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The characteristics of puffing of the carbonated emulsified fuel

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ABSTRACT

This paper presented the characteristics of puffing of carbonated emulsified fuel. Emulsified fuel saturated with CO_2 under $P_{CO_2} = 92$ kPa and $T_e = 288$ K and the degassed emulsified fuel were used in the experiment. An emulsified fuel droplet suspended from a thermocouple was inserted into an electric furnace. Puffing behavior was observed by using a high-speed video camera. The waiting time and the superheat temperature for the occurrence of puffing were measured. The mean waiting time of the emulsified fuel saturated with CO_2 decreased by about 25% compared with that of the degassed emulsified fuel. When the degassed emulsified fuel was used, there was a peak of puffing occurrence at the superheat temperature of 60 K. When the emulsified fuel saturated with CO_2 was used, there was a peak of puffing occurrence at the superheat temperature of 45 K. The superheat temperature at the peak decreased by 15 K. Puffing behavior of the carbonated emulsified fuel was more violent than that of the degassed emulsified fuel. These were because the dissolved CO_2 caused a reduction in the bubble nucleation energy. Moreover, a new equation which described the waiting time for puffing was proposed. This equation was based on the assumption that puffing occurred when the inner droplet temperature increased linearly. The calculated results of the waiting time were in good agreement with the experimental ones when puffing occurred near the initial linear region.

1. Introduction

There have been widespread applications of spray combustion of liquid fuel. However, the pollutant emissions from spray combustion such as NO_x and soot are serious global problems to be solved. Recently, many researchers have studied spray combustion for low-NO_x emission [1–5]. Emulsified fuel is regarded as one of the possible alternative fuels for reducing the emission of pollutants from practical combustion systems. Emulsified fuel consists of a base fuel and water with or without a trace content of surfactant. During the vaporization or combustion of the emulsified fuel droplet, the dispersed water can reach a superheat temperature. The superheat of a liquid which is in the thermodynamically meta-stable condition leads to bubble nucleation. The expanding vapor breaks a whole droplet or a part of droplet. These phenomena have been classified into micro-explosion and puffing. Micro-explosion is that the whole droplet breaks up into small droplets quickly. Puffing is that water vapor is blown out from the droplet surface with fine droplets (a part of the droplet breaks up). Therefore, the spray combustion of emulsified fuel offers several advantages, such as better combustion efficiency and less pollutant emission. Several experimental investigations have focused on puffing and micro-explosion of multicomponent and emulsified droplets [6–11]. Avedisian and Fatehi [6] have investigated the evaporation characteristics of water-in-fuel emulsified fuel droplets on a hot horizontal surface. Tsue et al. [7,8] have measured the waiting time for the occurrence of micro-explosion and discussed the occurrence probability of micro-explosion with statistical analysis. Segawa et al. [9] have investigated the combustion process and micro-explosion of oil-in-water emulsified fuel droplets in detail. Calabria et al. [10] have studied the combustion behavior of an emulsified fuel of pyrolysis oil. Watanabe et al. [11] have investigated puffing and micro-explosion behavior by using water-in-oil emulsified fuel. The more the waiting time decreases, the more combustion efficiency improves. Therefore, it is quite important to decrease and predict the waiting time for the occurrence of puffing and micro-explosion. Tsue et al. [12] have carried out experiments on droplet combustion in microgravity. They have shown that micro-explosion did not occur but puffing sometimes occurred during the lifetime of combustion. Although the occurrence of puffing and micro-explosion depends on the properties of the emulsified fuel such as surfactants, puffing is important for discussing the spray combustion of the emulsified fuel. Therefore, the waiting time for the occurrence of puffing is focused on in this study. The dissolved gas in the emulsified fuel offers a decrease in the waiting time because the dissolved gas

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Nomenclature

ΔA_e	activation energys [J]
C_p	heat capacity [kJ/kg K]
d	diameter [m]
h_c	convective heat transfer coefficient [W/m^2 K]
J	nucleation rate per unit volume [1/m^3 s]
k	Boltzman constant [J/K]
Nu	Nusselt number [–]
P	pressure [Pa]
Q	heat [W]
R	universal gas constant [J/(mol K)]
T	temperature [K]
t	elapsed time [s]
v	activity coefficient [–]
X	solute to solvent mole ratio [–]
x	coordinate [mm]
Z	pre-exponential constant [1/m^3 s]

Greek symbols

β	coefficient defined by Eq. 9 [K/ms]
$\Delta x_{distance}$	the distance between x_{tip} and $x_{measurement}$ [mm]
ε	emissivity [–]
ϕ	water content [–]
η	coefficient defined by Eq. 4
ν	activation coefficient [–]
ρ	density [kg/m^3]
σ	surface tension [N/m]
σ_s	Stefan–Boltzmann constant [W/m^2 K]
τ	waiting time [s]

Subscripts

e	emulsified fuel
g	gas
init	initial
l	liquid phase
measurement	measurement point in the electric furnace
p	puffing
sat	saturation
super	superheat
tip	tip of water-cooling probe
w	wall
0	bulk
1	solvent
2	solute
∞	equilibrium

reduces the bubble nucleation energy, as described later. However, there has been little effort to investigate the characteristics of puffing and micro-explosion, and the waiting time for the gas-dissolved emulsified fuel, although many single droplet experiments of the emulsified fuel have been carried out [6–11].

In this study, the characteristics of puffing of emulsified fuel saturated with CO_2 was investigated. The waiting time for the occurrence of puffing was also measured. Moreover, a new equation was proposed which describes the waiting time of the emulsified fuel saturated with CO_2.

