Experimental Thermal and Fluid Science 85 (2017) 201–212

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Hydrodynamics and heat transfer characteristics of oil-in-water emulsion droplets impinging on hot stainless steel foil

Hitoshi Fujimoto *, Wataru Obana [1], Masayoshi Ashida, Takayuki Hama, Hirohiko Takuda

Department of Energy Science and Technology, Graduate School of Energy Science, Kyoto University, Yoshida-honmachi, Sakyo-ku, Kyoto 606-8501, Japan

ARTICLE INFO

Article history:
Received 4 November 2016
Received in revised form 15 February 2017
Accepted 26 February 2017
Available online 28 February 2017

Keywords:
Oil-in-water emulsion
Droplet dynamics
Flow visualization
Boiling heat transfer

ABSTRACT

The hydrodynamics and heat transfer characteristics of oil-in-water (O/W) emulsion droplets impinging on a hot stainless steel foil were investigated experimentally. A two-directional flash-photography technique was adopted to track the time evolution of the droplet shapes. The temperature history of the foil during the collision with the droplets was also measured using a high-speed infrared thermometer. The main objective was to investigate the effects of varying the solid temperature and oil concentration on the heat transfer characteristics. The foil temperature was varied from 140 to 470 °C, and the oil concentration in the O/W emulsion was varied to be 1, 5, and 15 wt%. The impact velocity of the droplets was 1.0 m/s, and the pre-impact diameter of the emulsion droplets was approximately 2.5 mm for oil concentrations of 1 and 5 wt% and 2.4 mm for the oil concentration of 15 wt%. Water and base oil were also used as test liquids for reference. Because the boiling temperature of the oil (~300 °C) is considerably higher than that of water and the thermal conductivity of the base oil is appreciably smaller than that of water, the hydrodynamics and boiling phenomena of droplets are strongly dependent on not only the solid temperature but also the oil concentration. In the nucleate boiling regime, the heat removal increases with the solid temperature, reaches a peak, and then decreases; the peak heat removal depends on the oil concentration. The heat transfer characteristics are discussed in detail in terms of the liquid motion, flow boiling, and local concentration of the oil phase.

1. Introduction

A mixture of two kinds of immiscible liquids, in which one liquid is dispersed in the other liquid, is called an emulsion. Oil and water, with small amounts of surfactants, can form two types of emulsions depending on the mixing ratio of these liquids. One type is the water-in-oil emulsion, wherein oil is the continuous phase and small water droplets are dispersed in the oil. The other is the oil-in-water (O/W) emulsion, wherein oil droplets are dispersed in water. Fig. 1 shows a schematic of the O/W emulsion. Water and oil phases are combined using a surfactant that contains both hydrophilic and lipophilic groups [1]. The small oil droplets in the emulsion are kept in a metastable dispersed state because of the presence of the surfactant.

The lubricating properties of emulsion liquids have been extensively studied by researchers and engineers in the field of tribology [1–3]. Emulsions composed of water and oil are employed as the metalworking fluid in various operations such as rolling, cutting, ironing, and grinding [1–5]. In steel-making industries, spray jet impingement of O/W emulsions is widely used in cold rolling mills for lubrication and cooling. O/W emulsions are also utilized in hot and cold rolling mills in aluminum-making industries. In these processes, the oil phase in the O/W emulsion works as a lubricant for reducing the frictional forces between work rolls and rolled materials. O/W emulsions also remove the frictional and processing heat generated by the plastic deformation of rolled materials. This cooling process is of great importance for preventing “heat scratches” formed on the material surfaces [4] and reducing unwanted local thermal expansion/contraction of work rolls. The heat transfer characteristics of emulsion spray jets impinging on a hot solid play an important role in determining engineering demands [5]. However, to date, cooling conditions have been empirically determined without understanding the flow motion of the relevant emulsions in detail.

The impact of droplets impinging on a hot solid is an important component of the process of spray jet impingement. In conjunction with their hydrodynamic behavior, the heat transfer characteristics of individual droplets on a hot solid must be well understood to build more accurate numerical models for predicting heat transfer

* Corresponding author.
E-mail address: h-fujimoto@energy.kyoto-u.ac.jp (H. Fujimoto).
[1] Present address: JFE Steel Corporation, 1 Kawasaki-cho, Chuo-ku, Chiba 260-0835, Japan.

http://dx.doi.org/10.1016/j.expthermflusci.2017.02.024
0894-1777/

Nomenclature

A	area, m^2
c	specific heat, J/(kg·K)
d	foil thickness, m
d_p	pre-impact diameter of droplet, m
N	number of runs
q	heat flux, W/m^2
$\bar{q}$	time-averaged heat flux, W/m^2
t	time, s
T_m	measured foil temperature, °C
T_w	initial foil temperature, °C
υ	impact velocity of droplet, m/s

