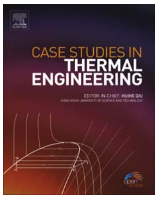
Case Studies in Thermal Engineering 8 (2016) 218–225

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

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



Effects of surface tension and wood surface roughness on impact splash of a pure and multi-component water drop

Meijuan Lan [a,b], Xishi Wang [a,*], Pingping Chen [a], Xiangdi Zhao [c,**]

[a] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei 230026, China
[b] Department of Information Engineering, Zhejiang Institute of Security Technology, Wenzhou 325016, China
[c] State Key Laboratory of Safety and Control for Chemicals, Qingdao 266071, China

ARTICLE INFO

Article history:
Received 9 June 2016
Received in revised form
24 July 2016
Accepted 31 July 2016
Available online 1 August 2016

Keywords:
Splash
Drop impact
Fire suppression
Water mist
Additive

ABSTRACT

Concerning the deeper understanding of the mechanisms on fire suppression with multi-component water mist/spray, the dynamical process of a water drop with or without additives impacting upon wood surfaces is preliminarily studied. The initial diameters of the pure water drop and the water drop with NaCl additive are about 2.4 ± 0.1 mm, and the diameter of the water drop with AFFF (Aqueous Film-Forming Foam) additive is about 1.8 ± 0.1 mm. The drop impact velocities are varied from 1.13 m/s to 2.80 m/s. A Photron FASTCAM high-speed video camera coupled with a Nikon 200 mm micro-lens is used to record the dynamical process of the drop impacting. The results show that the critical impact Weber number of the water drop with additives is obviously larger than that without additives, and the critical impact Weber number increases with decrease of the wood surface roughness. In addition, the current empirical models both on predicting the critical Weber number and the maximum spread factor just partially agree with the experimental results. The current results are limited to the interaction of a single water drop impacting upon a horizontal wood surface.

1. Introduction

Liquid drop impact upon a surface is interesting in a variety of practical applications, such as thermal spray coating by depositing (or propelling) molten droplets onto a substrate, fire suppression by water mist/spray, spray cooling of hot surfaces by impinging liquid droplets, ink-jet printing, spray painting, etc. [1–7]. The fluid dynamical phenomena of liquid drop impact on solid surfaces include spreading, receding, rebounding and splashing [8,9]. The collision of drops impinging onto solid metallic surface, solid and liquid coexist surface, structured rough substrates with grooves, have been widely studied [10–15]. However, most of the above studies mainly focused on drop impact upon metallic surfaces, there is few study focused on drop impact upon wood surfaces, although it may be the key mechanism of an A-type (solid combustible material) fire suppression with water-based agents. Chen et al. [16] and Lan et al. [17] studied the water drop impact on wood surfaces, but they did not consider the effects of additives on water drop impaction.

Water mist has been regarded as a better substitute of conventional means known as halon agents for fire suppression, and the fuel surface/flame cooling being considered as one of the dominant mechanisms [18–20]. There are two phenomena

---

[*] Corresponding author.
[**] Second corresponding author.
E-mail addresses: wxs@ustc.edu.cn (X. Wang), zhaoxd.qday@sinopec.com (X. Zhao).

http://dx.doi.org/10.1016/j.csite.2016.07.006
2214-157X/

Nomenclature

T	temperature (K)
R_a	average surface roughness (μm)
R_0	initial surface roughness (μm)
D	drop diameter (mm)
We	Weber number
Re	Reynolds number
V	drop velocity (m/s)
h	height (m)
g	gravity acceleration (m/s^2)
a	coefficient
b	coefficient
u	drop velocity at x direction (m/s)
v	drop velocity at y direction (m/s)
t^*	dimensionless time after drop impact

Symbols

σ	surface tension (mN/m)
μ	dynamic viscosity (mm/s)
ρ	density (Kg/m^3)
ξ	dimensionless spread factor
ζ	vortices

