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Experimental Study on The Effect of Initial Liquid Droplet Size on The Evaporation in a Heterogeneous Droplet

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Abstract
In the present work, we experimentally investigated the effect of initial liquid droplet size on the evaporation in the heterogeneous droplet. Spherical carbon and water were used for particle and liquid droplet comprising the heterogeneous droplet. four initial droplet volumes of 1, 2, 3 and 4 μl were considered when the diameter of the particle was 5 mm. The heterogeneous droplet was suspended with a rod at 20 cm away from the radiator which surface temperature was fixed to 473 K. Ambient temperature and relative humidity remained 296 K and 40 %, respectively, during the experiment.
As the results, the evaporation rate of 4 μl case increased about 1.8 times compared with that of 1 μl case. The evaporation rate increased almost linearly with the volume ratio, and that is related closely with the contact surface between particle and water droplet. Contact surface area remained almost constantly with time, whereas it increased with the initial volume of water droplet. The energy from radiator can be accumulated at the contact surface at the side of particle, thereby intensifying the evaporation of water droplet because more heat transfers from particle to droplet through the contact surface. Consequently, the initial volume of liquid droplet is one of the influence factors on the evaporation rate in the heterogenous droplet.

Keywords
Contact surface area, Evaporation rate, Heat transfer, Heterogeneous droplet

Introduction
Drop evaporation is an important topic of interest because it plays a crucial role in many engineering applications such as spray drying, fuel injection into combustion engines, medical care, controlling the deposition of particles on solid surfaces, rapid cooling by drop wise heat exchange and also occurs in natural processes such as rain, fog, dew, snow formation and is used in meteorological estimates [1]. Nowadays, one of the most important directions of development in the field of fire extinguishing technologies is the improvement of heat exchange between extinguishing liquid and combustion products in flame zone and in its close vicinity [2]. Firstly, sprinkler systems are intended to either control the fire or to suppress the fire. For instances, sprinklers are used to control the heat release rate of the fire to prevent building structure collapse, and pre-wet the surrounding combustibles to prevent fire spread. Lastly, water curtain, which is a thermal and smoke control system in a fire hazard, is mainly used to diminish radiative heat transfer from fire and prevent spreading of smoke. In the development and deployment of practical systems, it is very important to understand how the flame extinction characteristics depend on droplet diameter, number density, and overall water loading.
The traditional approach of droplet breakup when spraying extinguishing liquid received a lot of criticisms. In real practice the droplets of extinguishing liquid coalesce during their motion through flames. Moreover, soot particles in fire plume or ceiling jet flow have potential for adhering to the surface of water drops released from a nozzle at ceiling. When size of soot is comparable with that of drop, which is called as a heterogeneous droplet [3], evaporation rate of the droplet steeply increases, then it can cause explosive breakup. These effects complicate the problem of selection of initial droplet sizes and their control during the motion to absorb the fire energy as well as to expel both the oxidant and flammable combustion products. Piskunov, Shcherbinina and Strizhak [4] investigated the features of evaporation, boiling and explosive breakup of water droplets containing a non-transparent inclusion when immersed in gaseous environment at high temperatures corresponding to typical fires. They conducted experiments with droplets containing 1 mm size non-transparent and non-metallic inclusions. The previous researches [3, 4] were mainly focused on the explosive breakup phenomena of the droplet and showed that shape and size of inclusions have an influence on evaporation rate of droplet associated with total evaporation

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time or explosive breakup time in only high temperature range near film boiling regime. In practical engineering applications, it is very important in predicting the beginning and the end of nucleate boiling or film boiling regime at the interface between solid and liquid as well as instantaneous droplet sizes. This is because nucleate vapors on the surface of inclusion dramatically change heat transfer characteristics. For example, in the high temperature or film boiling regime, the quench proceeds rather slowly as liquid-solid contact is minimized by the rapid formation of an insulating vapor blanket at the droplet-solid interface [5]. Therefore, it is firstly necessary for understanding heat transfer phenomena in heterogenous droplet to develop a practical engineering model for evaporation including nucleate/transition/film boiling.
In the present work, we experimentally investigated the effect of initial liquid droplet size on the evaporation in the heterogeneous droplet before nucleate boiling regime as a basic study. Carbon and water were used for particle and liquid droplet comprising the heterogeneous droplet. four initial droplet volumes of 1, 2, 3, and 4 μl were considered when the diameter of the particle was 5 mm. The heterogeneous droplet was suspended with a rod at 20 cm away from the radiator which surface temperature was fixed to 473 K. Ambient temperature and relative humidity remained 296 K and 40 %, respectively, during the experiment.

