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International Journal of Heat and Mass Transfer 50 (2007) 5328–5333

International Journal of HEAT and MASS TRANSFER

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Technical Note

A model for droplet evaporation near Leidenfrost point

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Received 1 September 2006; received in revised form 15 March 2007
Available online 25 May 2007

Abstract

The droplet evaporation process after impinging on a solid wall near Leidenfrost point is theoretically analyzed. Considering the change of heat transfer effective in the evaporation process, it is divided into recoil stage and spherical stage, and the heat transfer models in these two stages are built, respectively. The effect of initial Weber number, initial droplet diameter, solid surface superheat and wettbility are included in the models. A correlation for predicting evaporation lifetime is obtained based on the theoretical analysis and experimental results. By comparing analysis results with experimental data, it is concluded that the evaporation process can be predicted by present model. The results imply that Leidenfrost point may be not the turning point of heat transfer mechanism. The effect of drop size and Weber number are also analyzed.

Keywords: Leidenfrost temperature; Evaporation; Drop impingement; Theoretical analysis

1. Introduction

The phenomena of evaporative liquid droplets impacting solid objects of high-temperature are of great importance in many technical applications, such as spray cooling in the heat treating of metallic alloys, impingement of oil droplets on turbine engines, and re-wetting of fuel rod in nuclear reactor. When a drop of liquid impact onto a hot solid surface, it may splash, rebound or remain on the surface. Then it boils and vanishes quickly. However, if the temperature of the solid surface is high enough, the drop is not anymore in contact with the surface, but levitates above its own vapor. The evaporation process becomes rather slow due to the poor heat transfer of vapor film. The Leidenfrost point is the wall temperature at which the total evaporation time of a droplet on a heated surface is the longest.

A number of experimental [1–9] and theoretical [9–12] studies on impact effect of liquid droplets to objects near Leidenfrost point have been reported in the literatures. It was found that one of the main factors affecting the Leidenfrost temperature is impact Weber number, denoted by We. Wachters and Westerling [1] first classified the dynamic regimes of the impact by We. For the impact with $We < 30$, the surface tension of the droplet dominates the impact process, and the droplet recoils and rebounds from the surface without disintegration. As $30 < We < 80$, the droplet undergoes a similar spreading and recoiling process as that for $We < 30$. In the rebounding process, the droplet may disintegrate into several smaller droplets. For the impact with $We > 80$, the impact inertial force is so long that splashing occurs in the spreading stages and the droplet breaks up into tiny droplets.

In the low Weber number cases, the droplet contacts with the surface after impact the heated wall, and the contacted surface is wetted. With the wetted area reaching its maximum, it starts to recede. Its outer boundary, which is the periphery of the wetted area, will merge with the inner boundaries, which are the peripheries of dry spots created inside the wetted area. The wetted area will subsequently disappear and a vapor film will be established beneath the liquid drop [2]. The spreading liquid film will slowly shrink from plate-like disk into a spherical drop.

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doi:10.1016/j.ijheatmasstransfer.2007.03.028

The contracting velocity relates to the surface temperature. The higher the surface temperature, the slower the spreading liquid film contracts into a spherical liquid drop [2–4,13].

In previous studies, Leidenfrost temperature was usually assumed to be the temperature at the turning point of heat transfer mechanism; so that liquid drop can not contact the solid surface when surface temperature is above Leidenfrost point, otherwise the drop can keep in contact with the surface. However, recent experiments [2,3,5] show that impacting drop can contact directly with solid surface at the initial stage after impact even if temperature of the solid surface is above Leidenfrost point. Some alternative criteria have therefore been defined, such as wetting limit temperature, hydrodynamic limit of contact and dry impact temperature. The wetting limit temperature [2] and dry impact temperature [3] are the critical points that secondary droplets contact directly with the surface, and they are lower than Leidenfrost temperature. The thermodynamic limit of contact [5] is the critical point that no contact can be observed since liquid-vapor interface approaching the surface is pushed away by vapor thrust before it comes into contact with the surface, this point is far higher than Leidenfrost temperature. The heat transfer phenomenon has no apparent change when the surface temperature exceeds Leidenfrost point. Therefore, the turning of evaporative drop's lifetime at Leidenfrost point maybe not due to the change of heat transfer mechanism, but the change of fraction of some factors.