2. Experiment

2.1. Preparing the emulsified fuel

Sorbitan Monooleate (Emasol O-10V, Kao Corp. HLB = 4.3) was used as an emulsifying agent to prepare the W/O emulsified fuel. The water content in the emulsified fuel was 20 vol.%. The amount of the surfactant added in the emulsified fuel was 0.75 vol.%. The W/O emulsified fuel was prepared by adding the water and the emulsifying agent into kerosene and stirring the mixture with a mechanical homogenizer (ULTRA-DISPERSER MODEL LK-21, Yamato Science, Japan). The mechanical homogenizer was set to a 20,000 rpm in rotation speed. After 10 min mixing, W/O emulsified fuel was formed. The procedures for degassing and dissolving CO_2 were carried out using the experimental setup as shown in Fig. 1. There was water in the desiccator. Water under the plate was flowed by a small pump. The degassing and carbonation procedures were carried out under a water vapor atmosphere to reduce the evaporation of dispersed water in the emulsified fuel. In this study, CO_2 was used to investigate the effect of a dissolved gas on puffing, due to the high solubility of CO_2 in water. First, the degassing procedure was performed to eliminate the effect of previously dissolved gas in the emulsified fuel. The emulsified fuel was put into the desiccator and mixed using a magnetic stirrer. When the degassing procedure had been carried out, the pressure in the desiccators was set to 46 kPa at the beginning by using a vacuum pump. After 0.5 h, the pressure was set to 4 kPa. Every 10 min, the pressure change was measured, and the pressure was set to 4 kPa. After the pressure change in the desiccator was almost constant (less than 0.5 kPa/h), the degassing procedure was completed. After the complication of the degassing procedure, CO_2 (95%) was introduced into the desiccator. The pressure in the desiccator was set to 96 kPa with supplying CO_2 at the beginning. Subsequently, the pressure decreased because the CO_2 dissolved into water. Every 10 min, the pressure change was measured, and the pressure in the desiccators was set to 96 kPa with supplying CO_2. After 1.5 h, saturation of CO_2 was completed because the pressure change in the desiccators was almost constant. Saturation with CO_2 was completed at the point when the CO_2 pressure in the desiccator (P_{CO_2}) was 92 kPa and the emulsified fuel temperature (T_e) was 288 K. The equilibrium dissolved CO_2 in water was 1798 mg/l-water under these conditions. In this study, the degassed emulsified fuel and the emulsified fuel saturated with CO_2 were used to investigate the effects of the dissolved gas on the waiting time for puffing.

The mass of the emulsified fuel just after the degassing procedure decreased by 0.1320 g (initial mass of the emulsified fuel was 18.02 g). The decrease in the mass of the emulsified fuel was the amount of evaporation of water because the evaporation rate of kerosene and the emulsifying agent was very small. Therefore, the water content in the emulsified fuel just after degassing was 19.54 vol.%. After the carbonation procedure, the mass of the emulsified fuel decreased by 0.0914 g. The mass of emulsified fuel just after the carbonation process was larger than that just after the degassing procedure. This is because CO_2 is dissolved into water and kerosene. The equilibrium dissolved CO_2 in decane ($C_{10}H_{22}$) is 3305 mg/L [13] (T = 300 K). Assuming that the Henry constant of kerosene was equal to that of decane ($C_{10}H_{22}$), and kerosene and water in the emulsified fuel were saturated with CO_2, the mass of the evaporated water after the carbonation procedure was 0.151 g. Based on the above assumptions, the water content in the emulsified fuel after the carbonation procedure was 19.5 vol.%. It was shown that the effect of the degassing and the carbonation procedure on the water content in the emulsified fuel was very small. The emulsified fuel was always mixed using a magnetic stirrer. When the experiment was carried out, the conical

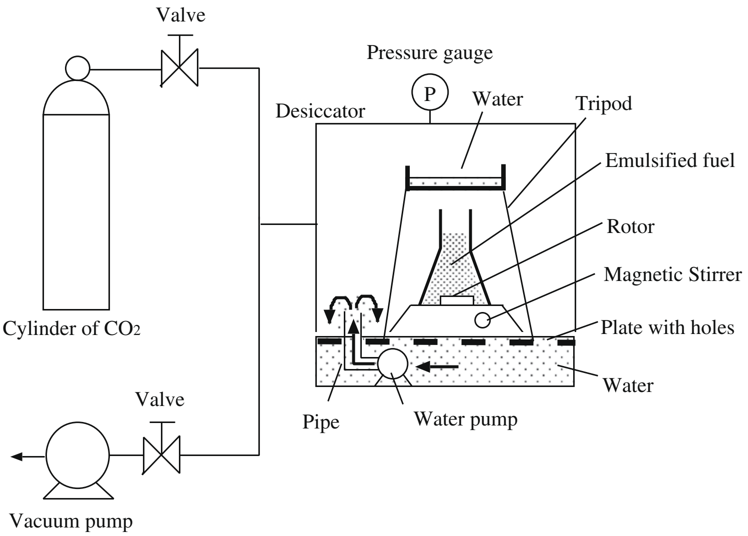


Fig. 1. Schematic diagram of experimental apparatus for degassing and dissolving gas.

flask was tightly covered except for when the emulsified fuel was aspirated using the micro-syringe.

When the diameter distribution of the dispersed water in the emulsified fuel was measured, WinRoof (Mitani Corp.) software was used to analyze the microphotographs.

2.2. Single droplet experiment

Fig. 2(a) shows a schematic diagram of the single droplet experimental apparatus. First, the emulsified fuel droplet was suspended from an R-type thermocouple with a diameter of 50 μm by using a micro-syringe. The experimental procedure after the suspension of the droplet is shown in Fig. 2(b). The water-cooling probe was inserted into the electric furnace (1). The droplet suspended from the thermocouple was inserted into the inner water-cooling probe in the electric furnace, and the droplet was moved to the position where a high-speed video camera was focused (2). Then, the water-cooling probe was removed (3), and the droplet started to heat up. The waiting time for the occurrence of puffing (τ_p was determined from the series of photographs, as described later. There were two holes to observe the droplet with the high-speed video camera. The electric furnace wall temperature (T_w) was set