Material and methods
To measure the volume change of the droplet, the experimental system consists of a telocentric lens (NAVITAR) combining two CMOS cameras (SONY, 5 Mega-pixels, 1fps and SONY, 8 Mega-pixels, 15fps) and multi-arrayed LED lamp (100W) as shown in Figure 1. All captured images were converted the gray scale of pixel intensities to determine the interface among multiphase materials such as water, air and particle as shown in Figure 2. With the captured images, the droplet volume of water volume was calculated by Image-J software using the LB-ADSA (low-bond axisymmetric drop shape analysis) method [6] under the assumption of axisymmetric droplet.

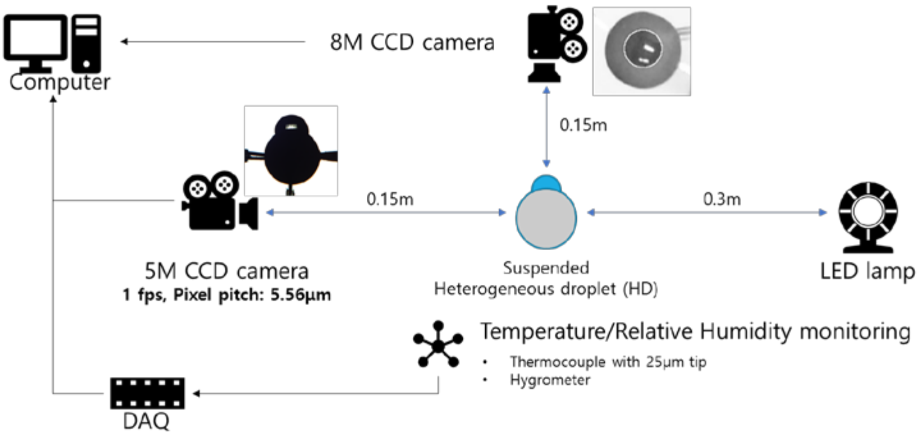

Figure 1. Schematic and picture of experimental apparatus.

Heterogeneous droplet consisted of a particle and a deionized(DI) water droplet. To investigate the effect of initial water droplet size, the diameter of particle was fixed to 5 mm whereas the volume of water droplet was changed from 1 μl and 4 μl. The spherical particle was manufactured with by a micro milling machine and was made up of graphite. The heterogenous droplet was suspended with a thin rod. Very narrow holes, which diameter and depth are about 0.5 mm, were drilled on the surface of the particle for inserting tips of the rod and thermocouples. Two K-type thermocouples (measurement range: 200 ~ 1250 K, error 0.4 %, OMEGA®) were used to measure the surface temperature of particle and the diameter of tip was 25 μm. The particle was bonded with the rod by using an adhesive had very lower conductivity not to influence the heat and mass transfer related with evaporation. The radiator consisted of quartz plate (W x H x D: 230 mm x 85 mm x 10 mm) and resistance coils and was used to heat the heterogenous droplet and it was 20 cm away from the droplet at the opposite site of the rod. The quartz surface temperature of radiator was adjusted by electrical power controller (Model: MT4Y, Autonics®) to remain 473 K. The spatial and temporal deviations in the surface were within $\pm$ 10 K and $\pm$ 1 K, respectively, in the steady state. The dosing system of water droplet consisted of pump, syringe and needle. As shown in Figure 2, the water droplet was placed on the top of the particle as much as a setting volume by using a syringe pump (LSP01-1A, Longerpump®) with a syringe (1001TLL, Hamilton®). The internal diameter of needle was 0.3 mm. Ambient temperature and relative humidity remained 290 K and 40 %, respectively, during the experiment. For each case, the experiments were carried out with five replicates and three data samples were used for the analysis of evaporation after the image processing.

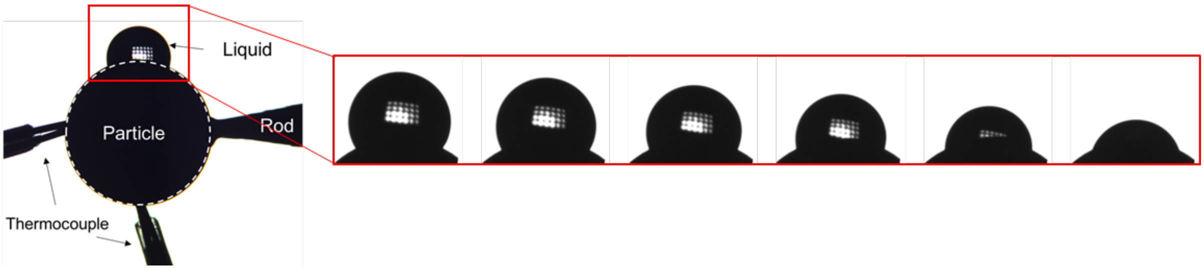

Figure 2. Heterogenous droplet suspended with a rod and converted images for image processing over time.