In the present study, we divided the evaporation process of a single impact droplet into two stages: recoil and spherical evaporation stages, respectively. The heat transfer models in these two stages are built, respectively. The effect of initial Weber number is included. Based on above models and experimental results, a correlation for predicting the lifetime of a single impact drop on the hot surface near Leidenfrost point is deduced. The explanation of the present model and comparison with experimental data and other correlation are also provided.

2. Model

After a liquid drop impinges on a solid surface near Leidenfrost point, the drop will initially spread on the surface. Vapor film will form quickly beneath the stretched drop after it reaches maximum diameter. Then the stretched drop levitates on the vapor film and recoil gradually into spherical shape. The evaporation process of spherical droplet is rather slow. At the end of evaporation, the drop disappears. In the present analysis, the initial spread stage of drop is omitted since it is very short (on the magnitude of millisecond). Then the total evaporation process is divided into two stages, namely recoil stage and spherical stage.

The maximum value of droplet size after impingement is very important for heat transfer in recoil stage. Roisman, Rioboo and Tropea [14] had deduced a theoretical model of maximum droplet radius as follow:

$$R_{\mathrm{m}} = \left(\frac{\overline{D}_1}{4} + \frac{\sqrt{6}A\overline{D}_1^2}{8}\sqrt{\frac{1-\cos\theta}{We}} + \frac{\sqrt{6}}{48A}\sqrt{\frac{We}{1-\cos\theta}}\right) \times D_0. \tag{1}$$

In Eq. (1), contact angle θ is employed. It is almost impossible to accurately measure the contact angle at high surface temperature. It has been reported that contact angle decreases with increasing of solid surface temperature [15,16]. In the high temperature regime, the contact angle decreases more steeply than that in low temperature regime [16,17]. The maximum droplet size also decreases with decrease of contact angle. Since, Leidenfrost temperature is very high, the minimum value obtained from Eq. (1) is used in the present study.

In the initial stage after impact, it was reported that the solid surface temperature fell dramatically due to the direct contact heat transfer and evaporation. However, this stage was very short [2–7] and the surface temperature recovered very quickly due to the formation of vapor film. In the recoil and spherical evaporation stage, the solid surface temperature should keep almost unchanged since the heat transfer intensity in these two stages is very low due to the insulation effect of vapor film. Therefore, no-wetting model is employed and the variance of surface temperature is omitted in present study.

The heat transfer model of evaporation droplet is similar to that of Biance, Clanet and Quéré [9]. It is assumed that the droplet after impact takes the form of a cylinder with radius λ and height h (Fig. 1). The mass change of droplet can be obtained:

$$\frac{\mathrm{d}m}{\mathrm{d}t} = -\frac{k}{L}\frac{\Delta T}{e}\pi\lambda^2, \tag{2}$$

where ΔT is the difference between the surface temperature and the saturated temperature of the liquid, k is the thermal conductivity of vapor, L is the latent heat of evaporation, e is the thickness of vapor film.

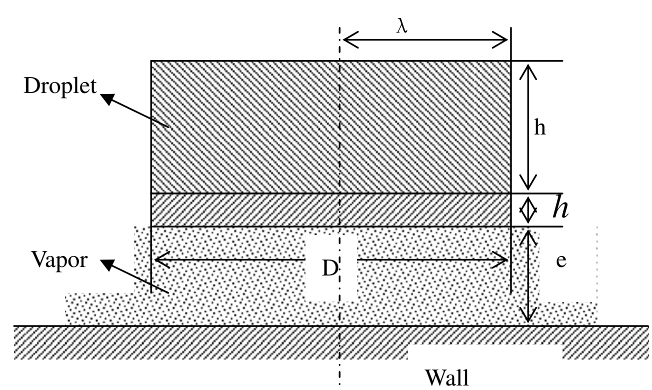

Fig. 1. Schematic of droplet and vapor model.

