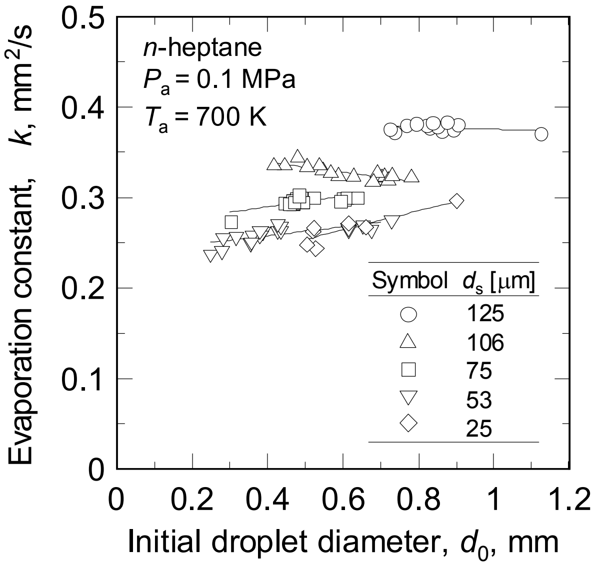


**Fig. 2** Effect of initial droplet diameter and suspender diameter on evaporation constant.

2 shows the evaporation constants at 700 K obtained for various initial droplet diameters and suspender diameters. The dependence of evaporation constant on the initial droplet diameter changes when the suspender diameter is varied. When the suspender diameter is large as compared with the initial droplet diameter, the evaporation constant decreases as the increase of initial droplet diameter. On the other hand, when the suspender diameter is small as compared with the initial droplet diameter, the evaporation constant increases as the increase of initial droplet diameter. This behavior of evaporation constant can be explained by two factors: heat transfer through a suspender and natural convection. The results of the previous work [19] showed that the rate of heat transfer through a suspender exceeds 40% of the total rate of heat transfer when the suspender diameter is 40% of the droplet diameter. Therefore, it is supposed that the evaporation constant decreases as the decrease of the ratio of suspender cross-sectional area to droplet surface area. Natural convection increases evaporation rate of a droplet and its effect on droplet evaporation increases as the increase of droplet diameter. Therefore, the increase of the evaporation constant in the region of large initial droplet diameter is supposed to be caused by the natural convection. Based on these considerations, the evaporation constant was replotted as a function of the suspender diameter in Fig. 3. It is clearly understood that, for a fixed value of initial droplet diameter, the evaporation constant increases as the increase of suspender diameter.

The evaporation constant free from heat transfer though a suspender was estimated by means of extrapolation of the curves in Fig. 3 to zero suspender diameter. The following simple model was employed to determine a function proper for the extrapolation.

On the assumption that a droplet is spherical, simple expression of the evaporation constant is

$$k = \frac{4hd}{\rho_l L}(T_\mathrm{a} - T_\mathrm{D}) \qquad (1)$$

where $h$ = heat transfer coefficient
$d$ = droplet diameter
$r_l$ = density of the fuel
$L$ = latent heat of the fuel
$T_\mathrm{D}$ = droplet temperature

Assuming that the droplet temperature is independent of the suspender diameter, this equation can be rewritten as