Subscripts

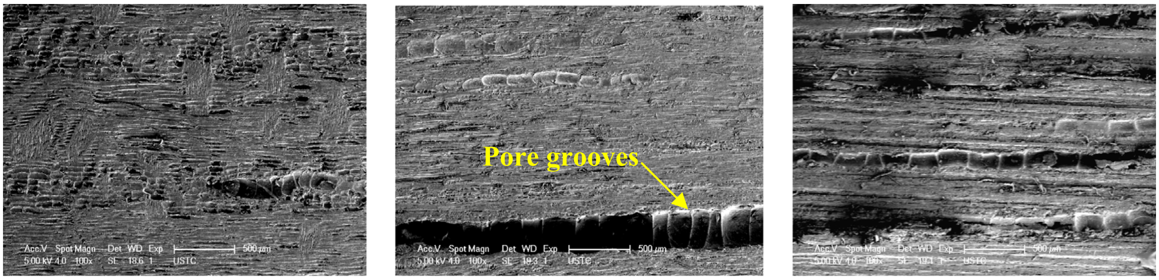
d	drop
g	gas
c	critical
max	maximum
w	wall
0	initial

that limit the efficiency of drop deposition from sprays: splashing and bouncing [21]. If the splashing and bouncing phenomena can be avoided or limited, the efficiency of fire suppression with water-based technologies may be well improved. Many studies had been done to improve the efficiency of the technologies by mixing additives into water [22–24]. Some of the results indicate that the efficiency of fire suppression with water mist or multi-component foam agents can be improved by adding additives with an optimized concentration, especially for wood crib fires. However, the reasons of such improvement and the interaction dynamics of a multi-component water drop impact upon wood surface are still not clear enough. Therefore, the impact process of a pure and multi-component water drop impinging upon different wood surfaces is conducted in this study.

2. Experimental apparatus and test conditions

The experimental apparatus mainly consists of a drop generator system, a 1000 W iodine tungsten filament lamp, and a high speed video camera etc. Water drop was generated at the tip of an injection syringe and detached off the needle under its own weight, and the schematic diagram had been described in detail elsewhere [25]. The drop impacting process was recorded by a Photorn FASTCAM high-speed video camera at 2000 fps with 1024 × 1024 pixels. The average surface roughness (R_a) of the wood surface was measured by a TR240 system with accuracy of 0.001 mm. The liquid viscosity and surface tension were measured by a Brookfield HBDV-II viscometer and a SL201 Surface Tension meter, respectively. A Sirion200 field emission scanning electron microscope (SEM) was used to observe the microstructure of the wood surfaces.

Three kinds of wood, such as paulownia, Fraxinus mandshurica and jatoba are considered, since they are the common combustible materials and widely used for making timber flooring, office furniture, etc. Before the experimental test, the wood blocks were dried to wipe off the water and resin previously. Fig. 1 gives the images of paulownia, Fraxinus mandshurica and jatoba surfaces scanned by SEM. It shows that paulownia block has exquisite surface, Fraxinus mandshurica block has big pore grooves, while jatoba has slimsy pore grooves. The measured basic density and the average surface roughness are listed in Table 1.



Paulownia surface Fraxinus mandshurica surface Jatoba surface

Fig. 1. Microscopic structure images of the three kinds of wood surface.

Table 1
Basic density and average surface roughness of the woods.

Wood type	Basic density (g/cm^3)	R$_a$ (μm)
Paulownia	0.24	3.185
Fraxinus mandshurica	0.56	3.635
Jatoba	0.82	8.347

The initial diameters of the pure water drop and the water drop with 5% NaCl are about 2.4 ± 0.1 mm, while the water drop with 4% AFFF has a relatively smaller diameter of 1.8 ± 0.1 mm due to its small surface tension. NaCl and AFFF are considered as water additives, since they have been tested as additive or agent for fire suppression with better efficiency [24]. The impact velocity of the drop is varied by adjusting the injector height from 6.5 cm to 40 cm and determined with $V_0 = \sqrt{2gh}$ [26]. The temperature and the humidity of the environment are 298 K and 65%, respectively. The detail parameters of the drop, such as its diameter, viscosity, surface tension are given in Table 2.