Moreover, the drop weight induces a radial Poiseuille flow of vapor outside the layer. The lubrication approximation is used due to the small thickness of vapor film. Thus, the flow rate has a scale of $e^3\Delta P/\eta\lambda$, where ΔP is the pressure imposed by the drop and η the vapor viscosity. The pressure is from the drop weight, so that $\Delta P = \rho_l g h$. By integrating the pressure over the contact area in term of the mass change, it gives

$$\frac{\mathrm{d}m}{\mathrm{d}t} = -\rho_v \frac{2\pi\rho^3}{3\eta}\rho_l g h, \tag{3}$$

In the recoil stage, the droplet radius closes to its maximum value. Therefore, it is assumed that the contact radius keeps the value R_{m}. Then,

$$h = m/\rho_l \pi R_{\mathrm{m}}^2. \tag{4}$$

Using Eqs. (2)–(4), the lifetime of recoil stage can be obtained:

$$\tau_1 = \frac{16(R_0^{9/4} - R_1^{9/4})}{9(\frac{k\Delta T}{L\rho_l})^{0.75}(\frac{\rho_v g}{\eta})^{0.25} R_{\mathrm{m}}}, \tag{5}$$

where R_0 is the initial droplet radius pre-impact and R_1 is the droplet radius at the beginning of spherical stage.

In the spherical stage, it is assumed that the contact area radius is half of drop height h,

$$\text{i.e.} \quad \lambda = h/2. \tag{6}$$

Using Eqs. (2), (4) and (6), the lifetime of spherical stage can be obtained:

$$\tau_2 = \frac{24[(2/3)^{1/3} R_1]^{1.25}}{5(\frac{k\Delta T}{L\rho_l})^{0.75}(\frac{4\rho_v g}{3\eta})^{0.25}}. \tag{7}$$

Then we get the total lifetime of evaporation:

$$\tau = \tau_1 + \tau_2. \tag{8}$$

In the recoil stage, the drop's bottom curvature, which determines the surface tension on the drop, will affect the contract velocity of drop. From Fig. 1, it can be seen that the curvature of drop relates to the vapor film thickness e, droplet diameter D and the change of droplet thickness $\dot{h}$. Therefore, a dimensionless parameter is defined as:

$$T_{\mathrm{n}} = \tau_1 e\dot{h}/D_0^2. \tag{9}$$

From Eqs. (2) and (4), this parameter can also be written as

$$T_{\mathrm{n}} = \tau_1 \frac{k\Delta T}{L\rho_l D_0^2}. \tag{10}$$

Some experiments on droplet evaporation have been reported. However, only total evaporation lifetimes have been shown in these literatures, and recoil stage lifetimes τ_1 are not available. From experimental total evaporation lifetimes τ and Eqs. (5), (7) and (8), R_1, subsequently τ_1 and T_{n} can be obtained. It has been reported that the splash will happen when $We > 30$. But the present model can not describe splash. Therefore, the data with $We > 30$ is not included in Fig. 2. When the initial droplet is very small, it will rebound up and down many times after impingement, which is also not included in this model.

