Pergamon

Int. J. Heat Mass Transfer. Vol. 40, No. 10, pp. 2490–2492, 1997

0017–9310/97 $17.00+0.00

PII: S0017–9310(96)00264–5

Theoretical study of droplet impingement on a solid surface below the Leidenfrost temperature

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(*Received* 7 *December* 1995 *and in final form* 26 *July* 1996)

INTRODUCTION

The experimental studies associated with the deformation of a liquid droplet impinging on hot surfaces have been demonstrating that the droplet impact dynamics depend on preimpact velocity, droplet diameter, liquid properties and surface conditions (material, roughness and temperature). However, there are few theoretical models completely describing the dynamics of a droplet spreading on hot surfaces. The complexity of the analysis of the fluid dynamics is exemplified by the modeling of boiling phenomena, which are believed to have sufficient effect on the spreading behavior of a droplet. It is, however, important to investigate the effects of other phenomena.

Chandra and Avedisian [1] studied the deformation process of a *n*-heptane droplet impinging on a stainless steel surface below the Leidenfrost temperature. They found that the apparent contact angle at the tip of the spreading droplet depends on the surface temperate. They moreover evaluated the maximum diameter of the wetted area ($D_{c,max}$) through the apparent contact angle using a theoretical model based on a macroscopic kinetic energy balance for isothermal droplet impingement. Although their model successfully predicted the experimental tendency that $D_{c,max}$ decreases as the surface temperature rises, the predictions were approximately 25% higher than the experimental results. Because of the simplification of their model, it has not been concluded how accurately the deforming behavior of the droplet can be explained by the change in the apparent contact angle. In the present paper, a theoretical model which gives better prediction for isothermal liquid droplet impingement [2, 3] is utilized to investigate this issue.

RESULTS

Fukai *et al.* [3] have demonstrated that the simulation technique used in this paper well predicted the deformation of a water droplet impinging on adiabatic glass plates of different wetting effects. The detailed features of the mathematical model are contained in Fukai *et al.* [2, 3], and will not be repeated here for brevity. Instead, a brief summary of the numerical procedure will be presented.

The simulation starts at the instant that a spherical droplet comes into contact with a flat solid surface. The Lagrangian approach is adopted. The mathematical model accounts for inertia, viscous, gravitation, surface tension and wetting effects. It is based on the complete Navier–Stokes equations applied to the axisymmetric system. The normal and tangential stress balance conditions are satisfied on the deforming free surface of the droplet. The stress balances in the vicinity of contact line is modeled through the apparent contact angles (the angle between liquid/solid interface and liquid/vapor interface). The no-slip and no-penetration conditions are satisfied at the droplet–solid interface. The governing equations are numerically solved by invoking the finite element technique. Triangular finite elements are used. As the deformation process advances in time, the distortion of the finite elements becomes exceedingly large. To circumvent this difficulty, a new triangular finite element grid is generated when the distortion of the existing finite elements exceeds a threshold value. The simulations performed in this study were corresponding to the condition where a *n*-heptane droplet of 1.5 mm diameter impinges on a solid surface with a velocity of 0.93 m s^{-1} [1]. The values of the liquid properties at room temperature were chosen: density = 680 kg m^{-3}, viscosity = 3.9×10^{-4} Pa·s and surface-tension coefficient = 2.1×10^{-2} N m^{-1}.

Figure 1 shows the sequences of frames for three values of dynamic contact angle ψ_c. These results correspond to the experiments for a stainless steel plate whose surface temperature T_w is 24 (no boiling), 100 (no boiling) and 150°C (nuclear boiling region), respectively [1]. The boiling point of the liquid is 98.4°C (atmospheric). It is apparent that a thin film is formed around the droplet immediately after impact. Mass accumulation at the periphery of the droplet subsequently occurs and a ring structure forms. The recoiling starts after the wetting area reaches a maximum. The frames at $1.6 \leqslant t \leqslant 6.2$ ms in Fig. 1(b) clearly demonstrate that the ring structure continues developing not only in the spreading stage but also in the recoiling stage. In Fig. 1 (b, c), upward bulk motion is observed as the ring structure approaches the axis of symmetry. As ψ_c increases, both the ring structure and the upward bulk motion become greater. The initial kinetic energy of the preimpact droplet is transferred into inertia, viscous and surface energies in the spreading stage. In the recoiling stage, the accumulated surface energy is reversely transferred to viscous energy and (not to the same degree) inertia energy, which causes the upward bulk motion. As the dynamic contact angle (strictly, equilibrium contact angle) increases, the surface energy accumulated in the spreading stage increases, causing greater upward bulk motion [3]. The difference in the degrees of upward bulk motion for the three cases in Fig. 1 is directly related to the corresponding difference in the accumulated surface energy. It should be noted that the configurations of the droplet frames qualitatively agree with the experimental results (cf. Figs. 2 and 9 in Ref. [1]).

