Scientific Research

Experimental Study on Latent Heat Storage Characteristics of W/O Emulsion by Ultrasonic Wave Impression

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ABSTRACT

The flowable latent heat storage material like Oil/Water type emulsion, microencapsulated latent heat material-water mixture or ice slurry, etc., is enabled to transport the latent heat in a pipe. Supercooling phenomenon of the dispersed latent heat storage material in continuous phase is obstructed by a latent heat storage. The latent heat storage rates of dispersed waterdrops in W/O (Water/Oil) emulsion are investigated experimentally in this study. The waterdrops in emulsion have the diameter within 3 - 25 µm, the averaged diameter of waterdrops is 7.3 µm and the standard deviation is 2.9 µm. Supercooling release of waterdrops in emulsion is examined by short time impressing of the ultrasonic. The direct contact heat exchange method is chosen as the phase change rate evaluation of waterdrops in W/O emulsion. The supercooled temperature is set as parameters of this study. The previous obtained experimental result, as the condition without impressing ultrasonic wave, showed that the 35 K or more degree from melting point brings 100% latent heat storage rate of W/O emulsion. It is clarified that it is possible to reduce 20 K of supercooling degree by impressing the ultrasonic.

1. Introduction

Recently, much attention has been paid to research on the latent heat storage system. Using of ice heat storage system brings an equalization of electric power demand, because it will be solved that the electric-power-demand-concentration on day-time of summer by the air conditioning. The flowable latent heat-storage system can scale down the pipe size due to the augmentation of the transported heat. Slurry type latent heat-storage (phase change material) system is one of the available cooling systems, which can take the place of the sensible (water) heat-storage system. Phase change emulsion [1] and phase change microcapsule slurry [2], clathrate hydrate slurries [3] etc. are mentioned as a typical slurry type latent heat storage substance. It is known that a super-cooling phenomenon disturbs a latent heat-storage [4,5]. A supercooling rate increases with reduction of disper-

sion droplet diameter except for the microencapsulated latent heat storage substance [6]. Some studies of super-cooling by bulk water have been reported. The pure water layers were cooled from upper side by five kinds of copper cooling surfaces (electrolytic polished, nickel-plated, buffed, porous, gold-plated copper disks) under various cooling rate (0.05 - 0.5 K/s), and the degrees of supercooling at the appearance of dendritic ice were measured by A. Saito, *et al*. [7]. As a result, the porous surface showed the lowest degree of supercooling. S. Okawa, *et al*. [8] investigated the effect of the electric field on freezing of supercooled water, experimentally. It was found that supercooled water freezes instantly by applying the electric charge at the voltage less than 100 VDC. The experimental results indicated that ultrasonic vibration strongly promotes the freezing of supercooled water, for both pure water and tap water by T. Inada, *et al*. [9]. Furthermore, they found that ultrasonic vibration

is also effective for making ice slurry. H. Inaba, *et al*. [10] reported the supercooling degree for the test tap water sample that was set in test tubes. The supercooling degree was decreased with an increase in the mass ratio of ice nucleating substance. However, it was clarified that the supercooling degree for each test sample increased by repeating the process of freezing and melting. T. Hozumi, *et al*. [11] studied the mechanism of the freezing of the supercooled water under the effect of the ultrasonic wave. It was shown that the impression of the ultrasonic wave (0.28 W/cm^2) brought the generation of ice nucleation on every experimental condition. All of these investigations were carried out by using the bulk water.

The freezing of waterdrop in W/O emulsion brings volume expansion. T. Inada *et al*. [12] measured the amount of freezes of the waterdrop in a W/O emulsion by microscope observation on the cooling rate of 0.067 K/sec. The counting of freeze numbers of the fine waterdrops is one of methods of measuring the degree of supercooling in W/O emulsion. However, this method does not measure the amount of latent heat storages itself. H. Inaba and S. Morita [13] showed the cold heat-release characteristics of emulsion by air-emulsion direct contact heat exchange method. By the same method, S. Aoyama and H. Inaba [14] described that the direct contact heat exchange characteristic between ice (averaged diameter 3.10 mm) and hot air. It can be said that the direct contact heat exchange method is the effective method for measuring the amount of latent heat storage. This study shows the experimental results of the latent heat-storage rate (supercooling rate of dispersed waterdrops) of the water in oil (W/O) emulsion by direct contact heat exchange method.

