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Visual Study of Droplet Bouncing Phenomena upon Impact on Hot Horizontal Surface

S. Illias[1,*], S. Hussain[1], M. S. A. Ishak[1], M. Z. M. Zain[1] and M. A. Idris[2]

[1] *School of Manufacturing Engineering, Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau, Perlis, Malaysia.*

[2] *School of Materials Engineering, Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau, Perlis, Malaysia.*

Abstract

When a droplet hits a hot surface beyond the Leidenfrost temperature, the droplet will bounce on the hot surface. This unique bouncing phenomenon only occurs in the film boiling region. This paper discusses the relationship between the residence time of droplet and droplet bouncing phenomena during droplet impact on hot horizontal surfaces. In this experiment, aluminum (mirror polished) was selected as a test surface. Degassed and distilled water were used in the experiment. The droplet diameter was fixed at 4.0 mm and the droplet temperature was kept at 16.0 °C. The droplet falling height was fixed at 65.0 mm corresponding to the impact velocity of 1.129 m/s. This unique droplet bouncing phenomenon was recorded at 10,000 fps (frames per second) by using a high speed video camera. From the theoretical calculation, the residence time or liquid-solid contact time of droplet during impact on hot surface was approximately 23.0 ms. Therefore, it is found that the measured residence time from the experimental data agrees closely with the theoretical calculation.

Keywords: Residence time, droplet bouncing, droplet impact, high speed video camera

INTRODUCTION

Boiling can be considered as one of the important element in the heat transfer research area because of its application in quenching process [1] , spray cooling technique [2], nuclear power plant during steam generation, etc. The boiling process is also very important in heavy industries such as steel production especially in the cooling section. Due to the importance of the boiling process, a deeper study and understanding is needed to improve our knowledge in liquid-solid contact interactions. One of the methods that are widely used to study the boiling phenomena is by conducting the drop impact experiment. This is a very simple and easy method and this experimental work is normally supported by a high speed imaging system.

Inada et al. [3-5] conducted several experimental works regarding droplet impact with hot surface. They conducted theoretical analysis of impact dynamics and heat transfer on a single, deformable, saturated drop in order to determine heat transfer effectiveness using idealized shapes and to model the deformation. Numerical results were obtained for various liquid drops in the non-wetting regime with droplet diameters of 0.22 to 4.0 mm, wall superheat temperatures of 200 to 600 K and Weber numbers of 12.3 to 50. As a result, they concluded that the correlation equation agrees well with the existing experimental data in the absence of air entrainment and drop subcooling [3]. They also reported that a vapor film thickness of below 5 μm for high drop subcooling (88 K) and above 10 μm for low subcooling (2 K) were identified at heated surface temperatures above 420 °C in the later half of the residence time [4]. Inada et al. [5] also conducted a theoretical study and analysis to determine film boiling heat transfer of saturated drops impinging on a heated surface, taking into account the dynamics of drop deformation. As a result, a new dimensionless parameter was derived which could relate the conductive heat transfer through a vapor layer and the evaporation rate of the liquid induced by surface tension.

Suhaimi et al. [6-9] also performed several droplet impact investigations in order to study this complicated phenomenon. In their experimental work, they concluded that degrees of liquid subcooling, droplet impact velocities and the initial temperatures of the solid may give an effect on the generation time of the vapor film during liquid-solid contact on hot surfaces [6]. They also concluded that cooler liquid and relatively higher impact velocities during drop impact can hold the wet area for a longer time based on their studies regarding vapor film generation in film boiling [7]. Suhaimi et al. [8] also conducted an experimental analysis of droplet bouncing phenomena on carbon heated surface in the film boiling region. They also performed an experimental analysis of micro-bubble emission boiling (MEB) which is also known as miniaturization boiling and its potential application for advanced cooling technique [9]. Meanwhile, Zuber [10] have studied the Leidenfrost point based on Rayleigh-Taylor instability analysis. In his studies, the transition film-boiling region was analyzed by considering the stability of a plane vortex sheet separating two inviscid fluids.

Over the last few decades, the boiling phenomena studies have captured great attention by researchers around the world [11-16]. They tried to study and understand the complicated boiling and evaporation characteristics and its mechanism especially the vapor film layer that is formed between the liquid and solid contact surfaces. Although many experimental papers and journals have been published, there are still mysteries and unsolved questions regarding liquid characteristics in the transition region and the formation of vapor film layer during liquid-solid contact at very high temperatures (film boiling region).