3. Results and discussions

3.1. Effects of surface tension on We_c

The critical Weber number, We_c, has been used to distinguish the phenomena of splash, i.e., shoot one or several daughter droplets, as a liquid drop impacts upon a surface. Fig. 2 shows the impact patterns of different water drops impinging on paulownia, Fraxinus mandshurica and jatoba wood block surfaces. It can be seen that the pure water drop has relatively small critical Weber number. For instance, splash start to occur when the pure water drop with $We = 129$ impact upon Fraxinus mandshurica and jatoba surfaces, while there is no splash occur to the cases with 5% NaCl or 4% AFFF water drop, even their Weber number increase to 187 and 350, respectively. The main reason is that the later two have relative small surface tension and the paulownia has the smallest basic density (see Tables 1 and 2). It is well known that the increase of surface tension will directly cause the increase of the contact angle. Thus, to the cases with larger surface tension, the impact splash would be easier occur because the upward velocity component of the liquid flow would be larger.

Brazier-Smith et al. [27] developed an empirical formula to predict the critical Weber number on smooth surface as,

$$We_c = \begin{cases} 2.5 \times 10^3 (d^*)^{-0.2}, & T_w \le 1000 \\ 7.9 \times 10^{10} (d^*)^{-1.4}, & T_w > 1000 \end{cases} \tag{1}$$

where T_w is the wall temperature, here is the wood surface temperature, d^* can be determined as,

$$d^* = \frac{\rho_d D_0 \sigma}{\mu_d^2} \tag{2}$$

Table 3 gives We_c obtained with both of experiment and calculation by Eq. (1). It indicates that the calculated results are quite different from the experimentally determined one. The main reasons are that the Brazier-Smith formula only considered the effects of the liquid properties, it did not consider the properties of the solid surface, especially the basic density and the roughness of the surface, which will be discussed in next part.

3.2. Effects of surface roughness on We_c

As discussed above, the effects of the wood surface properties should be considered, especially its surface roughness and density need to be considered when a liquid drop impact upon a wood surface. Stow and Hadfield [28] studied experimentally the splashing of a drop on dry, rough surfaces, and described their results by means of an empirical

Table 2
Initial diameter, viscosity and surface tension of the drops.

Drop type	Drop diameter (mm)	Viscosity (mm^2/s) (at 298 K)	Surface tension (mN/m)	Density (kg/m^3)
Pure water	2.4 ± 0.1	1.004	72.0	1.0×10^3
With 5% NaCl	2.4 ± 0.1	1.043	59.4	0.945×10^3
With 4% AFFF	1.8 ± 0.1	1.205	20.1	0.996×10^3

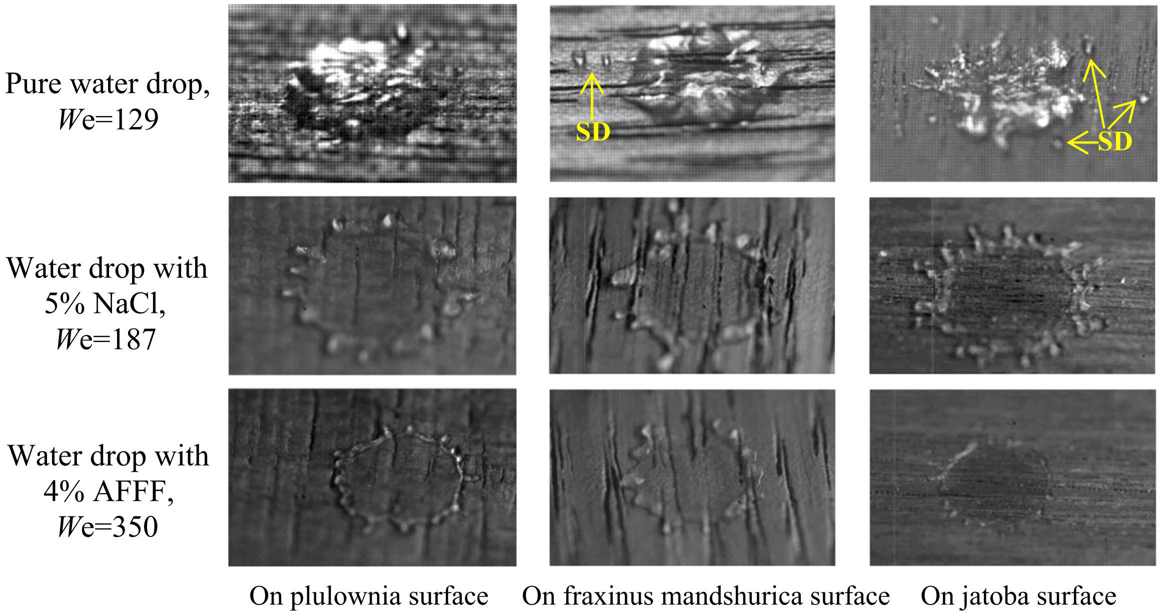


Fig. 2. Patterns of the drop impact on different wood surfaces. (SD: shoot one or several daughter droplets).