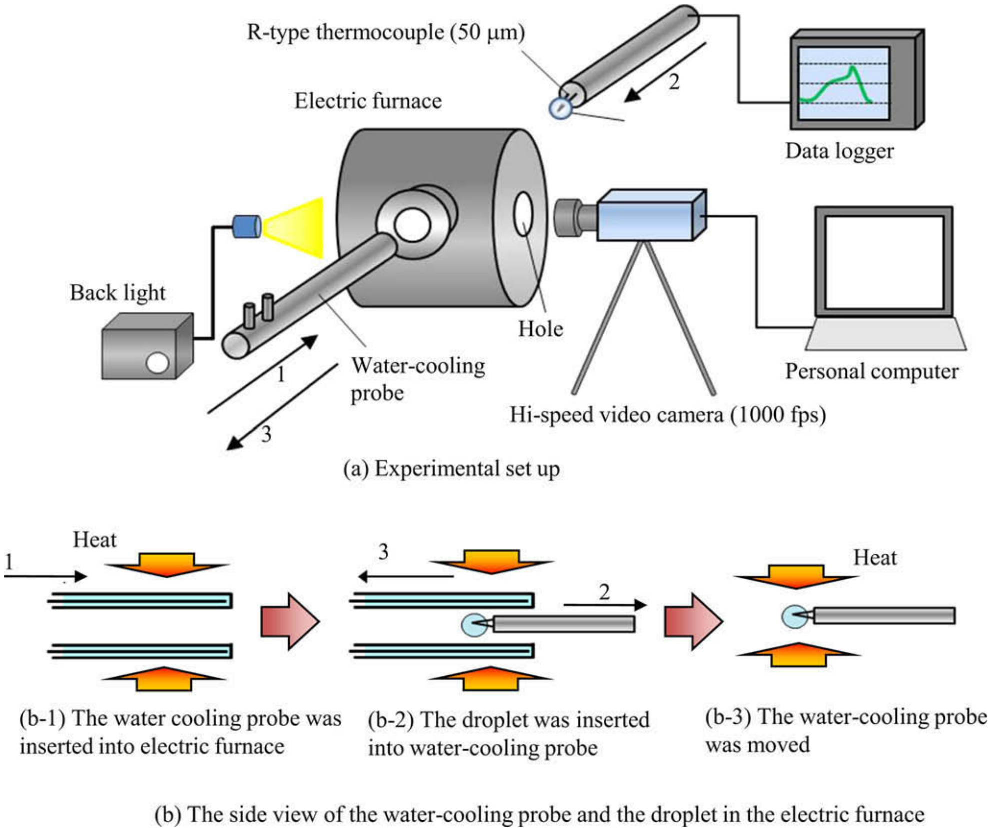
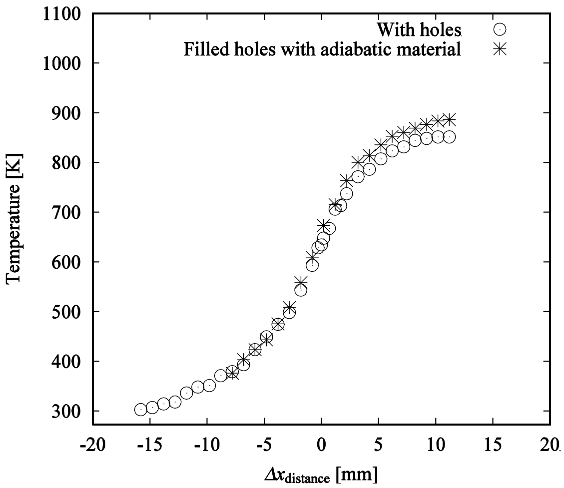
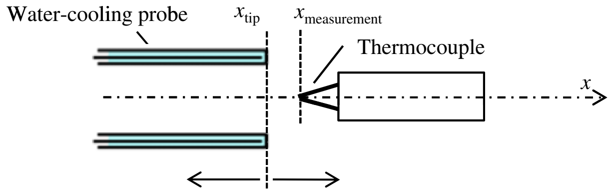


Fig. 2. Schematic diagram of experimental apparatus for a single droplet.

to 973 K. The surrounding gas temperature (T_g) at the measurement position in the electric furnace was 850 K (without the water-cooling probe). The surrounding gas was air. The droplet behavior during heating was observed using the high-speed video camera (VFC-1000SB, FOR-A Corp.) whose frame rate was 1000 fps. The initial diameter of the droplet was maintained at 0.7–1.3 mm. A data logger (MEMORY HiLOGGER 8423, Hioki Corp.) acquired the temperature data from the thermocouple with an interval of 10 ms. The temperature of the droplet inside was measured with the thermocouple. In this study, 17 droplets of the emulsified fuel saturated with CO_2 and 19 droplets of the degassed emulsified fuel were used to validate the mean waiting time.



(a) The effect of water-cooling probe on the temperature profile ($\Delta x_{distance} = x_{measurement} - x_{tip}$)



(b) The position of water-cooling probe and thermocouple (Thermo-couple position is fixed at the measurement point ($x_{measurement}$))

Fig. 3. Temperature profile in the electric furnace when the water-cooling probe is moved.

Fig. 3 shows the gas temperature profile in the electric furnace when the water-cooling probe was moved. The electric furnace had holes to observe the droplet behavior. The holes were filled with adiabatic material (ISOWOOL, ISOLITE INSULATING Co. Ltd.) to investigate the effect of holes on temperature distribution. When the gas temperature was measured, the water-cooling probe was moved along the x-direction and the R-type thermocouple was fixed at the measurement position where the high-speed video camera was focused. When $\Delta x_{distance}$ is negative, the thermocouple is in the water-cooling probe. The effect of small holes on the temperature distribution is not serious because the maximum temperature difference is 30 K at $\Delta x_{distance} = 10$ mm. In the water-cooling probe, the gas temperature is about 300 K. The maximum temperature in the electric furnace with holes is 850 K. Therefore, the moving speed of the water-cooling probe is important from the point of view of reproductivity. The moving speed of the water-cooling probe was fixed at 2 cm/s (±0.15 cm/s).

2.3. Definition of the zero point of elapsed time and the waiting time for puffing

Fig. 4 shows that the definition of $t = 0$ ms and waiting time for puffing (τ_p). When the distance between the tip of the water-cooling probe (x_{tip}) and the center of the droplet ($x_{droplet,center}$) is 0.5 mm, the elapsed time is set to 0 ms. It is difficult to define $t = 0$ ms in the temperature history. Therefore, the heating rate history is used to define $t = 0$ ms.