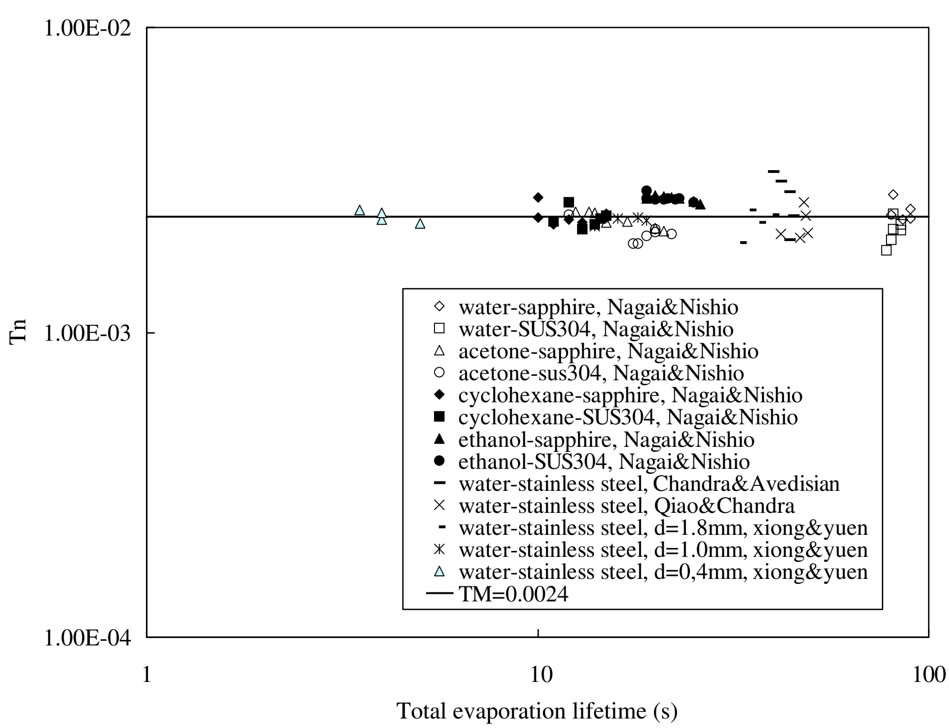

Fig. 2. Relationship between dimensionless parameter T_{n} and total evaporation lifetime.

Thus, only the data with $d \geqslant 0.4$ mm are chosen. The effect of Weber number and droplet diameter will be analyzed in the next section.

From Fig. 2, it can be seen that dimensionless parameter T_n is almost independent of the total evaporation lifetime τ. The value of T_n is close to a constant although the working medium, impact velocity, droplet size and surface superheat vary. If assuming $T_n = C$, τ_1 subsequently R_1 and τ_2 can be obtained from Eqs. (5), (7) and (10). Then a correlation of total evaporation lifetime can be gotten:

$$\tau = \frac{3.76\left[(D_0/2)^{2.25} - \frac{9}{16}C\frac{R_m A_2^{0.25}}{A_1^{0.25}}D_0^2\right]^{5/9}}{A_1^{0.75}A_2^{0.25}} + \frac{CD_0^2}{A_1}, \tag{11}$$

where $A_1 = \dfrac{k\Delta T}{L\rho_l}$, $\quad A_2 = \dfrac{\rho_v g}{\eta}$.

From Fig. 2, $C \approx 0.0024$.

3. Results and discussions

A typical case of acetone droplet impact experiment of Nagai and Nishio [3] is calculated by Eq. (11). The experimental and calculated results are shown in Fig. 3. The comparing results by two other heat transfer correlation for evaporation drop are also shown in Fig. 3. They are Inada and Yang correlation [12] and Baumeister correlation [18].

From Fig. 3, it can be seen that the results of present study are in good agreement with the experimental results. The turning up point of evaporation lifetime occurs although only one correlation is employed. It can be explained as below: according to Eq. (11), the recoil stage lifetime τ_1 decreases with increase of surface superheat. At the same time, the droplet radius at the beginning of spherical stage R_1 may increase according to Eq. (5), and this may increase the lifetime of spherical stage τ_2. Since, the heat transfer in spherical stage is worse than that in recoil stage, the combined effect of τ_1 and τ_2 causes that the change of evaporation lifetime τ with surface superheat is not monotone. This also implies that Leidenfrost point may be not the turning point of heat transfer mechanism.