Table 3
We_c of the drops determined experimentally and compared with Brazier-Smith formula.

Drop type	We_c			
	Calculated with Brazier-Smith formula	Determined with experimental data		
		On plulownia surface	On Fraxinus mandshurica surface	On jatoba surface
Pure	water	224	258	161
	129	With 5% NaCl	239	305
225	187			
With 4% AFFF	330	437	402	350

formula:

$$R_0 u_0^{1.69} = S_T(R_a) \quad (3)$$

where S_T, the critical value of the product for a drop to splash, depends on the arithmetic roughness R_a. In a next step they rewrote the Eq. (3) in terms of critical Weber number We_c, and Reynolds number Re_c:

$$\mathrm{Re}_c^{0.31} We_c^{0.69} = \xi(R_a) \quad (4)$$

According to the authors, the value of this splashing number decreases if R_a increases, but they did not detail its variation in their work. For the cases with small Ohnesorge numbers, the influence of viscosity effects is small and can thus be neglected, then the Stow and Hadfield formula can be improved as [29],

$$We_c = a\log^b\left(\frac{R_0}{R_a}\right) \quad (5)$$

This equation means that the critical Weber number for splashing is a logarithmic function of the initial drop radius and the roughness of the impacting surface. The values of a and b can be obtained by fitting this formula to the experimental data with least-squares method.

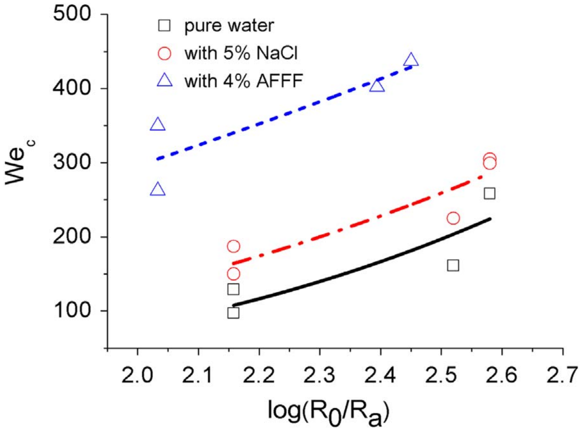


Fig. 3. Critical Weber number for splashing of a drop impact on different wood surfaces.

Fig. 3 indicates that the impact splash of a water drop with additives is obviously influenced by the roughness of the wood surfaces, i.e., We_c increases as R_a decreases. The tendency agrees with the results calculated by Eq. (5), where the value of the coefficients a and b are different for different wood surfaces. It should be noted that obvious differences still exist between the experimental data and the calculated results. The reasons may be that only the effects of surface roughness are considered, whereas the basic density of the wood surface, and the diameter, Weber number, surface tension of the liquid drop, should also be considered.

3.3. *Effects of impact kinetic energy on* We_c

In earlier studies, it has been found that the maximum spread factor has little dependence on the contact angles for flows with $Re > 10$, so in order to study the effects of the manner of the dissipation of impact kinetic energy on We_c, Gupta and Kumar [26] predicted the splash of an impacting droplet through considering the energy balance, where the energy equation was simplified as,

$$\frac{3(\xi_{\max}^2 - 12)}{We} + \frac{9\xi_{\max}^4}{2\mathrm{Re}} = \frac{\rho_d - \rho_g}{\rho_d} \tag{6}$$

where $We = \frac{\rho_d V_0^2 D_0}{\sigma}$, $\mathrm{Re} = \frac{\rho_d V_0 D_0}{\mu}$, $\xi_{\max} = \frac{D_{\max}}{D_0}$.