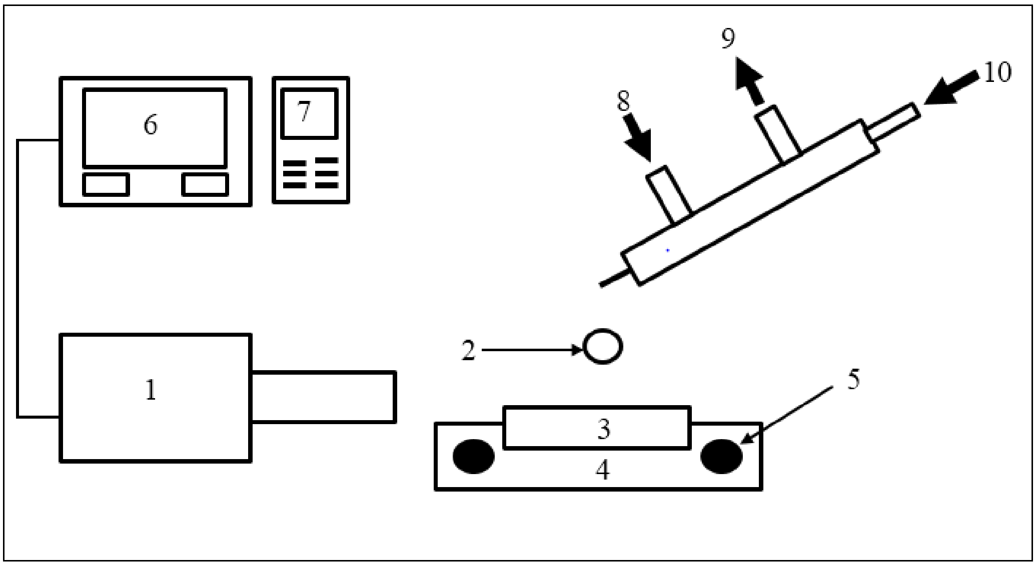
Recently, Gangtao Liang et al. [17] wrote a comprehensive review about recent progress in droplet impact experiment and its importance to the power plant technology and heavy industries. The review is divided into four parts, each centered on one of the main heat transfer regimes: film evaporation, nucleate boiling, transition boiling, and film boiling. Each of these regimes is discussed in detail in terms of available depictions of drop deformation and/or breakup, proposed heat transfer mechanisms, predictive correlations and/or models. It is shown that understanding the underlying physics for each heat transfer regime is highly dependent on the experimental methods that investigators have adopted, and broadness of available databases in terms of liquid type, drop size and momentum, impact angle, and wall material and surface roughness.

Apart from the droplet bouncing phenomena, there are other researchers such as Takata et al. [18-20] that had conducted a very interesting study regarding droplet impact experiment and boiling phenomena. They have conducted many experiments using high speed cameras. They studied the effects of different surface roughness, impinging velocity and droplet diameter on the behavior of droplets impinging onto a hot surface using high speed camera. They also conducted a study regarding maximum spreading and contact time of a droplet upon impact on a hot surface. They have reported that the cooling rate increases with an increase in the surface roughness. The contact time also increases with the decrease in the impinging velocity and with an increase in the droplet diameter. Other researchers [21-30] also performed experimental works regarding droplet impact on hot surfaces in order to study and understand the dynamic behavior of droplets, hydrodynamics phenomena, maximum spreading of droplets and many others.

In this research, experimental work have been conducted to study and analyze the relationship between the droplet bouncing phenomena and the liquid-solid contact time or residence time of droplet during impact on a hot surface. The comparison was made based on theoretical calculation. To support our experimental data, a high speed video camera was used in the experiment. The frame rate was set to be at 10,000 frames per second (fps).

