International Journal of Heat and Mass Transfer 116 (2018) 817–824

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Regimes during single water droplet impacting on hot ethanol surface

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ARTICLE INFO

Article history:
Received 10 April 2017
Received in revised form 4 August 2017
Accepted 10 September 2017
Available online 25 September 2017

Keywords:
Droplet impact
Hot surface
Fire suppression
Water spray

ABSTRACT

In order to deepen the knowledge of the mechanisms of liquid pool fire suppression with water mist/spray, a series of preliminary experiments were carried out for a water droplet impacting upon target liquid surface. Ethanol was chosen as the target liquid and heated to simulate the temperature conditions as it burned. The water droplet used in the experiments was about 2.0 mm with impact Weber number altering from 30 to 695. The results show that three typical impact regimes including crater-jet, penetration and surface bubble are observed. The pool temperature and Weber number have important influences on the impact behaviors and characteristic parameters including the crown height, and the energy conversion rate during the crater evolution and jet evolution. The maximum crown height depends on Weber number but is weakly dependent on the pool temperature. The ratio of the sum of crater potential energy and surface energy to initial impact energy is linearly related to the dimensionless pool temperature. Likewise, for the cases of crater-jet, as the Weber number and pool temperature increase, the conversion rate of crater potential energy and surface energy to jet potential energy and surface energy increases linearly.

1. Introduction

Droplet striking liquid or solid surface has many applications [1–4], such as spray cooling of hot surfaces by impinging liquid droplets, fire suppression by water mist/spray [5], sprinkling irrigation, plasma spraying [6], spray painting/coating, enhancing boiling, and fuel atomization [7]. Fundamental understanding the interaction mechanism of droplet/target surface is very important for these applications.

Droplet interaction with liquid surface has been focused more than one century [8–10]. Over the past thirty years, the subject has been further studied with the development of experimental apparatus such as High Speed Digital Camera and Particle Image Velocimetry. Liow [11] conducted a series of experiments on water droplet impinging onto water surface and plotted the distribution of the impact regimes on a *We-Fr* map ($We = \rho_d v^2 D_d/\sigma_d$, $Fr = v^2/gD_d$). Cole [12] carried out a systematic experiments by using advanced digital video as well as laser technology. A map of phenomena associated with liquid-liquid impact was founded and the impact behaviors were subdivided into several regimes based on Froude number. Both Rein [13] and Yarin [14] performed detailed reviews on this subject and concluded that the outcomes involved bouncing, coalescence, splashing, drop spreading, and jetting for single droplet impinging on a liquid surface. Also, Rein denoted that the mechanism causing the transition among different impact behaviors was not well understood. Recently, Liang et al. [6] published a review on mass and momentum interactions during single droplet impinging onto a liquid film. The paper discussed the formation of the crown sheet, ejecta sheet and splashing for high-velocity impact as well as the phenomena of spreading, coalescence and rebound in low-velocity impact. Morton et al. [15] numerically studied the flow regimes resulting from the impact of single water droplet on a deep water pool at speed in the range of 0.8–2.5 m/s. The results clarified the formation mechanism of bubble during the crater collapse. Zhang et al. [16] used optical and X-ray imaging to record the jet formation process. Two distinct jet including thin, fast and early-emerging ejecta and a slow, thick and late-emerging lamella were observed. Ray et al. [17] investigated the impact behavior of water droplet impinging onto a deep water pool and established a regime map with Weber numbers altering from 50 to 300 and Froude numbers from 25 to 600. Michon et al. [18] experimentally studied the impact phenomena of single droplet impact on a deep pool of the same aqueous liquid. Two different regimes including singular jet and the cavity jet were observed. The jet velocity was proportional to the capillary velocity $\sqrt{\sigma_t/\rho_t D_d}$.

However, all of the above researches were conducted at room temperature. At present, a few investigations focused on single droplet impacting onto a hot liquid surface from fire suppression

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https://doi.org/10.1016/j.ijheatmasstransfer.2017.09.030
0017-9310/

Nomenclature

E	energy
We	droplet Weber number
Fr	droplet Froude number
Re	droplet Reynolds number
θ	non-dimensional pool temperature
T	temperature
D	diameter
R	maximum crater depth
M	droplet mass
g	gravitational acceleration
C	coefficient
n	exponent
W	work
h	height
v	velocity
H	crown height