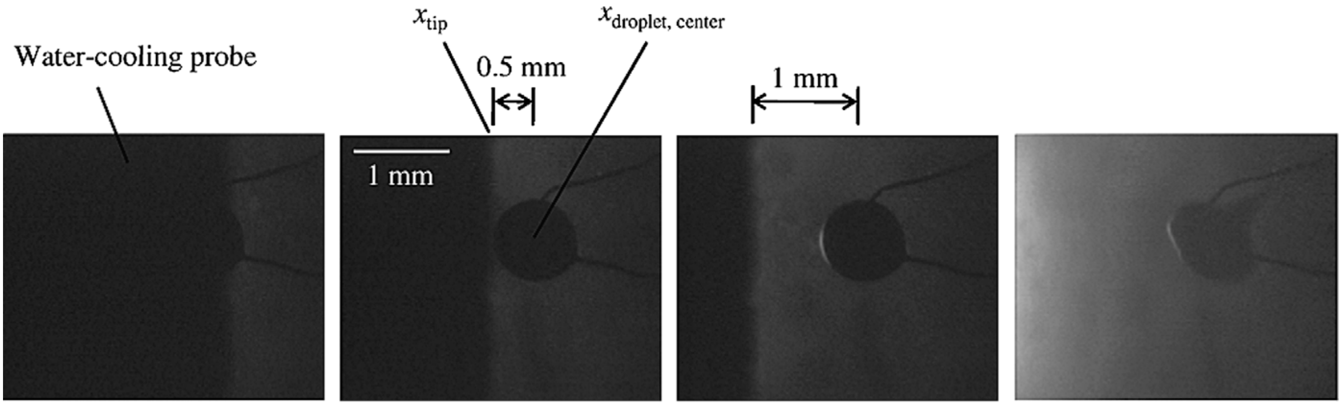
Fig. 5 shows the effect of initial diameter on the initial heating rate calculated from Eq. 1 (energy conservation equation).

$$\left.\frac{dT_e}{dt}\right|_{\text{initial}} = \frac{\pi d_e^2 h_c (T_g - T_e) + \pi d_e^2 \varepsilon_e \sigma_s (T_w^4 - T_e^4)}{\frac{\pi}{6} d_e^3 \rho_e C_{p,e}} \tag{1}$$

where T_g (gas temperature) is 616 K (at $x_{droplet,center} - x_{tips} = 0.5$ mm).

The point $t = 0$ ms is defined when the heating rate obtained from the inner droplet temperature is larger than the calculated initial heating rate, as shown in Fig. 5.

Fig. 6 shows the evaporation characteristics of the carbonated emulsified fuel ($d_{init} = 1.24$ mm). When the heating rate of droplets obtained from the temperature history is larger than the calculated heating rate, $t = 0$ ms is defined. The heating rate drastically decreases at the occurrence of puffing and micro-explosion due to rapid evaporation of dispersed water. Therefore, the waiting time for puffing and micro-explosion can be obtained from the heating rate.



$t = -20$ ms $t = 0$ ms $t = 20$ ms $t = 607$ ms (puffing : $\tau_p = 607$ ms)

Fig. 4. Definition of $t = 0$ ms and the waiting time for puffing (τ_p).

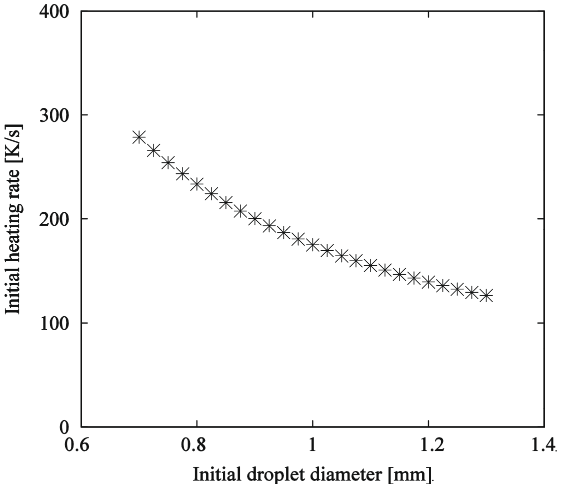


Fig. 5. The effect of the initial droplet diameter on the initial heating rate (calculated by Eq. 1).

Table 1
The waiting time for puffing and micro-explosion obtained from two different approach.

The definition method of τ_p	τ_p (puffing)	τ_p (micro-explosion)
From the series of photograph (Fig. 4)	869	1837
From the heating rate (Fig. 6(b))	870	1830

Table 1 shows the waiting time for puffing and micro-explosion by using the different definition method. The waiting time obtained from the series of photographs and that obtained from the heating rate are almost identical. The maximum error ($|\tau_{p,puffing}$ (obtained from the series of photographs) $- \tau_{p,puffing}$ (obtained from the heating rate)$|$) is 80 ms in this experiment. Although the zero point obtained from the heating rate is reasonably accurate, the waiting times for puffing described in this paper are obtained from the series of photographs.

3. Results and discussion

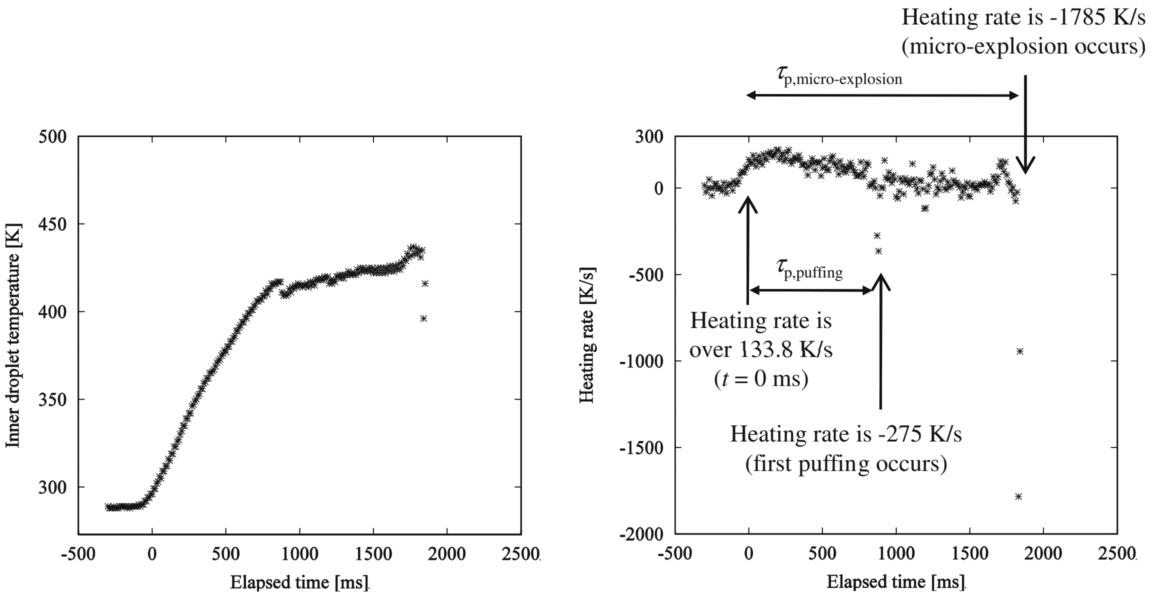
3.1. The size distribution of dispersed water droplets

