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Study on natural convection characteristics of oil/water emulsions inside a rectangular vessel with vertical heating/cooling walls

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ABSTRACT

Emulsions are mixtures of two immiscible liquids, which are important in various fields such as the food, cosmetics, and pharmaceutical industries. In industrial situations, natural convection may occur inside an emulsion owing to the temperature differences in the emulsion manufacturing and storage processes. Therefore, it is important to understand the natural convection characteristics of an emulsion for effective design of such systems. In the present study, oil-in-water (O/W) emulsions were prepared and the natural convection characteristics of the oil particles of the emulsions inside a rectangular vessel heated from one vertical wall and cooled from the opposite wall were investigated experimentally. Silicone oil was used as the dispersed phase of the O/W emulsion. The test samples were prepared with various oil particle sizes and oil volume fractions. We found that multiple convection layers formed inside the emulsion depending on the wall temperature difference, oil particle size, and oil volume fraction. Furthermore, the Nusselt number of an emulsion with a high oil volume fraction was higher than that of a single-phase fluid.

1. Introduction

An emulsion is a two-phase dispersed system in which two immiscible liquids are mixed by the action of a surfactant and one liquid is dispersed in the other liquid as small particles. Oil-in-water emulsions (O/W emulsions) are a common type of emulsion, which are used in various fields, such as the food, cosmetic, and pharmaceutical industries [1–3]. Furthermore, in recent years, it has become possible to use O/W emulsions as a heat storage medium with a certain fluidity by dispersing a phase change material with a high thermal storage density in the emulsion. These materials are expected to be regularly used in thermal storage applications [4–8]. Natural convection occurs inside an emulsion owing to the temperature difference between the manufacturing and storage processes of the emulsion (e.g., heat sterilization of milk, heat storage of emulsions). Natural convection of an emulsion is a complicated phenomenon in which convection is combined with floatation or sedimentation of a dispersed phase owing to differences in the density between the continuous phase and the dispersed phase, temperature differences, and convection caused by differences in the concentrations of particles.

Studies on natural convection in a two-phase dispersion fluid have mainly focused on natural convection of a water-solid fine particle suspension. Okada et al. [9] investigated natural convection of a suspension containing water and glass beads, and they found that multiple convection layers were formed inside the suspension and clarified the conditions leading to formation of a convection layer in a rectangular vessel. Khalil et al. [10] performed numerical analysis of the natural convection heat transfer of a nanofluid with nano-sized solid particles in a rectangular vessel. They found that the natural convection heat transfer was promoted by the presence of nanoparticles and they also developed various numerical models. Kang et al. [11] investigated the natural convection of a suspension consisting of water and glass beads with a very narrow particle size distribution and clarified that the convection layer formed by the suspension was affected by the initial particle concentration. Hagiwara et al. [12] investigated natural convection heat transfer of a hydrophilic particle suspension for nuclear waste remediation and evaluated the heat transfer characteristics and velocity profile of the suspension. They reported that the Nusselt number of the suspension depended on the wall temperature difference and particle size. These studies treated the natural convection associated with the sedimentation of dispersed particles. However, the natural convection associated with floating of dispersed particles has not been adequately determined. In a system based on an O/W emulsion, a buoyancy force acts on the oil particles because the density of oil is generally lower than that of water. A better understanding of the natural convection mechanisms of

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Nomenclature

A	surface area [m^2]
c_p	specific heat [J/(kg·°C)]
d	particle diameter [m]
h	heat transfer coefficient [W/(m^2·°C)]
H	height of the rectangular vessel [m]
HLB	HLB value [–]
k	thermal conductivity [W/(m·°C)]
m	mass [kg]
Nu	Nusselt number [–]
Pr	Prandtl number [–]
Q	applied heat [J]
Ra	Rayleigh number [–]
T	temperature [°C]
W	distance between the heating and cooling wall [m]
x	position from heating wall [m]
y	position from bottom of the rectangular vessel [m]

Greek symbols

ΔT	temperature difference [°C]
ϕ	volume fraction [%]
μ	viscosity [Pa·s]
ρ	density [kg/m^3]

Subscripts

c	cooling wall
d	dispersed phase
e	emulsion
emp	empirical value
exp	experimental value
h	heating wall
m	mean value
mix	mixture of Span 85 and Tween 80
o	oil
S	Span 85
T	Tween 80
w	water

an emulsion and its heat transfer characteristics is important for more effective design of these systems.