For the cases when

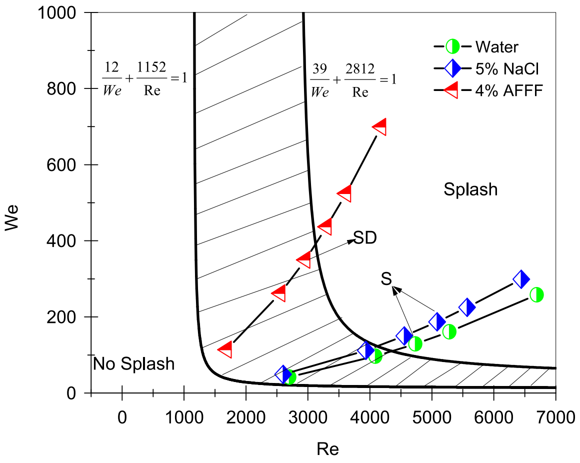
$$\frac{\rho_d}{\rho_d - \rho_g}\left(\frac{3\left(\xi_{\max}^2 - 12\right)}{We} + \frac{9\xi_{\max}^4}{2\mathrm{Re}}\right) > 1,$$

the spreading film will reach a maximum diameter without breaking up into daughter droplets, whereas when

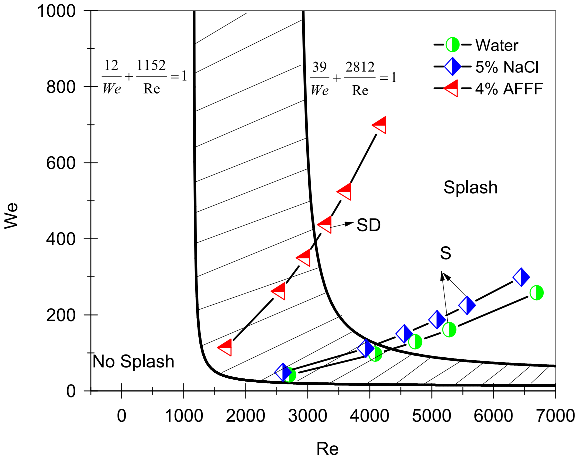
$$\frac{\rho_d}{\rho_d - \rho_g}\left(\frac{3\left(\xi_{\max}^2 - 12\right)}{We} + \frac{9\xi_{\max}^4}{2\mathrm{Re}}\right) < 1,$$

the spreading film will break into smaller drops when the maximum diameter has been reached. From different experiments, the maximum spread factor at breakup has been found to be between 4 and 5 [9].

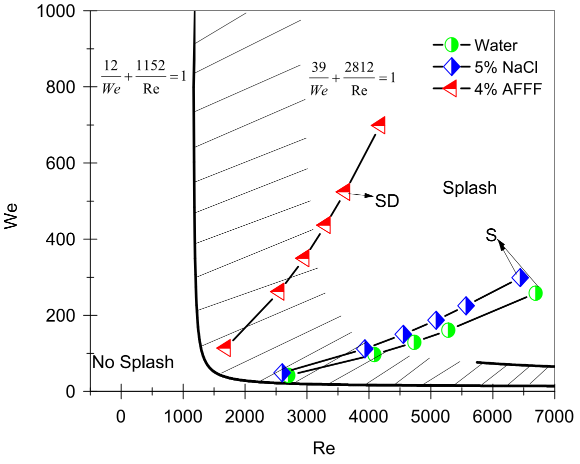
Using these values in Eq. (6), for the maximum spread factor at breakup, the analytical expression reduces to $12/We + 1152/\mathrm{Re} = 1$ for $\xi_{\max} = 4$ and $39/We + 2812/\mathrm{Re} = 1$ for $\xi_{\max} = 5$. Fig. 4 gives the comparison between the experimental data and the calculated results via this equation. The hatched area between the curves may be considered the region where the drop may or may not breakup after reaching the maximum spread factor. On the left side of the region, the drop will never breakup. On the right side of the region, the drop will always breakup. It can be seen that the experimental results of a pure water drop and the water drop with 5% NaCl additive impact on paulownia surface agree well with the calculated one, while obvious differences exist to Fraxinus mandshurica and jatoba surfaces. In the cases of water drop with 4% AFFF, there is no obvious splashing. This may be mainly caused by the small surface tension which usually leads $\xi_{\max}$ to increase as shown in Fig. 5.