P. Schalbart *et al*. [15] investigated the low-energy emulsification method of Oil-in-Water (O/W) emulsions that have a narrow droplet size distribution in the range of 200 - 250 nm. These nano-emulsions of tetradecane in water showed stability against sedimentation and creaming for more than 6 months and low viscosity (2 - 4 times than that of water). The mass percentages of the nano-emulsion are 20% tetradecane, 6% surfactant and 74% water. The waterdrops of this research are existed in 3 - 25 μm in diameter, and the average diameter is 7.3 μm and the standard deviation is 2.9 μm. It is thought that the stabilization of a nano-emulsion exceeds a microemulsion. In this research, it is adopted from the reason that micro-emulsion is easy to produce and close to utilization. It was found that the emplacement of the phase-change materials (PCMs) has no effect on the heat transfer inside the emulsion. Test emulsion set as an expected temperature was supplied to the heat storage tank, and it cooled with the low cooling rate. Authors' previous research [16], as the condition without impressing

ultrasonic, showed that the 35 K or more degrees from melting point brings 100% latent heat storage rate of W/O emulsion. The supercooled temperature and the cooling rate are set as parameters of this study. The evaluation is performed by comparison between the results of this study and the past one.

2. Experimental Apparatus and Procedure

2.1. Test Emulsion

Figure 1 shows the external appearance and the micrograph (×400) of test emulsion. The emulsion has fluidity, even if the dispersed water particles are the solid phase. Test W/O emulsion consists of tap water as dispersed phase, silicon oil as continuous phase and surfactant. The silicone oil of continuous phase is used TSF451-10 (Momentive Performance Materials Holdings Inc.). The emulsification is carried out by nonionic surfactant (DKS NL-Dash403: Daiichi kogyo seiyaku CO. Ltd.). The mass composition ratio of test emulsion is tap water 5%, silicon oil 94% and surfactant 1%. The specific heat of the emulsion used for data evaluation is calculated using the additive property law. The base data of water and silicon oil is used publication data [17,18]. The specific heat of surfactant is used the actual value that measured by water calorimeter. For example, the specific heat of an emulsion is 1.90 kJ/(kg·K) at 298 K. The diameter of distributed waterdrops ($N = 300$) in test emulsion exists d = 3 - 25 μm, the average diameter of $d_m = 7.3$ μm and standard deviation is $S = 2.9$ μm. The stable time of test emulsion is at least 210 minutes, so that the cooling of experiment is carried out within the stable time.

2.2. Experimental Apparatus

Figure 2 shows the schematic diagram of experimental apparatus for measuring latent heat storage rate of emulsion by direct contact heat exchange method. Experimental apparatus consists of the test section and the hot air supply line. The air supplied from a compressor is sent to the test section through a surge tank, an air-dryer, a heater, and a flow meter. Dried hot air is sent to the

