International Journal of Heat and Mass Transfer 118 (2018) 1160–1168

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Dynamic Leidenfrost temperature increase of impacting droplets containing high-alcohol surfactant

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ARTICLE INFO

Article history:
Received 5 August 2017
Received in revised form 25 October 2017
Accepted 18 November 2017
Available online 22 November 2017

Keywords:
Droplet impact
High-alcohol surfactant
Surface tension
Dynamic Leidenfrost temperature
Spreading dynamics

ABSTRACT

Methods to avoid the dynamic Leidenfrost effect are of great importance for high heat flux spray cooling which needs an efficient contact of liquid and superheated surface. In this paper, a novel method of increasing dynamic Leidenfrost temperature is proposed through addition of high-alcohol surfactant (HAS). Effects of 1-Octanol and 2-ethyl-hexanol surfactants on dynamic Leidenfrost temperature and spreading dynamic of droplets impacting on superheated surface were investigated for the first time using high-speed photography. Empirical correlations of dynamic Leidenfrost temperature and maximum spreading factor were obtained based on our experimental data. A possible explanation for the dynamic Leidenfrost temperature increase caused by HAS was proposed based on bubble bursting and bubble coalescence. The results show that dynamic Leidenfrost temperature is significantly increased by addition of HAS because of surface tension reduction. The empirical correlations of dynamic Leidenfrost temperature and maximum spreading factor show good agreement with maximum error of 5% and 10% respectively. These empirical correlations could provide reference value for the future research.

1. Introduction

Spray cooling and flash evaporation cooling [1,2] have attracted widespread attentions since they are effective heat removal technologies with high heat flux capacity. The cooling process is extremely complex involving numerous phenomena such as droplet impact, film convection and bubble boiling, however the underlying mechanism of these phenomena are poorly understood. Droplet impacting on hot solid surface plays a very important role during spray cooling process [3,4], and has attracted continuous research due to its relevance to a large number of applications, such as metal processing, fuel injection and fire suppression. Though there has been extensive research on droplet impact, many aspects of this phenomenon are still far from been fully understood due to the complexity of the phenomena involved [5].

To ensure the effective heat transfer of spray cooling and flash evaporation cooling, it requires the effective contact of the liquid and the hot surface. However, when the surface temperature is too high, a vapor layer forms immediately under the droplet and prevents the droplet making further contact with surface. This phenomenon is the so-called dynamic Leidenfrost effect [6,7], and the minimum surface temperature at which the impacting droplet bouncing without splashing is identified as dynamic Leidenfrost temperature (T_{DL}) [8]. Due to the poor thermal conductivity of vapor layer, the heat transfer is significantly reduced. Thus, efforts to avoid the Leidenfrost effect are of great importance for improving spray cooling heat transfer.

Many researchers have studied methods of increasing dynamic Leidenfrost temperature, such as modified surface structure [9-13], electrostatic suppression [14], and low frequency vibration [15]. Among these methods, modified surface structure has received much attention. However, this method was not suitable for many applications in which the surface features are fixed such as metal processing. As a more convenient method, modifying the liquid property by additive is rare to be seen. Only Bertola et al. [16–18] experimentally investigated the T_{DL} of water droplets containing polymer additives and found that 200 ppm polyethylene oxide could reduce T_{DL} of water droplets by 60 °C. As a reference, the effect of additives on static Leidenfrost temperature (T_{SL}) have been studied by many researchers. Huang et al. [19] increased T_{SL} by addition of dissolved salt and explained the increase effect by bubble coalescence suppression and salt deposition. Nagai et al. [20] increased T_{SL} by adding emulsions into water and explained the increase effect caused by surface tension decrease. But there have been disparate conclusions regarding the effect of surfactant.

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https://doi.org/10.1016/j.ijheatmasstransfer.2017.11.100
0017-9310/

Nomenclature

D_0	droplet initial diameter, m
D	spreading diameter, m
D_m	maximum spreading diameter, m
d	needle diameter, m
g	acceleration gravity, m/s^2
H	impact height, m
h	disk thickness, m
N	nucleation site number
Oh	Ohnesorge number
T_{DL}	dynamic Leidenfrost temperature, °C
T_{SL}	static Leidenfrost temperature, °C
T_{sur}	surface temperature, °C
T_{sat}	saturation temperature, °C
V	droplet impact velocity, m/s
We	Webber number

Greek letters

ρ_l	liquid density, kg/m^3
ρ_v	vapor density, kg/m^3
σ	surface tension, N/m
β	spreading factor
β_m	maximum spreading factor
θ	contact angle

Contrary to Nagai's conclusion, Qiao et al. [21] found that both T_{SL} and surface tension of water droplets were decreased by adding SDS. Thus, whether the surfactant could increase the T_{DL} of water droplets or not needs further study and new surfactant with better performance is need urgently.