(a) On paulownia surface



(b) On fraxinus mandshurica surface



(c) On jatoba surface

Fig. 4. Comparison of the critical Weber number for splash of the drop impact upon different wood surfaces. (Note: “SD” refers to shoot one daughter droplet, “S” refers to shoot several daughter droplets).

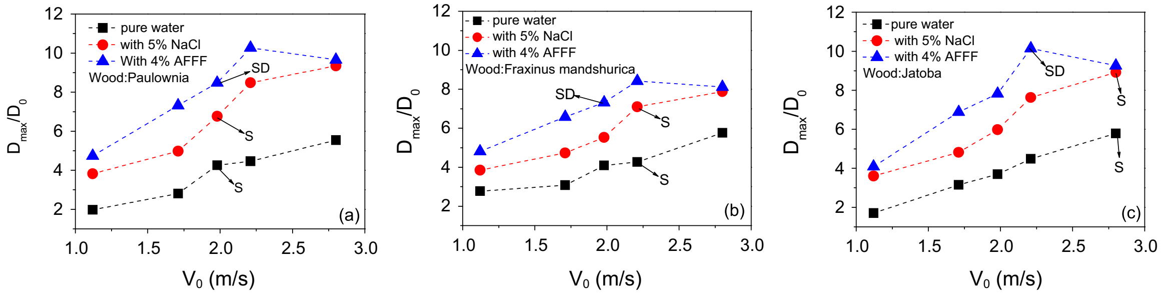


Fig. 5. Maximal spread factor of drop impacting on different wood surfaces. (Note: "SD" refers to shoot one daughter droplet, "S" refers to shoot several daughter droplets).

4. Conclusions

The experimental study on the impact of a water drop with additives on different wood surfaces has been performed. Following conclusions can be drawn:

1) The additives being considered obviously affect the critical Weber number for drop splash when it impacts upon wood surfaces, the smaller the drop surface tension is, the larger the critical Weber number will be.
2) The impact splash of a water drop with additives is obviously influenced by the roughness of the wood surfaces, i.e., We_c increases as R_a decreases.
3) The empirical models on predicting the critical Weber number and maximum spread factor just partially agree with the experimental results of a pure water drop and the water drop with 5% NaCl additive.

The current results are limited to the interaction of a single water drop impacting upon a horizontal wood surface, and future study would be focused on improving the model by considering the effects of not only the drop liquid properties, but the surface roughness, wettability, temperature and basic density of the wood surfaces, etc.

Acknowledgments

The authors appreciate the support of the National Key Technology Support Program of China (Grant no. 2015BAK37B03), the Natural Science Foundation of Anhui Province (Grant no. 1408085MKL95), and the open project program of the State Key Laboratory of Safety and Control for Chemicals (Grant no. 10010104-15-ZC0613-0114).