EXPERIMENTAL APPARATUS

Figure 1 shows a schematic diagram of the experimental apparatus which is similar with the previous publications [8, 9, 29]. The heated surface was made from solid aluminum material. The surface was polished until it became a mirror polished surface. The disk dimension was 8.0 mm height and 30.0 mm in diameter. This heated surface was retained horizontally and was heated from its periphery by an electric cartridge-type heater. Meanwhile, the droplet injection system was also designed to be very accurate and easy to adjust. Degassed and distilled water was used as a test liquid. The water droplet diameter was kept at 4.0 mm, and the falling height was fixed at 65.0 mm corresponding to the impact velocity of 1.129 m/s. This impact height is in the range that the droplet itself does not disintegrate or will not split by the collision energy of the droplet. Halogen lamp was used as the lighting system. The temperature of the water droplet was kept at 16.0 ºC by the circulation of the tab water in the circumference of the nozzle. Meanwhile, the temperature of the heating surface was measured by attaching thermocouples with ceramic adhesives at two different locations on the hot horizontal surface. The high speed video camera was also positioned horizontally. The droplet spreading phenomena was photographed in real time and was recorded at a frame rate of 10,000 frames per second (fps).



1. High speed video camera 2. Droplet 3. Material disc 4. Copper stage 5. Cartridge heater 6. TV Monitor 7. Monitor controller 8. Water in 9. Water out 10. Degassed and distilled water

Figure 1: Schematic diagram of the experimental apparatus and droplet injection system

RELATED FORMULA

The property of thermal inertia, $\beta_w = \sqrt{\rho\, C_p k}$ is a very important parameter that relates the different temperatures of two bodies in determining the interfacial temperature at the moment of contact (ρ, C_p and k in the equation are the density, specific heat and heat conductivity respectively). The interfacial temperature T_i at the moment of contact is given in Equation. (1)

$$T_i = \frac{T_{wi}\,\beta_w + T_f\beta_f}{(\beta_w + \beta_f)} \tag{1}$$

where T_{wi} is the initial temperature of the heated surface, T_f is initial temperature of the droplet, the subscripts w and f of the thermal property β refers to the cases of heated surface and droplet, respectively. Meanwhile, for the liquid-solid contact time or residence time τ_r, it can be calculated using Equation (2) which was verified by Rayleigh, [28]

$$\tau_r = \left(\frac{\pi}{4}\right)\sqrt{\frac{\rho {D_o}^3}{\sigma}} \tag{2}$$

where ρ, D_o and σ are the liquid density, initial diameter of the droplet, and the surface tension force, respectively. From the theoretical calculation, the residence time, τ_r for this experiment was approximately 23.0 ms. In the film boiling region, the liquid-solid contact time or residence time, τ_r represents the duration at which the droplet is in contact with the hot surface. It refers to the length of time the droplet stays on the hot surface beginning from the first impact until it bounces off the hot surface.

RESULTS AND DISCUSSION

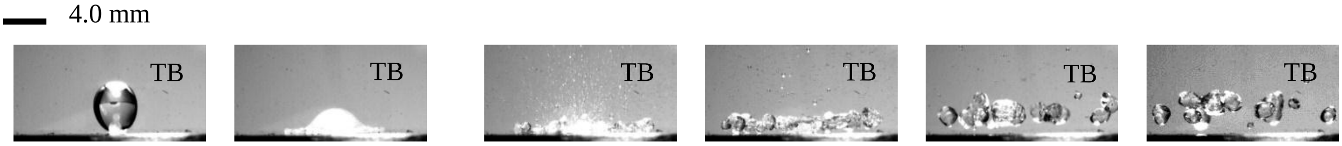
Figure 2 shows the sequential images of the boiling situation on the aluminum heated surface at the initial surface temperature, T_{wi} of 300 °C. The initial droplet size was 4.0 mm. The impact velocity was 1.129 m/s corresponding to droplet impact height of 65.0 mm. The numerical value under each photograph is the elapsed time after droplet collision. The transition boiling situations are marked as 'TB' in the images. From the images, it can be clearly observed that liquid dispersion particles were ejected from the mother droplet after the droplet touched the hot surface as shown in Fig. 2(c). Then the droplet breaks into several numbers of smaller droplets as shown in Figs. 2(e) and (f). This phenomenon represents the transition boiling region which is the region that exists between nucleate and film boiling. This liquid dispersion phenomenon also means that the hot surface still can transfer heat to the liquid even after the droplet had touched the hot surface. But, in this transition boiling region, it is believed that the heat flux that was removed from the hot surface is relatively smaller compared with the nucleate boiling region.