Fig. 7 shows the diameter distribution and mean diameter of the dispersed water in the emulsified fuel just after the mixing by the homogenizer (a), that just after the degassing procedure (b), that just after the carbonating procedure (c) and that after 2 h from the carbonation procedure (d) (the experiment was completed within 2 h). The dispersed droplets smaller than 0.55 μm were not measured because of experimental uncertainties. The diameter of dispersed water just after the degassing procedure is a little larger than that just after the mixing by the homogenizer. However, the diameter distribution of dispersed water just after the degassing procedure (b), that just after the carbonation procedure (c) and that when the experiment of carbonated emulsified fuel is finished (d) are also identical.

3.2. The results of the single droplet experiment

Fig. 8 shows the series of photographs of puffing and micro-explosion observed in this study. Puffing is that water vapor is blown out from the droplet surface with fine droplets (Fig. 8(a)). A micro-explosion is that the droplet breaks up into small droplets quickly (Fig. 8(b)). The waiting time for the occurrence of puffing (τ_p) is focused on in this study. During heating, some droplets burned. The droplets which did not burn were also observed. However, the effect of dissolving gas is not strongly correlated with droplet burning.

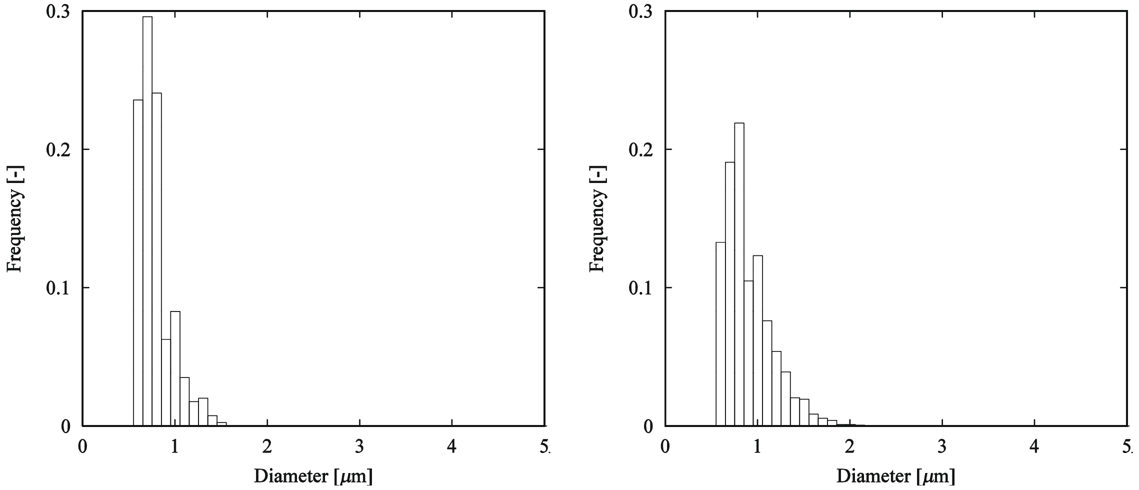
Fig. 9 shows the evaporation characteristics of droplets of degassed and carbonated emulsified fuel. The measured data are not shown when droplet diameter is less than 600 μm. When a droplet of emulsified fuel is heated, the inner droplet temperature increases rapidly. When emulsified fuel saturated with CO_2 is used, puffing occurs at $T_{e,p} = 408$ K. Then intermittent puffing is observed. Puffing occurs just after inner droplet temperature



(a) Temperature history

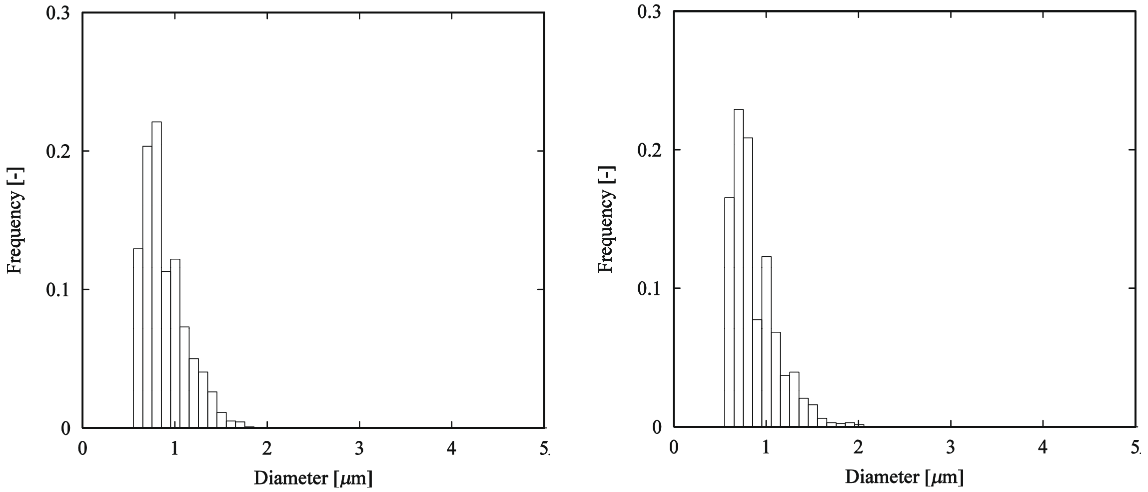
(b) Heating rate history
(definition of t = 0 ms in temperature history)

Fig. 6. The evaporation characteristics of carbonated emulsified fuel droplet (d_{init} = 1.24 mm).