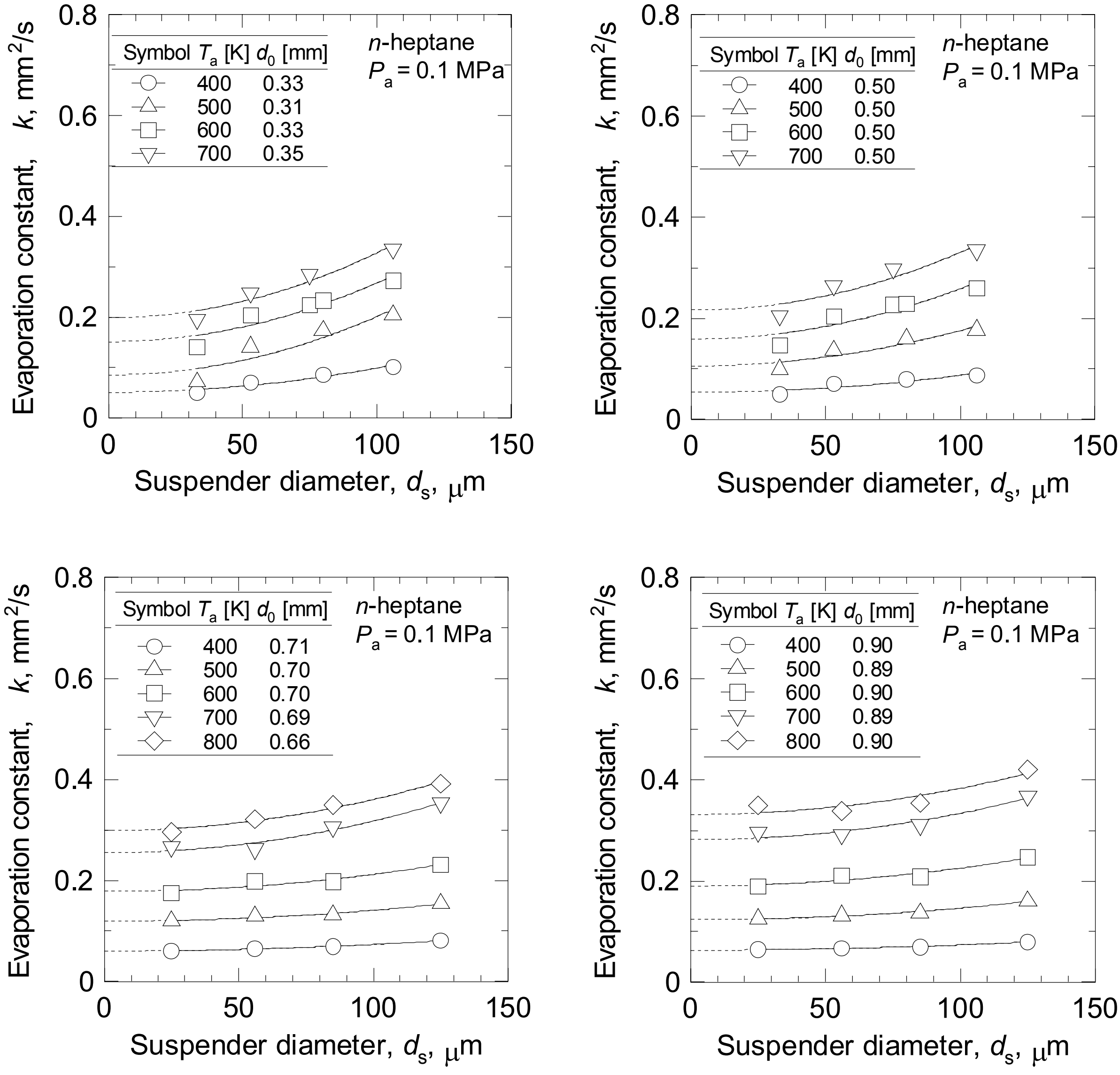


**Fig. 3** Effect of the suspender diameter on evaporation constant.

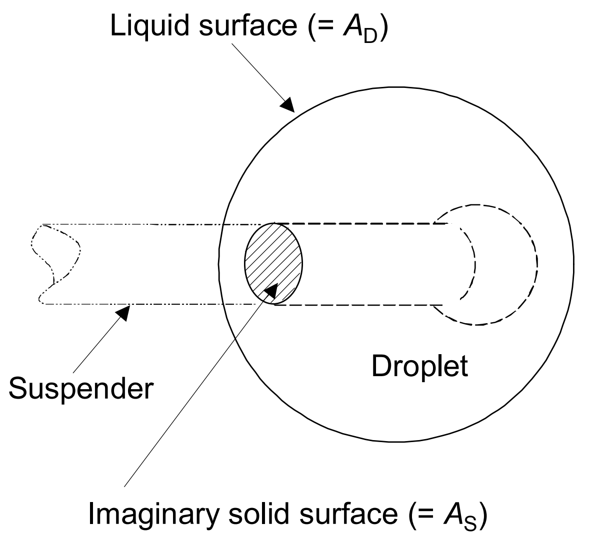


**Fig. 4** Schematic diagram of a fuel droplet suspended at the tip of a grass fiber.

$$k = a_1 h \quad \text{where} \quad a_1 = \frac{4d}{\rho_l L}(T_a - T_D) \tag{2}$$

The variable $a_1$ is independent of the suspender diameter.