The results of Inada and Yang correlation are close to that of present model illustrated as Fig. 3. But they can not represent the turning up of evaporation lifetime. The results of Baumeister correlation are far bigger than the experimental data. The reason may be due to worse heat transfer capacity caused by its spherical assumption.

The effect of droplet diameter is analyzed by simulating the experiment data of Xiong and Yuen [8]. Three cases with initial droplet diameters 1.8 mm, 1.0 mm and 0.4 mm, respectively are simulated and shown in Fig. 4. It can be seen that the evaporation lifetime is underestimated by present model with the decrease of droplet diameter. The reason is that the droplet may rebound up and down many times after impact when its diameter is small enough. Therefore, the application regimes of present model should be limited to that diameter bigger than 0.4 mm.

The case that $We > 30$ is also analyzed by simulating the experiment of Qiao and Chandra [7]. The working medium is *n*-heptane, and Weber number is 62.84 if saturated parameter is employed. The experimental and calculated results are shown in Fig. 5. From the figure, it can be seen that the calculated evaporation lifetimes by present model are far longer than experimental data. The reason is that splash occurs after impact and the original droplet breaks up into many tiny droplets which has much shorter lifetime. The results of Inada and Yang correlation and Baumeister correlation have also big deviations from experimental data.

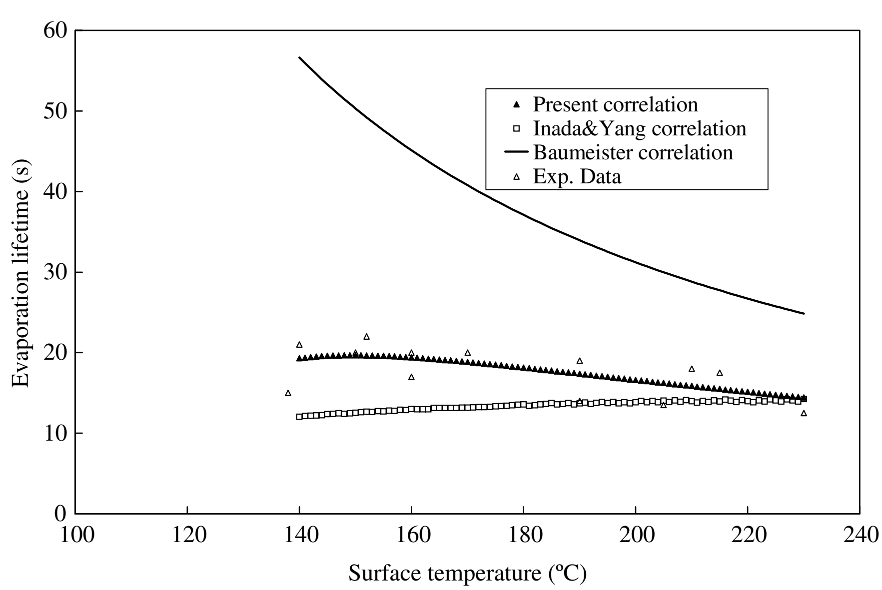

Fig. 3. The relationship between droplet evaporation lifetime and surface temperature (acetone).