Greek symbols

ΔT	temperature decrease °C
λ	thermal conductivity, W/(m·K)
ρ	substrate density, kg/m^3
σ	error range, °C

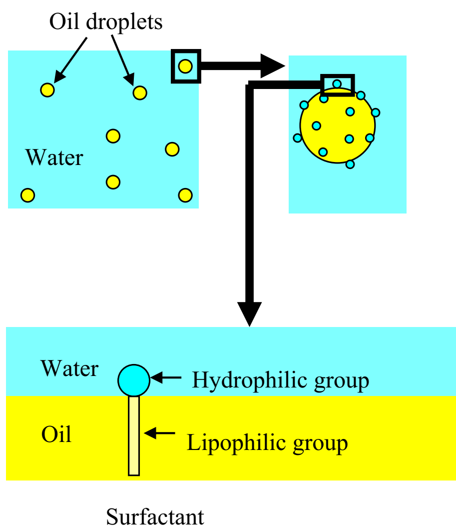

Fig. 1. Schematic of oil-in-water (O/W) emulsion.

rates. Numerous studies have been conducted on droplet–substrate collisions, and some excellent reviews have also been published [6–11]. Several research groups have measured the conjugate heat transfer of droplets and a hot substrate, incorporating photographic observation of the liquid motion, using single-component liquids like water or fuel [12–16]. However, an extensive literature survey produced no similar works that have been published on O/W emulsions. Addressing this deficiency is the primary objective of the present study.

Prior fundamental works reported that several parameters significantly influence the evaporation behavior of emulsion droplets on a hot solid. Some of the prior works studied water-in-fuel emulsions for combustion engine applications. Kimoto et al. [17] observed the vaporizing behavior of emulsified fuel droplets on a hot brass surface. They found that the size of the water droplets in the emulsion played an important role in determining the characteristics of the boiling phenomena of the droplets. Avedisian and Fatehi [18] reported on the evaporation characteristics of water-in-heptane and water-in-decane emulsion droplets with diameters of approximately 3 mm on a hot polished stainless steel surface at 292–407 °C. The droplet evaporation depended significantly on the temperature of the solid and the emulsion components.

In another prior work related to the present study, Prunet-Foch et al. [19] investigated the impact of 2.7-mm-diameter O/W emulsion droplets impinging at a velocity of 3.5 m/s onto a stainless steel surface. They showed that the splash and fingering phenomena of emulsion droplets differ from those of water and are significantly influenced by the roughness of the solid and the type of organic coating on the solid surface. These researchers discussed their results not only from the hydrodynamic aspect, but also from the physicochemical aspect, considering that the emulsion has two constituents with different adherence characteristics in the dispersed system.

Takashima and Shiota [20] studied the evaporation characteristics of O/W emulsion droplets on a hot brass surface and reported that the evaporation behavior of the droplets depended not only on the mixing ratio of the water and oil but also on the solid temperature. Nagai et al. [21] investigated the deformation and oil adhesion characteristics of an O/W emulsion impinging on a hot aluminum solid in a die casting process. They found that the Leidenfrost temperature was not strongly affected by the droplet impact velocity but was significantly affected by the oil concentration and liquid temperature. Furthermore, they clarified that liquid–solid contact certainly occurred even at surface temperatures higher than the Leidenfrost temperature.

These works reveal that the evaporation/boiling behavior and flow motion of emulsion droplets on a hot solid is affected by various factors such as the emulsion components, oil concentration, and solid surface conditions, including solid temperature. However, the published literature includes few experimental works on emulsion droplet impact characteristics. Therefore, more studies are needed to understand the fundamental principles of the heat transfer characteristics between a hot solid and emulsion droplets.

In the present study, the hydrodynamics and heat transfer characteristics of O/W emulsion droplets impinging on a hot stainless steel foil were studied by means of flash photography and transient foil temperature measurements. In the experiments, a two-directional flash-photography technique was adopted for observing the motion of the droplets [22]. The time history of the solid temperature during the collision with the droplets was measured by a high-speed quantum-type infrared thermometer from behind the foil.

The oil concentration in the emulsion and the solid temperature were systematically varied. The composition of the base oil was 95.0 wt% mineral oil and 5.0 wt% emulsifier, which is commonly used in actual metal sheet-rolling processes. The oil concentration in the O/W emulsion was varied to be 1, 5, and 15 wt%, and water and base oil droplets were also tested for reference. The boiling temperature of the base oil (~300 °C) is considerably higher than that of water, and the thermophysical properties of the test liquids are strongly dependent on the oil concentration, as listed in Table 1. A stainless steel foil with a thickness of 0.1 mm was used as the test substrate. The initial solid temperature was varied from 140 to 470 °C. It is found that the deformation behavior and boiling phenomena of the emulsion droplets are strongly influenced by the solid temperature and oil concentration. The heat transfer characteristics are discussed in detail in terms of the liquid motion, flow boiling, and local oil concentration.