(a) Original emulsified fuel (d_{mean} = 0.77 mm)

(b) Just after degassing procedure (d_{mean} = 0.90 mm)



(c) Just after carbonation procedure (d_{mean} = 0.88 mm)

(d) When the experiment is finished (after 2 hours from (c), d_{mean} = 0.87 mm)

Fig. 7. Diameter distribution of dispersed water in the emulsified fuel at each step.

increases linearly. The droplet diameter just before the occurrence of puffing is almost the same as the initial diameter. The waiting time for the occurrence of puffing is 648 ms. When degassed emulsified fuel is used, puffing occurs at $T_{\text{e,p}} = 434$ K. The waiting time for the occurrence of puffing is 1280 ms. The droplet diameters oscillate during puffing occurrence because water vapor is generated and blown out. The oscillation of droplet diameter of carbonated emulsified fuel is larger than that of degassed emulsified fuel during puffing. The droplet diameter of the carbonated emulsified fuel decreases more rapidly than that of the degassed emulsified fuel. These results indicate that puffing behavior of carbonated emulsified fuel is more violent than that of degassed emulsified fuel. Violent puffing has the possibility that the combustion behavior improves because the local turbulence is enhanced. The waiting time for the occurrence of puffing (τ_{p}) decreases by 632 ms when emulsified fuel saturated with CO_2 is used. This is because the bubble nucleation energy is reduced due to dissolved CO_2. It is well known that a liquid can be superheated without the occurrence of phase transformation even though it is in a meta-stable condition. As the liquid temperature increases, the nucleation of vapor bubbles occurs. Then, the rapid vaporization causes puffing and micro-explosion. Therefore, the occurrence of puffing and micro-explosion is associated with the steady state rate of nucleation J. Based on homogeneous nucleation theory [14], the steady state rate of nucleation J can be given by the following equations:

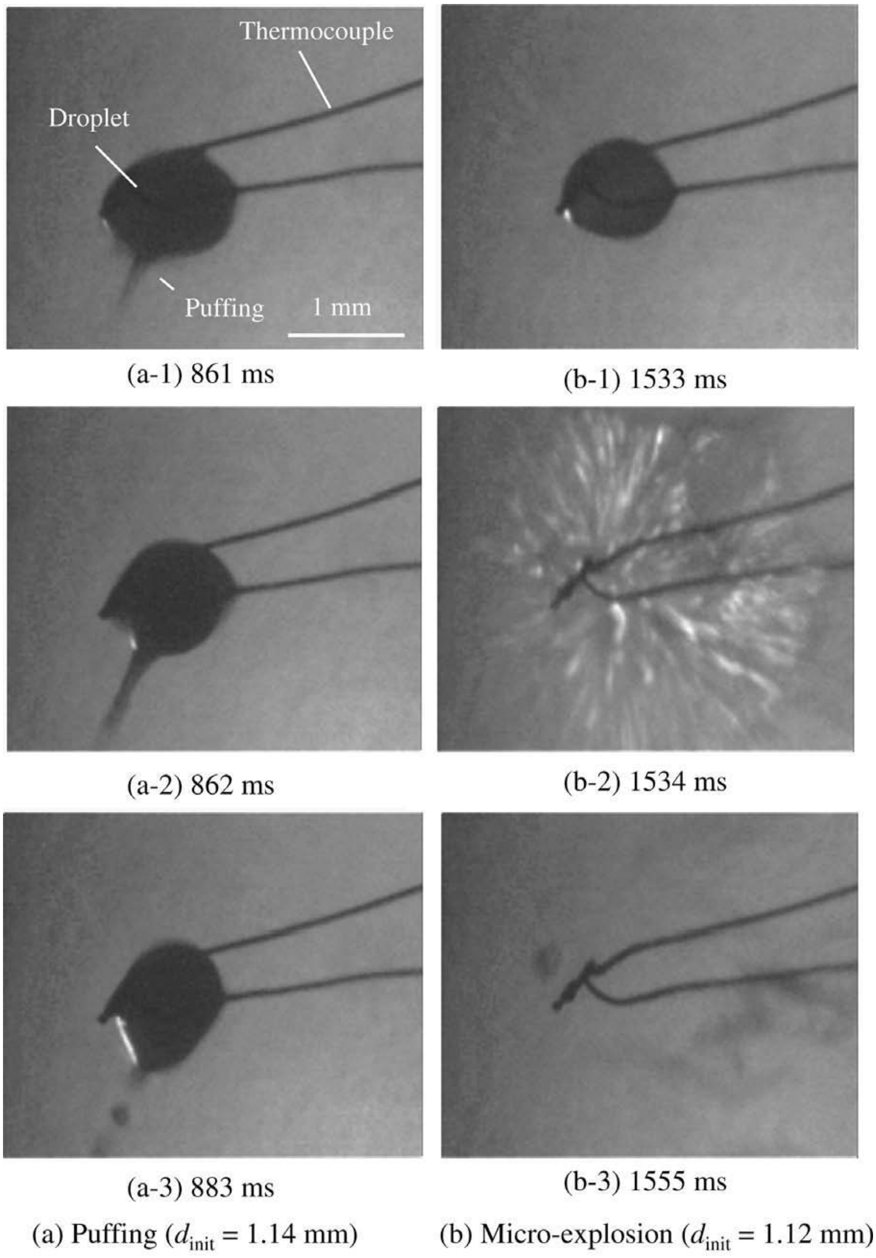
$$J = Z\exp\left(-\frac{\Delta A_{\text{e}}}{\text{k}T}\right), \tag{2}$$

where ΔA_{e} is activation energy for bubble nucleation. When the gas is dissolved in the liquid, ΔA_{e} is given by the following equations:

$$\Delta A_{\text{e}} = \frac{16\pi\sigma^3}{3\{\eta' P_\infty + P_0(X_2/X_{2s}) - P_0\}^2}, \tag{3}$$

$$\eta' = \left\{\exp\frac{v_{1l}(P_0 - P_\infty)}{\text{R}T_0} - X_2\right\}, \tag{4}$$

where X_2 is the solute-solvent mole ratio in the liquid phase, X_{2s} is the solute-solvent mole ratio in a liquid saturated with the gas, and



(a-1) 861 ms (b-1) 1533 ms

(a-2) 862 ms (b-2) 1534 ms

(a-3) 883 ms (b-3) 1555 ms

(a) Puffing (d_{init} = 1.14 mm) (b) Micro-explosion (d_{init} = 1.12 mm)

Fig. 8. The series of photograph when puffing and micro-explosion occurred (degassed emulsified fuel is used).