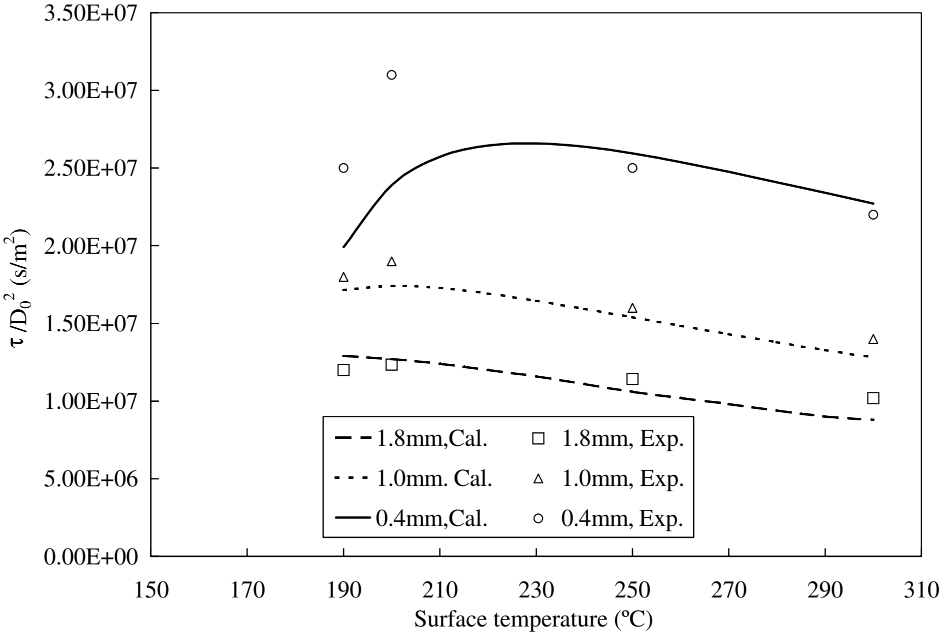

Fig. 4. The effect of droplet size on evaporation lifetime.

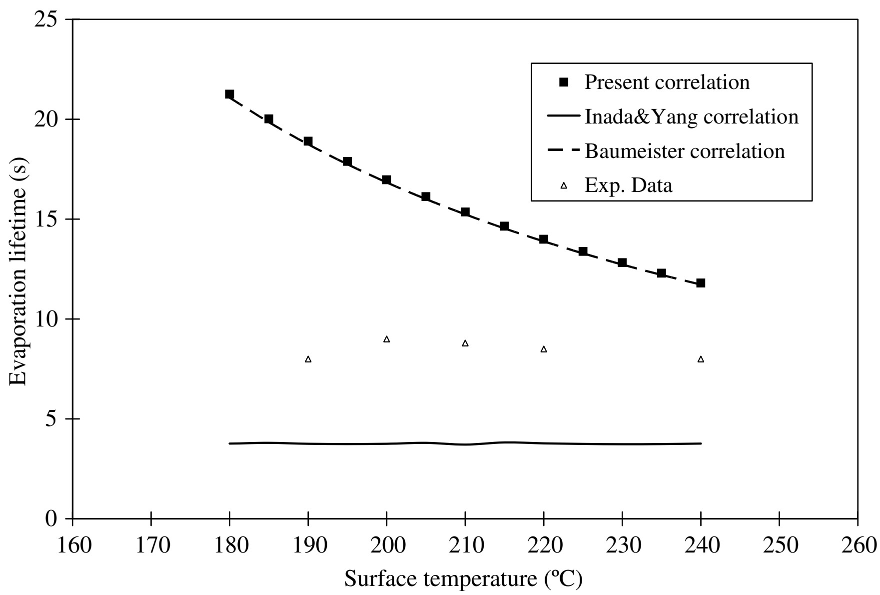

Fig. 5. The relationship between droplet evaporation lifetime and surface temperature (*n*-heptane).

4. Conclusion

A theoretical analysis has been conducted to study the droplet evaporation process after liquid drop impinging on a solid wall near Leidenfrost point. The evaporation process is divided into two stages: recoil stage and spherical stage. The heat transfer models in these two stages are built, respectively. The maximum contact radius is calculated by a theoretical model. A dimensionless parameter has been derived which relates the recoil stage lifetime to the vapor film thickness, droplet diameter and height. Based on the theoretical analysis and experimental results, a correlation for predicting evaporation lifetime is obtained. By comparing experimental data with analysis results, it is concluded that the evaporation process can be predicted by present model. The results also indicate that Leidenfrost point may be not the turning point of heat transfer mechanism.

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