Meanwhile, Figure 3 shows the sequential images of boiling situation on hot aluminum surface at initial surface temperatures, T_{wi} of 320 °C in the film boiling region. This film boiling condition is marked as 'FB' in all images. The impact velocity was 1.129 m/s which is similar with Fig. 2. As can be seen from the high speed images, the droplet begins to spread on the hot surface after the first impact as shown in Fig. 3(b) at about 8.0 ms. No liquid dispersion was observed on the hot surface during this liquid-solid contact. This means that a stable vapor film had been generated when the droplet touched the hot surface. This vapor film exists between the liquid and the hot surface. Furthermore, this vapor film hinders the heat transfer from the hot surface to the liquid. This is the main reason why the cooling performance becomes worst in the film boiling region. In other words, heat cannot be removed from the hot surface to the liquid due to this vapor film formation.

As shown in Figure 3, after the droplet impact, the mother droplet kept spreading on the hot surface until it reached its maximum spreading diameter. Then, the receding process took place as shown in Fig. 3(c) at 16.0 ms. The mother droplet receded close to its initial diameter again. For easy understanding, this maximum spreading phenomena has been discussed in our previous publication [29]. Finally, after the spreading and receding process comes to its end, the droplet begins to bounce and starts to float over the hot surface from 23.0 ms up to 44.0 ms. As reported by Inada et al. [3], this bouncing phenomena is likely caused by the vapor pressure that was released from the hot surface. The high speed image shown in Fig. 3(e) strongly supports this unique bouncing phenomenon. From the images, it was found that the droplet reached its maximum bouncing height of about 1.42 mm from the surface at about 36.0 ms. Then, the droplet touched the hot surface again at approximately 44.0 ms as shown in Fig. 3(f).

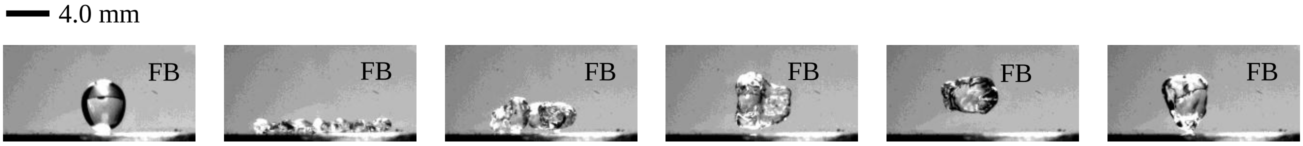
Figures 4 shows the relationship between residence time, τ_r of a droplet and bouncing phenomena of a droplet after impact on hot aluminum surface at three different surface temperatures of 320, 340 and 360 °C. When the droplet makes a contact with the hot surface, it begins to spread on the hot surface until it reaches its maximum spreading. Then, the droplet begins to recede close to its original diameter. Then, the droplet will bounce from the hot surface due to the vapor pressure release by the hot surface. As mentioned before, the theoretical calculation of the residence time, $\boldsymbol{\tau}_r$ of a droplet was 23.0 ms. From the point of view of the author, the residence time or liquid-solid contact time refers to the time where the liquid stays on the hot surface after the first impact until the droplet starts to bounce on the hot surface.

As shown in Figure 4, the residence time is almost the same for all cases even when the surface temperatures are different. The liquid solid-contact time also is very close to each other which is about 23.0, 22.8 and 23.6 ms for surface temperatures of 320 °C, 340 °C and 360 °C, respectively. Therefore, it can be concluded that the residence time, τ_r of a droplet is very close with the theoretical calculation. The evidence of this unique phenomenon was strongly supported by the high speed camera images shown in Fig. 3(d). Furthermore, it was observed that the maximum bouncing height reached by the droplet was approximately 1.42 mm at about 36.0 ms for surface temperature of 320 °C. Meanwhile, for the surface temperature of 340 °C and 360 °C, the maximum bouncing height was about 4.50 mm and 5.64 mm, respectively. The maximum bouncing for both cases was greater than 4.0 mm which is larger than the droplet initial diameter itself. The duration of bouncing and floating time is also much longer compared to the surface temperature of 320 °C. For all three cases, the patterns of the bouncing graphs seem to show a similarity between each other. The droplet will start bouncing when the elapsed time reaches approximately 23.0 ms. From the high speed images, it was observed that the droplet will float freely above the hot surface and finally descends to touch the hot surface. For easy understanding, the measurement of the initial surface temperature, residence time between theoretical and experimental work, maximum bouncing time and maximum bouncing height are tabulated in Table 1.