Results and discussion

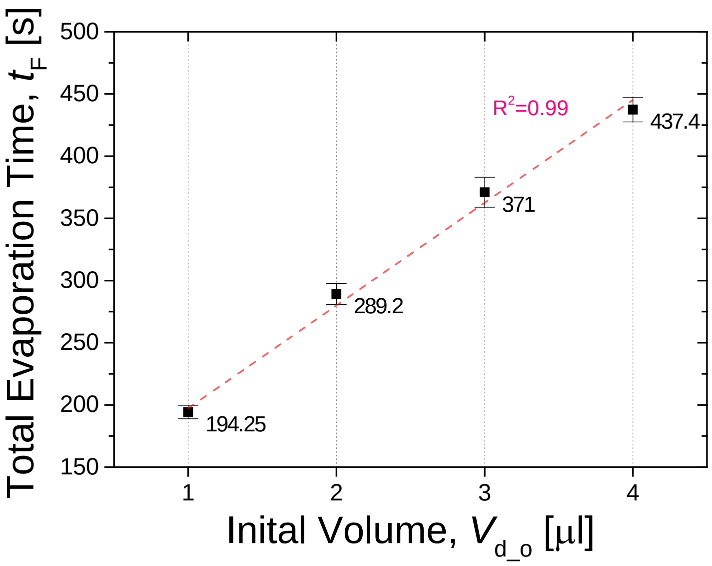

Figure 3. Total evaporation time with the initial volume of water droplet.

Figure 3 shows total evaporation time with the initial volume of water droplet. Total evaporation time (t_F) linearly increased with the initial volume of water droplet (V_{d_o})as shown in Figure 3. The evaporation time of 4 µl case increased about 2.3 times compared with that of 1 µl case. Also, Figure 4 shows the variation of volume of water droplet with normalized time (t_n) which was defined as the ratio of any instantaneous time (t) to the total evaporation time (t_F) in each case. In each point of line in Figure 4. The volume of water droplet linearly decreases after at least t_n=0.2 in all cases, that is, evaporation process reached a quasi-steady state.

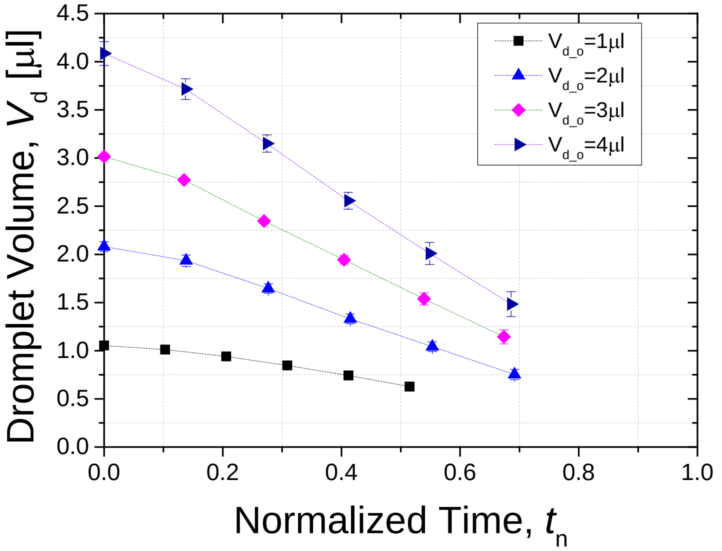

Figure 4. Evolution of volume of water droplet.

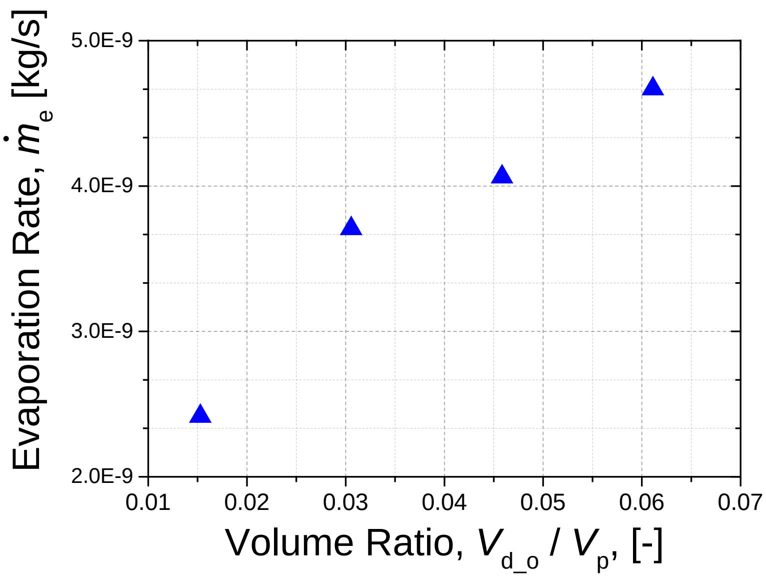

Figure 5. Evaporation rate during the quasi-steady state evaporation.