The main objective of the present study was to investigate the natural convection characteristics of an emulsion inside a rectangular vessel heated from a vertical wall and cooled from the opposite wall. An O/W emulsion was used as the test sample and silicone oil was used as the dispersed phase of the emulsion. The emulsions were prepared with a variety of oil particle sizes and the oil volume fraction and effects of these parameters on the stratification conditions and heat transfer characteristics of the emulsions were investigated. Furthermore, the wall temperature difference of the rectangular vessel was varied and the effects of the wall temperature difference on these characteristics were also investigated.

2. Experimental apparatus and procedure

2.1. Sample preparation

Generally, emulsions are classified as either W/O (water-in-oil) type or O/W (oil-in-water) types. In this study, O/W type emulsions were used and prepared by mechanical emulsification in which oil droplets were dispersed in water by mechanical shear stress. To prepare an emulsion, a suitable surfactant is also needed. The HLB number (1–20) is used to classify a surfactant's emulsifying characteristics. In general, W/O emulsions are produced from surfactants with a low HLB number, whereas O/W emulsions are produced from surfactants with a high HLB number. Typically, a mixture of surfactants is used to produce stable emulsions, in which case the HLB number can be calculated from the HLB numbers of each surfactant as follows:

$$HLB_{mix} = \frac{m_S HLB_S + m_T HLB_T}{m_S + m_T} \tag{1}$$

The surfactants used in this study were polyoxethylene (20) sorbitan monooleate (Tween80, Wako pure chemical industries) and sorbitan trioleate (Span85, Wako pure chemical industries), which have HLB numbers of 15 and 1.8 respectively. HLB numbers between 8 and 12 are required to form stable O/W emulsions. To achieve a nominal HLB number of 10, a Span85 to Tween80 mass ratio of 1:1.63 was used. The following procedure was used to generate the emulsions. First, water and Tween80 were mixed and agitated at 5000 rpm by a homomixer (HM-310, AS-ONE) for 5 min at 25 °C. Silicone oil with a kinematic viscosity of 100 mm^2/s (ELEMENT14PDMS100-J, Momentive Performance Materials Japan, LLC) and Span85 were then mixed and agitated at 5000 rpm for 5 min. The mixture of oil and Span85 was then slowly poured into the water and Tween80 mixture. The resulting mixture was then agitated at the prescribed stirring speed for 5 min. In this study, both the volume fraction of the oil and mean particle size of the dispersed oil were changed. The mean particle size was varied by changing the stirring speed of the homomixer. Fig. 1 shows the particle size distributions of emulsions with 10 vol% oil prepared at each stirring speed. The particle size distribution was measured with a laser diffraction particle size analyzer (SALD-200V, SHIMADZU). The relative volume fraction represents the percentage of particles having a particle size in a certain range with respect to the entire volume of the whole particle. As shown in Fig. 1, the particle diameter decreased as the stirring speed was increased because the shear stress applied to the oil particles increased at more rapid stirring speeds. The particle diameter was also affected be the oil volume fraction;

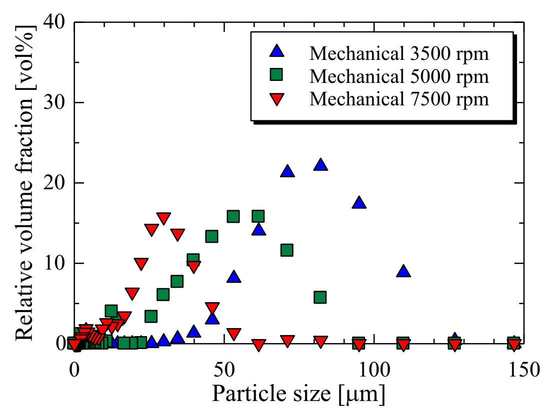

Fig. 1. Particle size distributions of the emulsions prepared at various rotational speeds (ϕ = 10 vol%).