Figure 4 shows the schematic diagram of a suspended droplet. The suspender tip included in the droplet was regarded as a part of the droplet and its temperature was assumed to be equal to the droplet temperature. Heat transfers into the droplet from a liquid surface and an imaginary solid surface (see Fig. 4). Therefore total heat interface area of the droplet can be expressed as

$$A = A_D + A_S \tag{3}$$

where $A$ is total surface area, and $A_D$ and $A_S$ are liquid surface area and suspender cross-sectional area (= p$d_S^2$/4) respectively. Using $A$, $A_D$ and $A_S$, $h$ can be expressed as

$$h = (A_D h_D + A_S h_S) / A \tag{4}$$

where $h_D$ and $h_S$ are the heat transfer coefficients on the liquid surface and the imaginary solid surface respectively. Heat transfers from the imaginary solid surface to the droplet by conduction. It can be assumed that $h_S$ is equal to l/d, where l is the thermal conductivity of the suspender material and d is the thickness of thermal boundary layer of a droplet. Therefore $h_S$ is dependent on $d$ but independent of $d_S$. From the Eqs. 3 and 4, one can have

$$h = \{(A - A_S)\, h_D + A_S h_S\} / A$$
$$= h_D + A_S(h_S - h_D) / A$$
$$= a_2 + a_3 d_S^2 \tag{5}$$

where

$$a_2 = h_D, \quad a_3 = \frac{\pi(h_S - h_D)}{4A} \tag{6}$$

The variables $a_2$ and $a_3$ are dependent on $d$ but constant with $d_S$. Thus, Eq. 2 can be expressed as

$$k = a_4 + a_5 d_S^2 \tag{7}$$

where $a_4 = a_1 a_2$ and $a_5 = a_1 a_3$. These valuables $a_4$ and $a_5$ are dependent on $d$ but constant with $d_S$. The evaporation constant obtained in this work was determined from the $d^2$-$t$ curves in the fixed range of $d^2 < d_0^2/2$. Therefore, Eq. 7 suggests that, when the evaporation constant is plotted as a

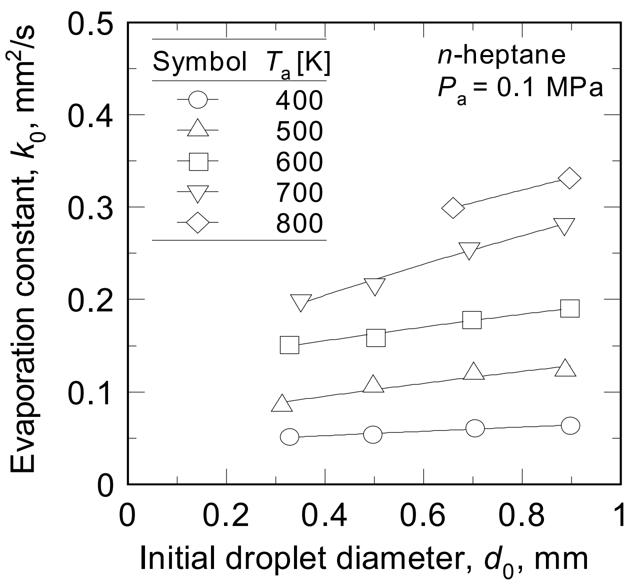


**Fig. 5** Effect of initial droplet diameter on evaporation constant free from heat transfer though a suspender.

function of the suspender diameter for a fixed value of initial droplet diameter, plots lie on the curve of parabola which opens upwards and whose apex exists on the vertical axis. The dashed lines in Fig. 3 show the results of extrapolation using the relationship between the evaporation constant and the suspender diameter expressed as Eq. 7. The constants $a_4$ and $a_5$ in Eq. 7 were determined for each ambient temperature and initial droplet diameter by the least squares method (see the solid lines in Fig. 3). It can be seen that the relationship between the evaporation constant and the suspender diameter is well expressed by Eq. 7.