Greek symbols

χ	ratio of crater potential energy and surface energy to initial impact energy
φ	ratio of the sum of potential energy and surface energy of the jet to that of crater
α	dimensionless crater radius
ζ	axial coordinate of the center of the sphere
δ	surface tension
μ	viscosity
ρ	density
ρ'	ratio of target liquid density to droplet density
σ'	ratio of target liquid surface tension to droplet surface tension

Subscripts

d	droplet liquid
total	total energy
crater	crater potential energy
m	maximum crater depth
t	target liquid
non	non-dimensional crater depth
0	instantaneous state
∞	environmental state
boiling	boiling state
j	liquid column or jet
g-crater	crater Gravitational potential energy
s-crater	crater surface energy
g-jet	jet Gravitational potential energy
s-jet	jet surface energy
others	all of the energy except for potential energy and surface energy

perspective. For instance, Manzello and Yang [19] explored the impingement mechanism of a droplet impacting on a hot liquid surface and found that the pool temperature played an important role on the appearance of splashing, and the critical impact Weber number for splashing decreased with the pool temperature increasing. In addition, Manzello et al. [20] experimentally studied a distill water or HFE-7100 droplet impinging on a heated cooking peanut oil and observed that water droplet fragmented and a vapor explosion occurred when the oil was less than 180 °C for HFE-7100 droplets. Wang et al. [5] investigated single water droplet striking three kinds of fuel surface and pointed out that liquid pool temperature mainly affected the sizes of splashed daughter droplets and the bounced jet height. On this basis, Wang et al. [21] carried out a series of experiments on a water droplet with or without additives impacting upon a hot molten-ghee surface. They stated that the vapor explosion behavior of the water drop with additives would be weaker than that of pure water. Gao et al. [22] experimentally explored the heat transfer of single droplet impinging on a film flow by using an IR camera. They reported that the impact of droplet caused the temperature around the droplet landing location to change.

Although previous studies [5,9–22] have experimentally studied the impact behaviors of single droplet impinging onto a hot liquid surface from fire suppression perspective, how does a water droplet cool the fuel surface, especially what is the behavior when the water droplet impacts on a hot liquid fuel surface, are still not clear. In addition, the ranges of Weber number and pool temperature in previous studies are too small to obtain systematical impact results. In order to deepen the knowledge of fire suppression mechanism of water suppressant, the fuel surface is heated to simulate the temperature conditions as it burns. The impact behaviors are visualized through systematic experiments of single water droplet impacting on a hot ethanol pool, which is widely used in water mist/spray fire extinguishing experiments [5,23,24]. Moreover, the paper provided a global picture of different types of fluid flow in the transitional regime between crater-jet, penetration and surface bubble, and described relationships among them. In quantitative analysis, the influences of liquid pool temperature and droplet impact Weber number on the maximum crown height, and the energy conversion rate during the crater evolution and the jet evolution are discussed detailedly. The results will be helpful to reveal the pool fire suppression mechanism with water mist/spray.

2. Experimental apparatus

Experimental setup used in the experiments is similar to the experimental apparatus of previous studies [25,26], as shown in Fig. 1. The main components include a droplet generator, a container, a heating device, an imaging system and a LED backlighting.

Single water droplet is produced by a droplet generator which is comprised of a syringe and a needle. The water droplet is formed at the needle tip and detaches off under its own weight. The impact velocity is measured by tracking the location of the droplet centroid 1 ms prior to impact, with a measuring accuracy ±0.05 m/s. To obtain different impact Weber numbers, the dropping height between the droplet generator and the liquid surface is varied, thus the droplet impact Weber number is ranging from 30 to 695. The droplet diameter is about 2 mm, which is acquired by pixel analyzing, and the measuring error is 1 pixel with size of 0.025 mm. A commercial heating device is used to heat the target liquid, which is held by a quartz glass container. To monitor the temperature distribution of ethanol pool, five K-type fine thermocouples with an accuracy of ±0.5 °C are placed at 1 mm, 3 mm, 6 mm, 20 mm, and 56 mm beneath the target liquid surface. According to the temperature profile with time, the temperature varied by at most 3 ± 0.5 °C from the pool bottom to the liquid surface. The target liquid temperature is varied from 30 °C to 78 °C. The fuel surface tension and viscosity are measured by QBZY-3 surface tension meter and DV-1 viscometer, respectively, and are displayed in Table 1. Both the instruments are produced by Shanghai FangRui Instrument CO., LTD. The imaging system including a high-speed video camera (Phantom V710) which is produced by America Phantom