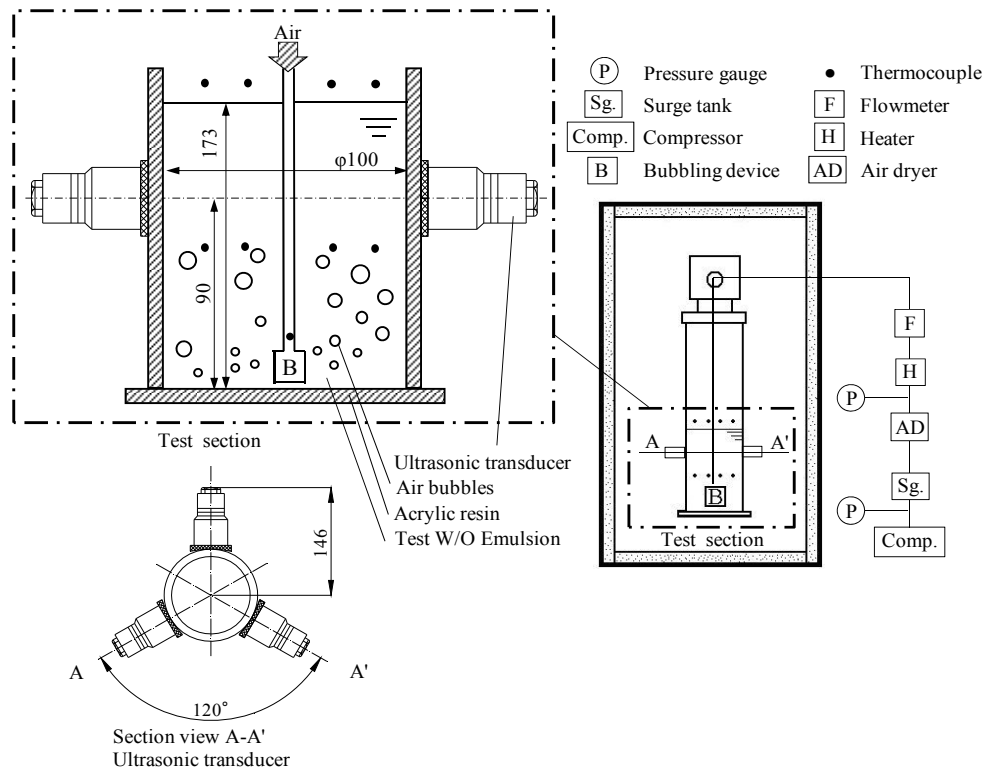

Figure 1. Appearance and micrograph of emulsion.

Figure 2. Experimental apparatus.

bubbling device that set in the bottom of the test section. The generated air bubble is directly heat exchanged by contact with a test sample. The inlet air temperature is fixed to 303 K. The heat quantity is calculated by a difference between inlet and outlet air temperature. All temperature measurement is performed by K-type thermo couples which have diameter 0.18 mm. The test section is made of transparent acrylic resin, and it has an inner diameter 100 mm, a height 550 mm and 10 mm in thickness. The 3 units of ultrasonic transducer (Alex Corporation, ultrasonic oscillator NMS150-3FP, the oscillating frequency 28, 50 or 80 kHz, max. output 150 W) are attached to the acrylics cylinder pipe. The whole of test section is stored in a low-temperature-controlled room, and is made into the structure which prevents the influence by the temperature change by freezer on-off by covering with thermal insulation. **Table 1** indicates the experimental conditions of this study.

The experiment of this research is conducted by the following procedures.

1) Set 233 K in a temperature control room;

2) Set sample into the test section;

3) Cool the sample below to the melting point of the latent heat storage material;

4) Impress the ultrasonic wave at 268 K (20 sec, 75% of 150 W × 3 units) and keep cooling;

5) Heat exchange by the temperature controlled dry air at the test section;

Table 1. Experimental conditions.

Frequency of ultrasonic f	28, 50, 80 kHz
Air mass flow G_a	0.06465 kg/min
Air pressure P	0.1 MPa
Inlet air temperature T_{ain}	303 K
Initial temp. of emulsion T_{ei}	283 ± 0.5 K
Temp. of freezer T_f	233 K
Cooling rate u_c	0.0015 - 0.0045 K/sec
Height of emulsion Z	173 mm
Degree of supercooling ΔT	5 - 20 K
Adding time of ultrasonic τ_u	20 sec

6) Measure the data and calculate the quantity of heat.