References

[1] M. Rein, Phenomena of liquid drop impact on solid and liquid surfaces, Fluid Dyn. Res. 12 (1993) 61–93.
[2] X.S. Wang, G.X. Liao, B. Yao, W.C. Fan, X.P. Wu, Preliminary study on the interaction of water mist with pool fires, J. Fire Sci. 19 (2001) 45–61.
[3] C. Ukiwe, A. Mansouri, D.Y. Kwok, The dynamics of impacting water droplets on alkanethiol self-assembled monolayers with co-adsorbed CH_3 and CO_2H terminal groups, J. Colloid Interface Sci. 285 (2005) 760–768.
[4] S.F. Lunkad, V.V. Buwa, K.D.P. Nigam, Numerical simulation of drop impact and spreading on horizontal and inclined surfaces, Chem. Eng. Sci. 62 (2007) 7214–7224.
[5] M. Marengo, C. Antonini, Roisman IV, C. Tropea, Drop collisions with simple and complex surfaces, Curr. Opin. Colloid Interface Sci. 16 (2011) 292–302.
[6] C. Antonini, A. Amirfazli, M. Marengo, Drop impact and wettability: from hydrophilic to superhydrophobic surfaces, Phys. Fluids 24 (2012) 677–686.
[7] B. Yildirim, S. Müftü, Simulation and analysis of the impact of micro-scale particles onto a rough surface, Int. J. Solids Struct. 49 (2012) 1375–1386.
[8] S.D. Aziz, S. Chandra, Impact, recoil and splashing of molten metal droplets, Int. J. Heat Mass Transf. 43 (2000) 2841–2857.
[9] A.L. Yarin, Drop impact dynamics: splashing, spreading, receding, bouncing, Annu. Rev. Fluid Mech. 38 (2006) 159–192.
[10] S.D. Aziz, S. Chandra, Impact, recoil and splashing of molten metal droplets, Int. J. Heat Mass Transf. 43 (2000) 2841–2857.
[11] J. Bico, U. Thiele, D. Quere, Wetting of textured surfaces, Colloids Surf. A 206 (2002) 41–46.
[12] F.J. Hong, H.H. Qiu, Modeling of substrate remelting, flow, and resolidification in microcasting, Numer. Heat Transf. A 48 (2005) 987–1008.
[13] D. Sivakumar, K. Katagiri, T. Sato, H. Nishiyama, Spreading behavior of an impacting drop on a structured rough surface, Phys. Fluid 17 (2005) 100608–100618.
[14] W. Wang, F.J. Hong, H.H. Qiu, The impact of thermal contact resistance on the spreading and solidification of a droplet on a substrate, Heat Transf. Eng. 27 (2006) 68–80.
[15] M. Henrikki, F. Robert, I. Olli, R.H.A. Ras, Rebounding droplet-droplet collisions on superhydrophobic surfaces: from the phenomenon to droplet logic, Adv. Mater. 24 (2012) 5738–5743.
[16] P.P. Chen, X.S. Wang, Experimental study of water drop impact on wood surfaces, Int. J. Heat Mass Transf. 54 (2011) 4143–4147.
[17] M. Lan, X.S. Wang, A case study on the dynamic process of water drop impacting on heated wood surface, Case Stud. Therm. Eng. 2 (2014) 23–28.
[18] J.R. Mawhinney, J.K. Richardson, A review of water mist fire suppression research and development, Fire Technol. 1 (1997) 54–90.
[19] M.B. Kim, Y.J. Jang, M.O. Yoon, Extinction limit of a pool fire with a water mist, Fire Saf. J. 28 (1997) 295–306.
[20] X.S. Wang, G.X. Liao, J. Qin, W.C. Fan, Experimental study on effectiveness of extinction of a pool fire with water mist, J. Fire Sci. 20 (2002) 279–295.
[21] A. Mounir, B. Denis, W. Gerard, B. Daniel, R. Salima, Impact dynamics of surfactant laden drops: dynamic surface tension effects, Exp. Fluids 48 (2010) 49–57.

[22] Z. Jiang, W.K. Chow, J. Tang, S.F. Li, Preliminary study on the suppression chemistry of water mists on poly(methyl methacrylate) flames, Polym. Degrad. Stab. 86 (2004) 293–300.

[23] X.M. Zhou, G.X. Liao, B. Cai, Improvement of water mist's fire-extinguishing efficiency with MC additive, Fire Saf. J. 44 (2006) 39–45.

[24] X.S. Wang, Y.J. Liao, L. Lin, Experimental study on fire extinguishing with a newly prepared multi-component compressed air foam, Chin. Sci. Bull. 54 (2009) 492–496.

[25] X.S. Wang, X.D. Zhao, Y. Zhang, X. Cai, R. Gu, H.L. Xu, G.X. Liao, Experimental study on the interaction of a water drop impacting on hot liquid surfaces, J. Fire Sci. 27 (2009) 545–559.

[26] A. Gupta, R. Kumar, Droplet impingement and breakup on a dry surface, Comput. Fluids 39 (2010) 1696–1703.

[27] P.R. Brazier-Smith, S.G. Jennings, The interaction of falling water drops: Coalescence, Proc. R. Soc. Lond. Ser. A 326 (1972) 393–408.

[28] C.D. Stow, M.G. Hadfield, An experimental investigation of fluid flow resulting from the impact of a water drop with an unyielding dry surface, Proc. R. Soc. Lond. 373 (1981) 419–441.

[29] R. Kai, F. Francois, Influence of surface roughness on liquid drop impact, J. Colloid Interface Sci. 203 (1998) 16–30.