Figure 5 shows evaporation rate with the volume ratio of the initial volume of water droplet ($V_{\mathrm{d\_o}}$) to the volume of particle (V_{p}) during the period of quasi-steady state evaporation. Here, the evaporation rate, $\dot{m}_e$ [kg/s], is the product of water density and the decrease rate of droplet volume during the quasi-steady evaporation, i.e., t_{n} > 0.2 in Figure 4. The evaporation rate of 4 μl case increased about 1.8 times compared with that of 1 μl case. The evaporation rate increased almost linearly with the volume ratio, and that is associated with the contact surface area between the droplet and the particle illustrated in Figure 6. In terms of thermal-physical property, the particle is an opaque and non-evaporating material, and it has larger thermal conductivity in comparison with water. The energy from radiator, therefore, can be accumulated at the contact surface at the side of particle, thereby intensifying the evaporation of water droplet.

In this study, contact surface area was calculated by image processing and Figure 7 shows the evolution of contact surface area with normalized time. Contact surface area remained almost constantly with time, whereas it increased with the initial volume of water droplet. Therefore, the initial volume of liquid droplet is one of the influence factors on the evaporation rate in the heterogenous droplet.

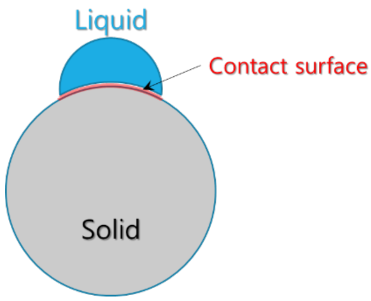

Figure 6. Schematic of the heterogeneous droplet.

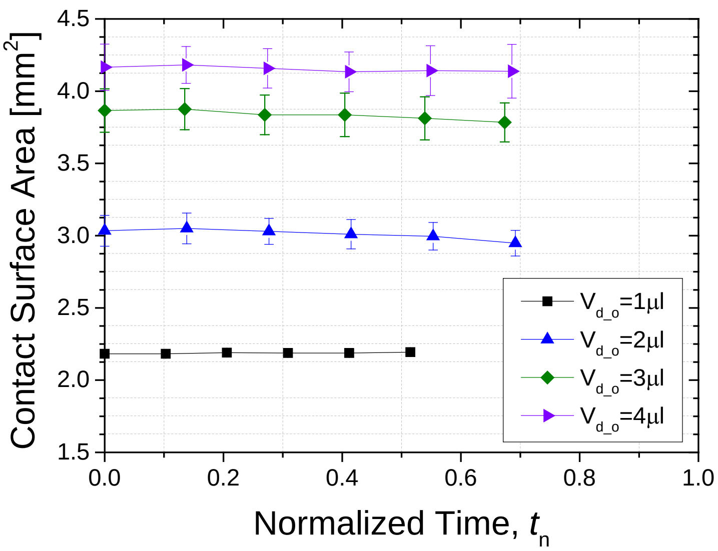

Figure 7. Evolution of contact surface area with normalized time.

Conclusions

In the present work, we experimentally investigated the effect of initial liquid droplet size on the evaporation in the heterogeneous droplet as a basic study.

- Total evaporation time linearly increased with the initial volume of water droplet. The evaporation time of 4 μl case increased about 2.3 times compared with that of 1 μl case.
- The evaporation rate of 4 μl case increased about 1.8 times compared with that of 1 μl case. The evaporation rate increased almost linearly with the volume ratio.
- Contact surface area remained almost constantly with time, whereas it increased with the initial volume of water droplet. The energy from radiator can be accumulated at the contact surface at the side of particle, thereby intensifying the evaporation of water droplet because more heat transfers from particle to droplet through the contact surface.

Consequently, the initial volume of liquid droplet is one of the influence factors on the evaporation rate in the heterogenous droplet.

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Nomenclature

$\dot{m}_e$ evaporation rate [kg/s]

t_{F} total evaporation time [s]

t_{n} normalized time [-]

V_{d} volume of water droplet at any instantaneous time [μl]

$V_{\mathrm{d\_o}}$ Initial volume of water droplet [μl]

V_{p} volume of particle [μl]

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