2.3. Quantity of Heat Storage Calculation

Figure 3 shows the time history of test emulsion temperature on experiment. The variation of temperature is shown from the emulsion set time into test section. The temperature of an emulsion decreases with time and reaches the melting point of water 273 K in about 800 seconds. The ultrasonic is impressed 20 seconds when the emulsion temperature reaches to 268 K. Test emulsion is continuously cooled till reach to the supercooling
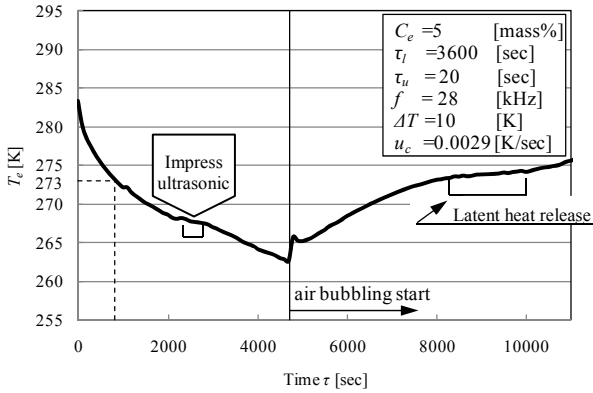
Figure 3. Time history of T_e.

degree 10 K (263 K) in about 4800 seconds. Test emulsion's mass used for the experiment is m_e = 1.5 kg and the temperature controlled room temperature is set T_f = 233 K. The cooling rate u_c of this research is about u_c = 0.0015 - 0.0045 K/sec. After the completion of cooling, a bypass line is changed and the dried air (303 K) is flowed to air bubbling device in test section. The temperature of test emulsion rises by jet of an air bubble. The constant temperature near the melting point of the water resulting from latent heat release is observed in about 8200 - 10,000 seconds.

The amount of latent heat storages is measured with the measurement data at the time of heat release. The exchanged heat quantity of air is calculated by Equation (1), in which the mass flow rate of air G_a, specific heat C_{pa} and the temperature difference of inlet and outlet air $(T_{ain} - T_{aout})$. The sensible heat of test emulsion is derived by Equation (2), in which specific heat of emulsion C_{pe}, mass of emulsion m_e and temperature difference of emulsion by time step $(T_i - T_{i-1})$. The quantity of latent heat storage of emulsion is calculated by Equation (3). The amount of theoretical latent heat of dispersed water in emulsion is expressed by Equation (4). All condition of this experiment is carried out by C = 5 mass% and m_e = 1.5 kg, so that the theoretical latent heat of test emulsion is calculated Q_{lt} = 25 kJ by using latent heat of ice Q_m = 333.7 kJ/kg. Equation (5) is defined as the latent heat storage rate of emulsion.

$$Q_{tot} = \sum G_a \times C_{pa} \times (T_{ain} - T_{aout}) \quad (1)$$

$$Q_s = \sum C_{pe} \times m_e \times (T_i - T_{i-1}) \quad (2)$$

$$Q_l = Q_{tot} - Q_s \quad (3)$$

$$Q_{lt} = C/100 \times m_e \times Q_m \quad (4)$$

$$\varphi = Q_l / Q_{lt} \times 100 \quad (5)$$

The measurement accuracy of the experiment was authorized in advance by using the silicone oil as the test sample. The accuracy approval experiment of the direct heat exchange method was conducted 6 times by carrying out 10 K temperature rise of the silicone oil. These pre-experimental results showed the calorimetric measurement accuracy ±1.7% of this research of a sensible heat base. It is checked by previous test that the amounts of sample heating by ultrasonic impression (20 seconds), is less than 3% (0.75 kJ) of the latent heat of emulsion.

3. Experimental Results and Discussions

Latent Heat Storage Rate of Test W/O Emulsion

Figure 4 indicates the variation of the quantity of latent heat storage Q_l of test W/O emulsion with the supercooling degree ΔT_{sc} on each cooling rate u_c. The quantity of latent heat storage Q_l of test W/O emulsion increases with increasing of the supercooling degree ΔT_{sc}. The solid line in a figure shows the averaged value by the experimental data of this study. The maximum line and minimum line by an experimental value are shown in the figure with the dashed line. It seems that the correlation with a cooling rate is not seen as for the amount of latent heat storages. A loose increase is observed until the amount of latent heat storages reaches the supercooling degree of about ΔT_{sc} = 3 K. In supercooling degree 3 - 12 K, the rate of increase of the amount of latent heat storages is large.