The evaporation constant was corrected to the value when $d_S = 0$ using Eq. 7 to obtain the evaporation constant which is free from the heat transfer through a suspender. Figure 5 shows the dependence of the corrected evaporation constant $k_0$ on initial droplet diameter for various ambient temperatures. It was found that the corrected evaporation constant increases as the increase of initial droplet diameter and increasing tendency is remarkable for higher ambient temperatures. This dependence of the corrected evaporation constant on initial droplet diameter and ambient temperature is supposed to be due to natural convection.

The effect of natural convection on droplet combustion and liquid fuel combustion from porous spheres was reported by several researchers [2, 6, 7, 19-23]. With reference to their results, the effect of natural convection on droplet evaporation was derived from the dependence of the corrected evaporation constant on initial droplet diameter and ambient temperature. The natural convection effect on the corrected evaporation constant can be expressed as

$$k_0 = k_{00}(1 + b_1\mathrm{Ra}^n) \tag{9}$$

where $k_{00,\,Ta}$, $b_1$ and $n$ are constants and Ra is the Rayleigh number. The constant $k_{00}$ is the evaporation constant free from natural convection and heat transfer through a suspender. The Rayleigh number was calculated from the arithmetic mean of the near-surface mixture and the ambient gas properties. The results of previous measurements [24] were used to determine droplet temperature. The initial droplet diameter was used as a characteristic length. To make comparison of the corrected evaporation constants at different ambient temperatures possible, Eq. 9 was normalized as

$$\frac{k_0}{k_{0,\,\mathrm{Ra}\sim 20}} = b_2(1 + b_1\mathrm{Ra}^n) \tag{10}$$

where $k_{0,\,\mathrm{Ra}\sim 20}$ is a corrected evaporation constant when Ra is around 20 and $b_2$ is a constant. The reason why the corrected evaporation constant at Ra ~ 20 was chosen for normalization of Eq. 9 is that experimental data existed at about Ra ~ 20 for all ambient temperatures. The normalized