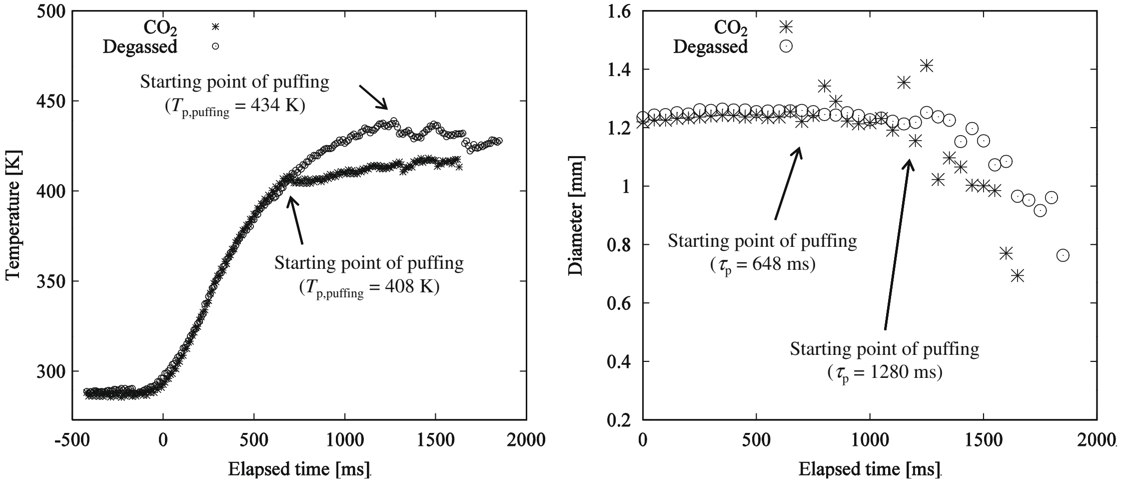
subscripts 1 and 2 refer to the solvent and solute, respectively. Hence, ΔA_e is reduced by the presence of dissolved gas in the liquid. In this research, the evaporation characteristics of the degassed droplet ($X_2 = 0$) and the droplet saturated with CO_2 ($X_2 = X_{2s}$) were investigated.

Fig. 10 shows superheat temperature distribution when puffing occurs. When uniform temperature distribution in the droplet is assumed, the superheat temperature of the dispersed water T_{super} is determined as follows:

$$T_{super} = T_{e,p} - T_{sat}(P), \tag{5}$$

where $T_{e,p}$ is the emulsified fuel droplet temperature just before the occurrence of puffing, and T_{sat} is the saturation temperature of water corresponding to pressure. Because nucleation of water vapor is a random process due to a density fluctuation, there are variations of superheat temperature when the secondary atomization occurs. When degassed emulsified fuel is used, there is a peak of superheat temperature of puffing occurrence at 60 K, and the mean superheat temperature is 55 K. When emulsified fuel saturated with CO_2 is used, there is a peak of superheat temperature of puffing occurrence at 45 K, and the mean superheat temperature is 49 K. The peak of superheat temperature decreased by 15 K. The mean superheat temperature decreased by 6 K.

Fig. 11 shows the effect of the initial diameter on the mean waiting time for the occurrence of puffing (τ_p). With increases in the initial diameter, the mean waiting time increases approximately linearly because the heating rate decreases with an increase in the initial diameter. The mean waiting time for emulsified fuel saturated with CO_2 decreases by about 25% compared with that for degassed emulsified fuel. It is instructive to express the waiting time by a simple equation. When emulsified fuel saturated with CO_2 is used, the waiting time is fairly short and puffing occurs while inner droplet temperature exhibits a linear increase, as shown in Fig. 9. Based on this characteristic, an equation



(a) Temperature history

(b) Diameter history

Fig. 9. The evaporation characteristics of droplet of degassed and carbonated emulsified fuel (d_{init} = 1.23 mm (degassed), d_{init} = 1.22 mm (CO_2)).

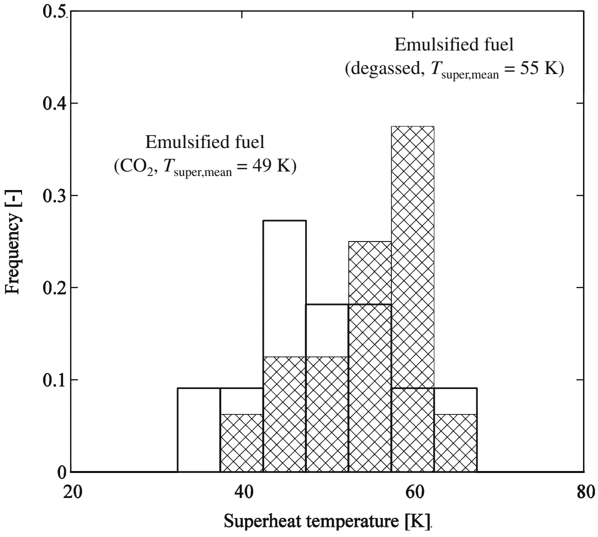


Fig. 10. Superheat temperature distribution when puffing occurs.