Figure 5 shows the relationship between the number of freezed waterdrops in test emulsion, that converted from the amount of latent heat storage, and the supercooling degree. The number of freeze waterdrops is increased with increasing of the supercooling degree.

Table 2 is indicated the achievements of passed researches about bulk supercooling water. As for the research on bulk water, the influence about the type of water, the heat transfer surface, the volume, the cooling rate has been considered and the method of supercooling release.

Figure 6 shows the variation of probability of freezing φ with the supercooling degree ΔT_{sc}. Probability of freezing φ is calculated by probability distribution function for the purpose of performing comparison with the data of other researchers about supercooling release of bulk water. The broken and chain lines in a figure show the results of the bulk water of (a) Okawa *et al*.: Electricity (b) Inada *et al*.: Ultrasonic and (c) Inaba *et al*.: Ice nucleating substance. The data of (b) Inada *et al*. is the result of tap water by using the ultrasonic impressing. The data of (c) Inaba *et al*. shows the result of the same heat transfer surface and a cooling rate. The W/O emulsion's probability of freezing φ reaches to about 100% in the supercooling degree ΔT_{sc} of more than 15 K. As compared with the same conditions of bulk water, it is understood that the supercooling degree of a W/O emulsion is large and it is difficult to carry out a latent heat storage.
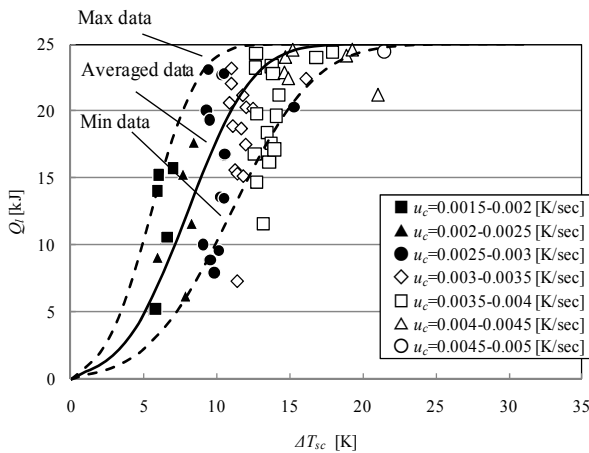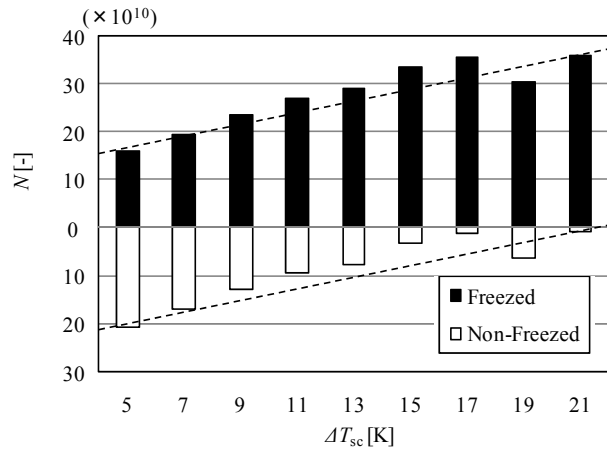
Figure 4. Variation of Q_l with ΔT_{sc}.

Figure 5. Relationship between N and ΔT_{sc}.

Table 2. Achievement of passed researches on bulk water.