(a) 0.0 ms (b) 2.0 ms (c) 6.0 ms (d) 10.0 ms (e) 16.0 ms (f) 22.0 ms

Figure 2. Sequential images of boiling situation on aluminum heated surface at the initial surface temperature of 300 °C.



(a) 0.0 ms (b) 8.0 ms (c) 16.0 ms (d) 23.0 ms (e) 36.0 ms (f) 44.0 ms

Figure 3: Sequential images of boiling situation on aluminum heated surface at the initial surface temperature of 320 °C.

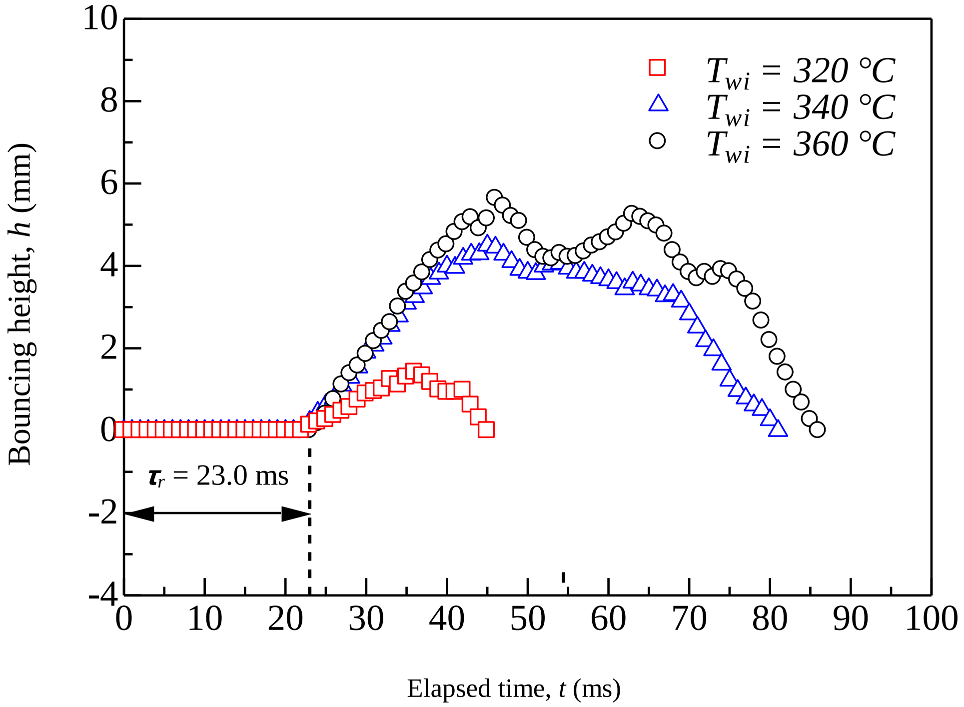


Figure 4: The relationship between residence time, τ_r and droplet bouncing phenomena at the initial surface temperature, T_{wi} of 320, 340 and 360 °C

Table 1: Initial surface temperature, residence time (theoretical and experimental) and bouncing height comparison

Initial surface temperature, T_{wi} (° C)	Residence time, $\boldsymbol{\tau}_r$ (Theoretical, Eq. 2) (ms)	Residence time, $\boldsymbol{\tau}_r$ (Experimental) (ms)	Maximum bouncing time, t (ms)	Maximum bouncing height, h (mm)
320	23.0	23.0	36.0	1.42
340	23.0	22.8	45.0	4.50
360	23.0	23.6	46.0	5.64

CONCLUSION

From the high speed images and experimental results, it was found that the water droplet will start bouncing at the time of approximately 23.0 ms (340 °C), 22.8 ms (320 °C) and 23.6 ms (360 °C) after its first impact on the hot surface. The bouncing graph for each different surface temperature studied also exhibited similar patterns. These values were also found to be similar or close to that calculated theoretically and hence showed that the liquid-solid contact time or residence time of a droplet can be estimated using Equation 2.

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