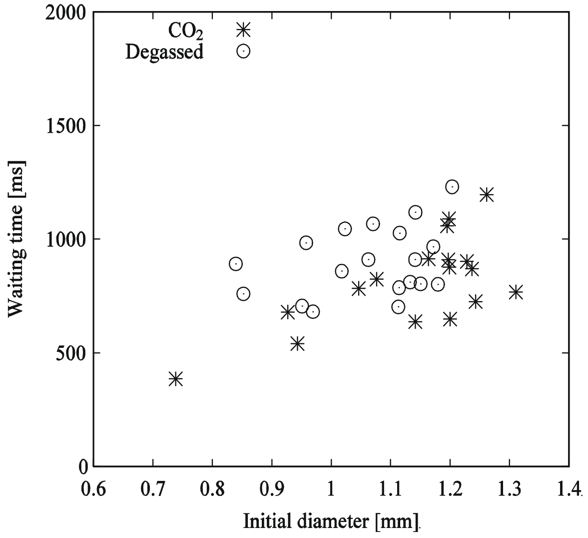


Fig. 11. The effect of the initial diameter on the waiting time for puffing.

which describes the waiting time can be proposed. The energy conservation equation for a droplet is shown by the following equation:

$$\frac{\pi}{6}d_e^3\rho_e C_{p,e}\frac{dT_e}{dt} = \pi d_e^2 h_c(T_g - T_e) + \pi d_e^2\varepsilon_e\sigma_s(T_w^4 - T_e^4) + Q_{latent}, \qquad (6)$$

where Q_{latent} is the rate of latent heat transport of droplet evaporation. When puffing occurs in the initial linear period, dT_e/dt is expressed by using mean waiting time ($\tau_{p,mean}$) and mean temperature just before puffing occurs ($T_{p,mean}$) as follows:

$$\frac{dT_e}{dt} = \frac{T_{P,mean} - T_{e,init}}{\tau_{p,mean}}. \qquad (7)$$

The evaporation rate is small in the initial period because the droplet temperature is low. For simplification, Q_{latent} is ignored and the rates of convective and radiative heat transfer can be approximated by the initial rates. The mean waiting time for puffing is expressed as follows:

$$\tau_{p,mean} = \frac{T_{p,mean} - T_{e,init}}{6\beta}d_{e,init}, \qquad (8)$$

$$\beta = \frac{h_c(T_{gas} - T_{e,init}) + \sigma_s\varepsilon_e(T_w^4 - T_{e,init}^4)}{\rho_{e,init}C_{p,e,init}}. \qquad (9)$$

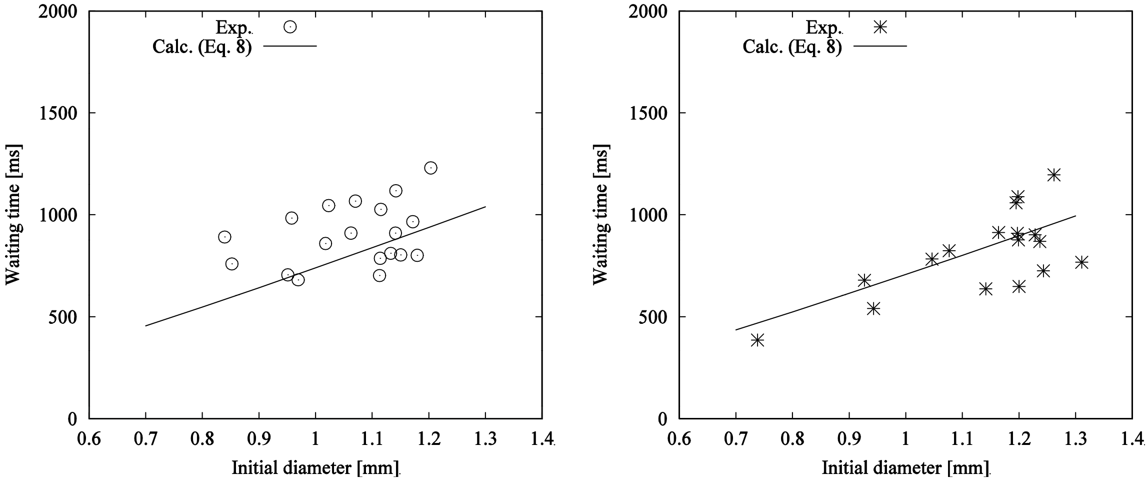
$T_{p,mean}$ is obtained from Fig. 10 and Eq. 5. T_{gas} is set to 800 K which is the average temperature at $x_{distance}$ = 0–20 mm (Fig. 3(a)). *Nu* is taken to be 2 because the experiment was carried out under static condition. The emissivity of the emulsified fuel (ε_e) is assumed to be 0.95 [15]. The only experimental parameter is $T_{p,mean}$ in this equation. The heat capacity and density of the emulsified fuel are expressed as follows [16]:

$$C_{p,e} = \frac{\rho_{water}\phi_{water}C_{P,water} + \rho_{kerosene}(1 - \phi_{water})C_{p,kerosene}}{\rho_e}, \qquad (10)$$

$$\rho_e = \rho_{water}\phi_{water} + \rho_{kerosene}(1 - \phi_{water}), \qquad (11)$$

where ϕ_{water} is the water content in the emulsified fuel. The density and heat capacity of kerosene are set to 874 kg/m^3 [17] and 2.01 kJ/kg K [18], respectively.

Fig. 12 shows a comparison of calculated and experimental results for the waiting time. When degassed emulsified fuel is used, puffing occurs beyond the linear increase period, as shown in Fig. 9. Therefore, the calculated waiting times are a little smaller than the experimental ones. When emulsified fuel saturated with CO_2 is used, the calculated results are in good agreement with the exper-



(a) Degassed

(b) CO_2

Fig. 12. The comparison between the experimental results and calculation results.

imental results because puffing occurred near the initial linear region.

4. Conclusion

In this study, the characteristics of puffing of an emulsified fuel saturated with CO_2 were investigated. The mean waiting time for emulsified fuel saturated with CO_2 decreased by about 25% compared with that for degassed emulsified fuel. When degassed emulsified fuel was used, there was a peak of puffing occurrence at the superheat temperature of 60 K, and the mean superheat temperature was 55 K. When emulsified fuel saturated with CO_2 was used, there was a peak of puffing occurrence at the superheat temperature of 45 K, and the mean superheat temperature was 49 K. The peak of superheat temperature decreased by 15 K. The mean superheat temperature decreased by 6 K. Moreover, a new equation which described the waiting time for puffing was proposed. This equation was based on the assumption that puffing occurs when the inner droplet temperature increases linearly. Although the calculated waiting times for puffing of degassed emulsified fuel were a little smaller than the experimental results, those of carbonated emulsified fuel were in good agreement with experimental results because puffing occurred near the initial linear region.

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