	Authors	Ref.	Water type	Heat transfer surface	Vol. cm^3	ΔT_{sc} K	U_c K/sec	Supercooling release method
(a)	Okawa *et al*.	[8]	Pure water	Acrylic/Water	0.005	4 - 6	0.0037	Electricity
(b)	Inada *et al*.	[9]	Tap water	Copper/Water	1.3	1.5 - 4.5	0.039 - 0.049	Ultrasonic
(c)	Inaba *et al*.	[10]	Distilled water	Oil/Water	1.0	2 - 4	0.005 - 0.008	Ice formation
(d)				Oil/Water	1.0	3 - 7	-	Piston
(e)	Hozumi *et al*.	[11]	Ultra pure water	Oil/Water/Oil	0.05	4 - 10	-	Piston
(f)				Polypropylene/Water	1.0	2 - 9	0.0017	Ultrasonic
(g)				Glass/Water	100	3 - 5	-	Waterdrop
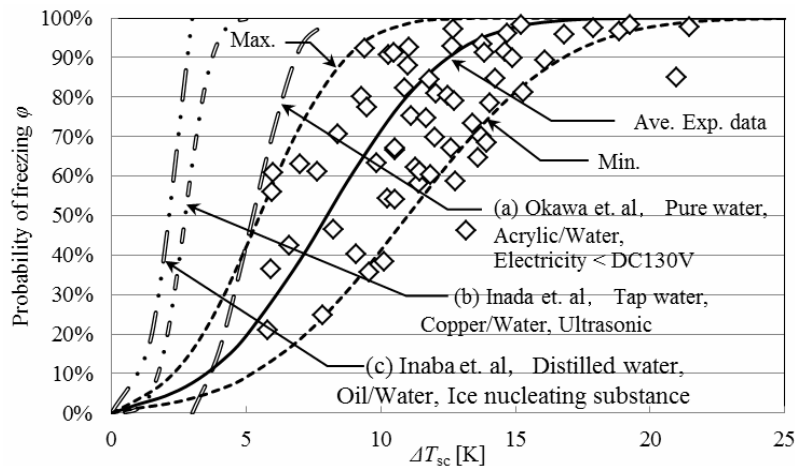
Figure 6. Relationship between φ and ΔT_{sc}.

Figure 7 indicates the relationship between φ and ΔT_{sc} on each experimental condition of impressing or without impressing the ultrasonic. It is clarified that it is possible to reduce 20 K of supercooling degree by impressing the ultrasonic wave.

4. Conclusions

It was performed by experimental study of supercooling release of W/O emulsion by ultrasonic impression, and the following conclusions were obtained:

1) It is suggested that the W/O emulsion's probability of freezing by using ultrasonic reaches to about 100% in the supercooling degree of more than 15 K.

2) It is clarified that as compared with the same conditions of bulk water, the supercooling degree of a W/O emulsion is large.
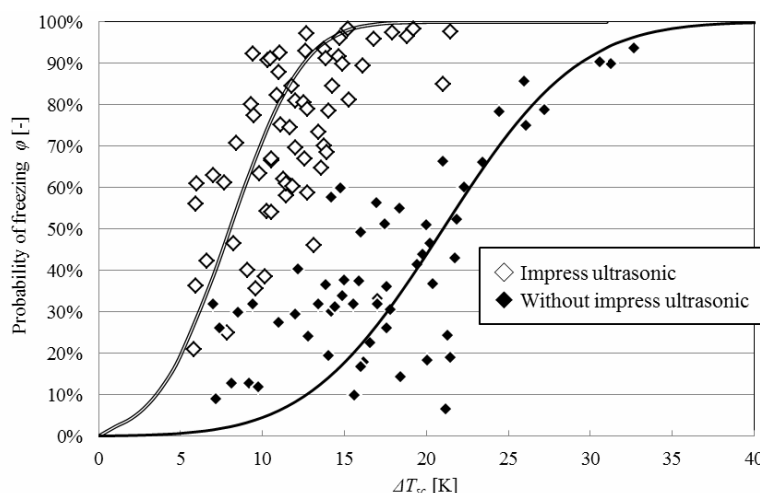
Figure 7. Variation of φ with ΔT_{sc}.

It is revealed that ultrasonic impression is the method of supercooling release of W/O emulsion.

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