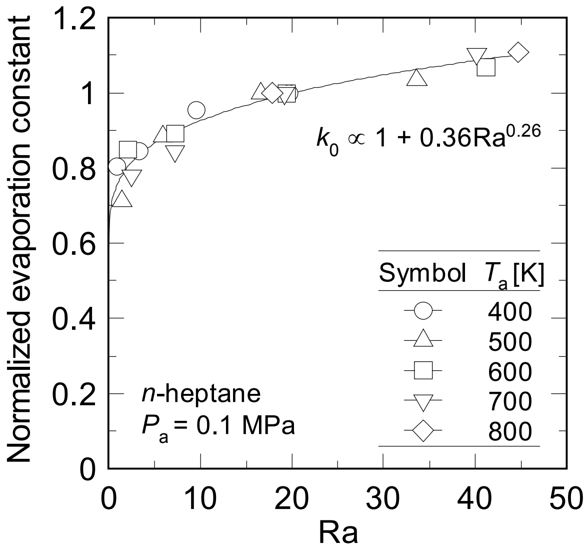


**Fig. 6** Dependence of normalized corrected evaporation constant on the Rayleigh number.

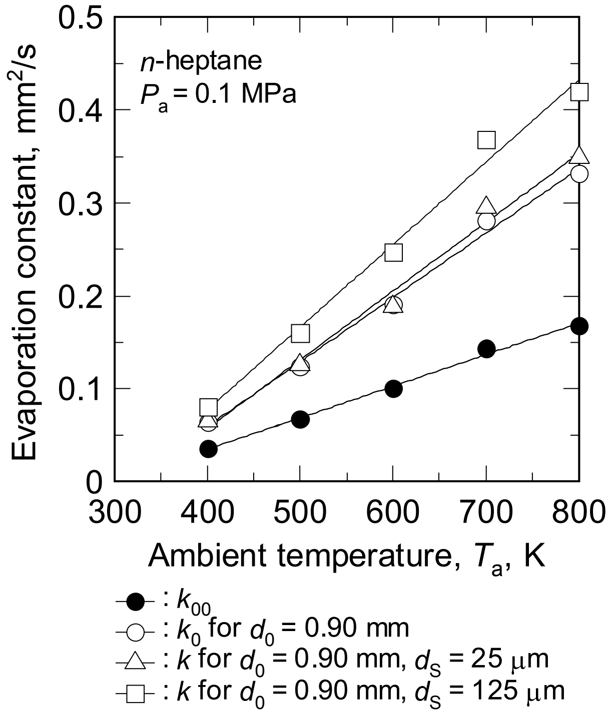


**Fig. 7** Effect of natural convection and suspender on evaporation constant.

corrected evaporation constant as a function of Ra is shown in Fig. 6. The plots for various ambient temperatures lie on an identical curve. The constants $b_1$, $b_2$ and $n$ in Eq. 10 were determined by the least squares method. The index $n$ was 0.26, which is close to the value for combustion reported in Ref. 6, 7 and 16. This agreement supports that the dependence of the corrected evaporation constant on initial droplet diameter is caused by natural convection. The natural convection effect on the corrected evaporation constant was expressed as

$$k_0 = k_{00}(1 + 0.36\mathrm{Ra}^{0.26}) \qquad (11)$$

where $k_{00}$ is the corrected evaporation constant for a non-convective flow field (Ra = 0) and has the relation of $k_{00} = b_2 k_{0,\,\mathrm{Ra}\sim 20}$. Here, $k_{00}$ is the true characteristic value for droplet evaporation because it is the evaporation constant free from natural convection and heat transfer through a suspender. Figure 7 shows the determined values of $k_{00}$ for each ambient temperature. The corrected evaporation constant for $d_0$ = 0.90 mm and the evaporation constants for $d_0$ = 0.90 mm in the cases of $d_S$ = 25 and 125 μm were also plotted to show the effects of natural convection and suspender on the evaporation constant. It can be seen that $k_{00}$ increases linearly as the increase of ambient temperature. The corrected evaporation constant for $d_0$ = 0.90 mm is about twice as large as $k_{00}$. This fact means that, if there is no suspender effect, natural convection makes the evaporation constant about double in the case of $d_0$ = 0.90 mm. The effect of suspender on the evaporation constant strongly depends on the suspender diameter. The evaporation constant for a natural convection field is enhanced about 3% in the case of $d_S$ = 25 μm and about 30% in the case of $d_S$ = 125 μm.

The effects of suspender and natural convection on the evaporation constant were successfully distinguished and determined by simple experiments. The assumptions which were employed to determine these effects from the experimental data, such as the assumption that droplet temperature is not affected by suspender diameter, should be proved by further detailed studies.

## 4. Conclusions

Droplet evaporation experiments using a suspended n-heptane droplet were carried out in natu-

ral convection fields at atmospheric pressure. The effects of suspender and natural convection on the evaporation constant were determined separately by simple experiments. Results can be summarized as follows:
(1) Evaporation constant was obtained for various initial droplet diameters and suspender diameters. Dependence of the evaporation constant on initial droplet diameter changes when the suspender diameter is varied. When the suspender diameter is large as compared with the initial droplet diameter, the evaporation constant decreases as the increase of initial droplet diameter. On the other hand, when the suspender diameter is small as compared with the initial droplet diameter, the evaporation constant increases as the increase of initial droplet diameter.
(2) Evaporation constant increases as the increase of suspender diameter for a fixed value of initial droplet diameter.
(3) The relationship between evaporation constant $k$ and suspender diameter $d_S$ for a fixed value of initial droplet diameter was expressed as $k = c_1 + c_2 d_S^2$, where $c_1$ and $c_2$ are constants dependent on ambient temperature and initial droplet diameter.
(4) Natural convection effect was expressed as $k_0 \propto 1+0.36\mathrm{Ra}^{0.26}$, where $k_0$ is the evaporation constant free from heat transfer though a suspender and Ra is the Rayleigh number.
(5) Evaporation constants free form natural convection and heat transfer through a suspender were obtained for various ambient temperatures.

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