In our previous researches, high-alcohol surfactant (HAS) such as 1-Octanol and 2-ethyl-hexanol (2EH) was innovatively proposed to improve spray cooling heat transfer [22,23]. It was concluded that trace amount of 1-Octanol and 2EH could significantly enhance spray cooling heat transfer [22–24]. Also, 1-Octanol and 2EH could significantly enhance the heat and mass transfer of LiBr absorption chiller [25,26]. What's more, compared with dissolved salt additives, HAS could avoid nozzle clogging and devices corrosion. Thus, HAS is a superior choice for heat transfer enhancement due to advantages of little additive amount and higher compatibility with devices. So, what is the effect of HAS on the dynamic behavior and T_{DL} of water droplets? This issue is of great importance for spray cooling and flash evaporation cooling heat transfer enhancement. However, no public literature is found concerning the effect of HAS on dynamic Leidenfrost effect at present.

To solve above problems, the present work is aimed at investigating the effect of HAS (1-Octanol and 2EH) on droplet behavior impacting on superheated surface, including the dynamic Leidenfrost effect and the spreading dynamic. The T_{DL} and maximum spreading factor (β_m) of Leidenfrost droplet is determined by high-speed photography. To understand how the surfactant affect the dynamic Leidenfrost effect, the surface tension and viscosity of water containing surfactant are measured. Considering the effect of surface tension and viscosity, Weber number (We) alone is not complete to describe the effect of surfactant, thus Ohnesorge number (Oh) is used to assistant the analysis. Then, the dependence of T_{DL} and β_m on We and Oh is studied, and the corresponding empirical correlations are obtained. Finally, a possible explanation for the increase effect of HAS on the T_{DL} is proposed based on bubble bursting and bubble coalescence.

2. Experimental system

2.1. System description

The experimental setup is illustrated in Fig. 1. Droplets are released from a syringe needle with inside diameter of 0.5 mm and then impact on the hot surface. The hot surface is the upper surface of a copper block (40 mm in length, 40 mm in width and 20 mm in thickness). The needle is positioned above the upper surface of copper block. The impact velocity of the droplet is controlled by varying the needle's height. The heating equipment is provided by Shenzhen Fan and air electronical technology Co. Ltd. Two electric heating rods (total power of 2000 W) are fixed inside the copper block at a distance of 10 mm from the bottom surface and 3 mm from the central axis. A dished groove is scooped in the center of the hot surface to restrict the droplets. The groove is 2 mm in depth and 20 mm in diameter. The temperature of the heated block is regulated by a temperature control system with PID controller and measured by a Type-K thermocouple placed 1 mm below the surface. As the thermocouple is very close to the surface, so the surface temperature is approximately equal to the temperature of thermocouple. The temperature control system keeps the temperature of the copper block at comparatively stable temperatures. The variation of the temperature is controlled within ±1 °C. The impact dynamic and boiling behavior of the droplet are recorded by a high-speed camera (Phantom VEO410) with frame rate of 4000 fps and resolution of 1280 × 800. A LED lamp of maximum 100 W (Superflash LED100A) is placed opposite to the camera to illuminate the droplets. During experiments, the LED lamp is bright enough at brightness of 20%. Thus, the heating effect of the lamp is negligible.

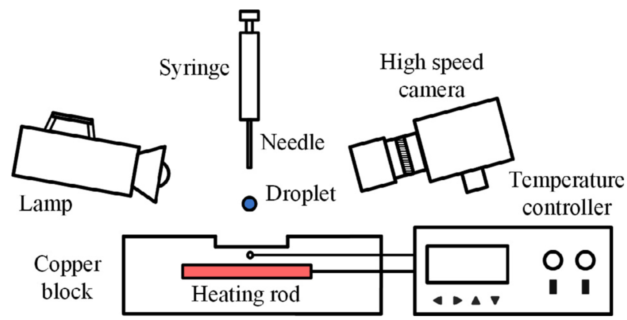

Fig. 1. Schematic diagram of experimental system.

2.2. Procedure

Before experiments, test solutions of water added by 1-Octanol and 2-ethyl-hexanol (2EH) surfactants are prepared with different concentrations from 100 ppm to 1000 ppm. The surface tension and viscosity of surfactant solutions at room temperature are measured by a surface tension meter (Shanghai Fangrui Instrument Co. Ltd) and a viscometer (Brookfield Inc), respectively. It should be noted that the quantity relevant to drop impact is the dynamic surface tension, since the droplet is in non-equilibrium state during the experiments. However, as the maximum falling time and impact time of droplet is less than 110 ms (impact height is 2–6 cm) and Cheng et al. [27] found that the change of dynamic surface tension during the first 110 ms is very small, the static surface tension values are used instead of dynamic surface tension to simplify the analysis. As shown in Fig. 2, the surfactants could dramatically