Figure 2 shows the results for $\psi_c = 96°$. The degree of the upward bulk motion is greater than that in Fig. 1 (c). In the calculation, the wetted area continues decreasing after 20 ms and vanishes at 20.5 ms. The computation was terminated at this instant because the present model does not consider the separation of the droplet from the surface. In the exper-

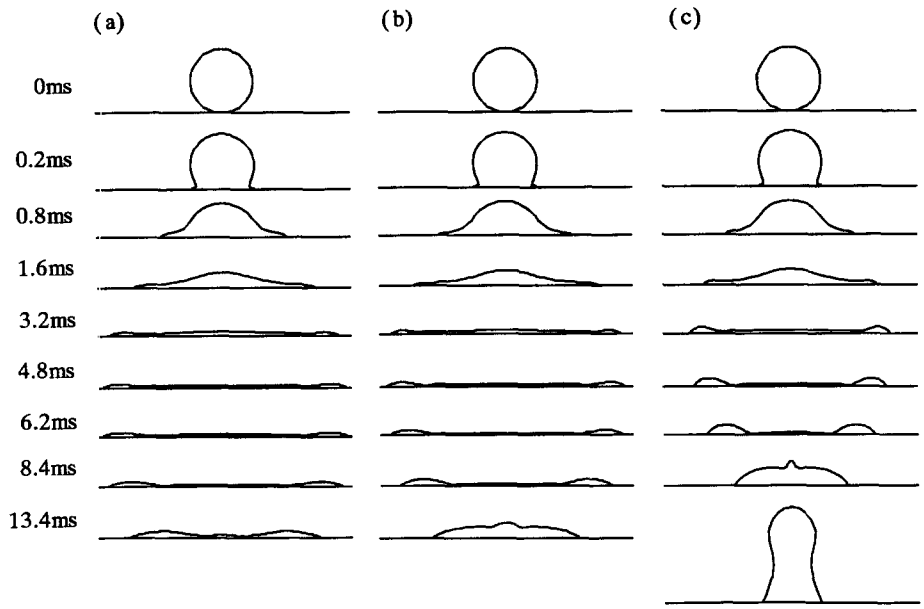

Fig. 1. Sequence of frames showing the predicted droplet spreading for: (a) $\psi_c = 32°$; (b) $\psi_c = 42°$; (c) $\psi_c = 68°$.

iment ($T_w = 180°C$ for stainless steel surface) corresponding to this calculation, nuclear boiling was clearly observed at 1 ms $\leqslant t \leqslant$ 8 ms, and the droplet subsequently levitated on the surface at $t = 20 \sim 25$ ms (cf. Fig. 10 in Ref. [1]), with which the predicted time agrees. The separation phenomena of a wetted droplet have sometimes been related to vapor pressure caused by nuclear boiling at the solid–liquid interface [1, 4]. However, the present model demonstrates that the vapor pressure is not a unique driving force for the separation phenomena.

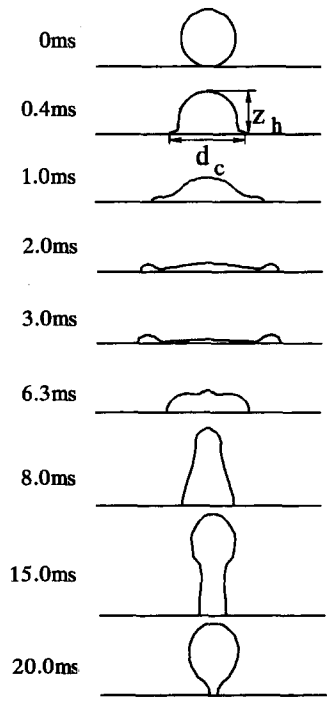

Fig. 2. Sequence of frames showing the predicted droplet spreading for $\psi_c = 96°$.

Figure 3 shows the time variations of the dimensionless diameter of the wetting area $D_c(=d_c/d_0)$ and the dimensionless droplet height $Z_h(=z_h/d_0)$, where d_0 is the droplet diameter. The definitions of d_c (the diameter of the wetted area) and z_h (the droplet height) are represented in Fig. 2. First of all, it should be noted that the model well predicts the experiments for an isothermal condition ($T_w = 24°$). The reason for the disagreements in the values of D_c for $T_w = 100$ and 150°C is might be due to the effect of boiling or evaporation. However, the calculations predict the experimental tendency that the rise in the surface temperature decreases the maximum diameter of the wetted area ($D_{c,max}$) and delays the instant (t_{max}) at which D_c reaches $D_{c,max}$. Though experimental data for Z_h is lacking, the calculations predict that

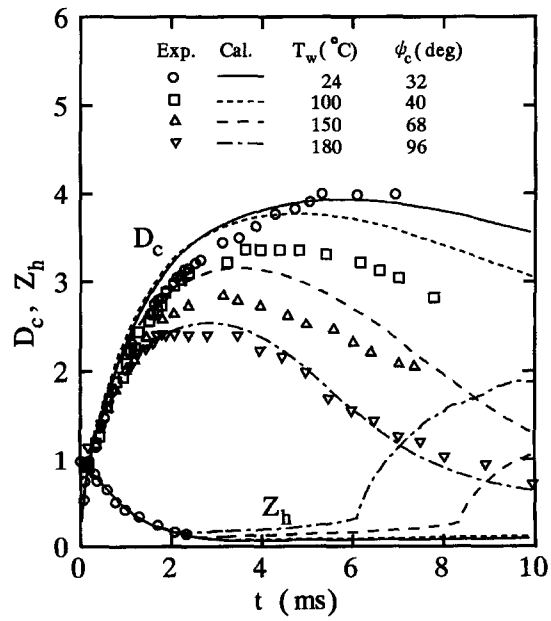

Fig. 3. The variation of the diameter of the wetted area with time. Comparison between theory and experiment [1].

Z_h strongly depends on T_w in the recoiling stage more than in the spreading stage.

Figure 4 shows the dependence of $D_{c,max}$ and t_{max} on advancing contact angle. Because the apex of the experimental D_c vs t curve is flat for a rather large time span as shown in Fig. 3, it is difficult to pinpoint t_{max} corresponding to $D_{c,max}$. t_{max} for the experiments is thus defined as the center of the flat portion in the curve. For $D_{c,max}$, it is apparent that the present model gives better prediction than the model developed by Chandra and Avedisian [1]. In addition, the present model predicts the change in t_{max}. These findings show that the overestimation of their calculations is mainly due to the simplification of the isothermal droplet impact

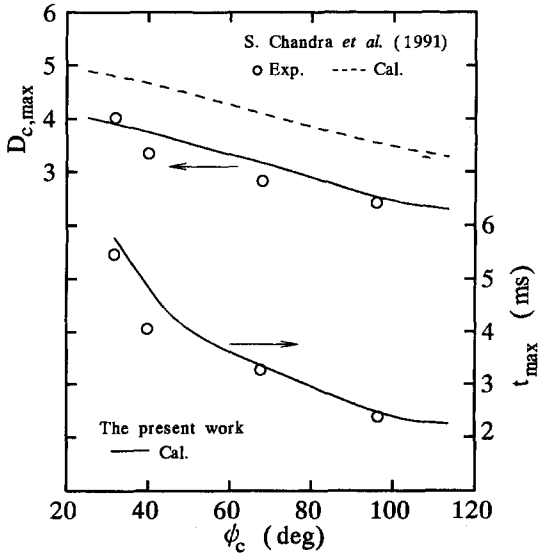

Fig. 4. The dependence of the characteristic length and instant of the spreading droplet on dynamic contact angle.

phenomena in their model. The studies associated with evaporating meniscus of a liquid film [5–7] and that of a liquid droplet spreading under the control of capillary forces [8] pointed out that evaporation in the vicinity of contact line essentially affects meniscus profile. Accordingly, the change in the apparent contact angle experimentally observed by Ref. [1] results from evaporation due to heat flow from the solid surface. A comparison of the present calculations with the experiments in Fig. 4 thus suggests that meniscus profile plays an important role in the spreading behavior of a liquid droplet impinging on hot surfaces.

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