1. Introduction

Characterizations of liquid droplet and hot surface interaction’s thermal-hydraulics have profound importance for various industrial applications utilizing spray cooling and quenching applications such as ex-vessel cooling for in-vessel various industrial applications utilizing spray cooling and interaction’s thermal-hydraulics have profound importance for

Up to this date liquid droplet impingement phenomenon onto hot surfaces has drawn massive attention from a broad spectrum of research fields. Although tremendous experimental and computational work exist in the literature, thermal-hydraulic mechanism of droplet impingement boiling on hot surfaces received several contradictory approaches due to the sensitivity of the phenomena on the complex and uncontrollable boundary conditions (BC) of the problem. We investigate the parametric variation of droplet boiling regimes due to the experimental BCs (e.g. surface roughness, ambient pressure) by performing separate effect tests employing high-speed visualization system.

2. Experimental setup

Experimental setup, a schematic layout shown in Fig. 1, is composed of hot-plate, liquid metal container, syringe pump, high-speed camera and halogen lamps. Syringe pump drives distilled water inside the syringe, which is connected to a plastic microtube (150 μm inner diameter), to form a droplet having approximately 2.5 mm diameter at the tip of the tube. Droplet dispatch and impinge onto hot-surface from a determined height ranging from 10 mm to 20 mm when it reaches to maximum weight of water which can be supported by the surface tension forces. U-alloy 70 (an alloy of Bi, Pb, Cd, and Sn, having melting point of 70 °C) is used as a hot surface and assumed to be non-deformable due to the droplet impact since its density and surface tension are much higher than those of water. U-alloy is heated up with a hot plate which is connected to a temperature controller, and a thermocouple, submerged into liquid metal, records the temperature variations near to the surface. As a solid hot-surface, polished copper plate (30x30 mm, 0.5 mm thick) is employed. Time resolved images are recorded with a high-speed camera operating at spatial and temporal resolutions of 256x256 pixels and 10 kHz respectively. 200 mm Nikon Micro Nikkor lens is adapted to the camera to have larger spatial resolutions.

Fig. 1 Schematic view of experimental setup.

3. Results and Discussions

3.1 Effect of surface roughness

One of the important parameter in boiling phenomena whose effects still cannot be resolved sufficiently due to its tremendously varying characteristic due to the type of material and surface chemistry. Fig. 2 shows temporal progression of water droplet after impingement on liquid metal and on a copper plate under ambient conditions with similar Weber numbers. When the droplet impinge onto copper plate having a temperature of 313 °C which is well above estimated Leidenfrost point (LFP) and regarded as lower temperature boundary of film boiling regime, wavy structures on droplet surface can be discerned from varying non-uniformity of image intensities (Fig.2a). Those structures evidence that vapor layer beneath the droplet is having intermittent pressure fluctuations which disturbs lower surface of droplet, promote and propagate
unstable waves across the liquid surface. Pressure variations are likely to be caused by the non-uniformity of surface structures (surface roughness), since indented uneven structures lead to non-uniform heat transfer to the liquid surface with intermittent direct contact conduction by rupturing the vapor film. Elevated heat transfer promotes vapor production rate resulting in droplet bounce back from the surface with keeping its integrity. On the other hand, with zero surface roughness (liquid metal surface) droplet reaches its largest integral diameter after 2.8 ms, soon after a liquid spurt is monitored from the water-liquid metal interface at 3.1 ms suggesting that vapor layer reached the maximum pressure and erupted (Fig. 2b). This blast of vapor wieldy disrupts and fragments the outer layers of droplet resulting in flying out of small secondary droplets. Unlike to cupper surface, no major disturbances developed on the droplet surface until a sudden blast taking place on the interface. Based on this observation, we may speculate that a stable vapor layer is formed under the droplet (unlike cupper plate case) and it uniformly degraded the heat transfer rate from surface to the droplet. Upon vapor layer reaching sufficient pressure, but not sufficient for lifting the droplet yet, it preferred to erupt from the periphery due to its possession of insufficient pressure for droplet lift. If the surface temperature would be high as much as producing sufficient rate of vapor mass, droplet could be lifted off.

3.2 Effect of pressure

To quantify the boiling behavior of the impinging droplet, stepwise variation of contact angle (wetting) is designated as a valid parameter describing the onset of boiling (Fig.3).

Ambient pressure is another one in among the most important parameters governing the boiling phenomena. Emmerson reported that droplet evaporation time is reduced as the pressure increases. He explained that tendency association with the decrease in latent heat of vaporization due to increasing pressure. He also noted that whereas LFP increases with pressure, droplet evaporation time or droplet lifetime remain shorter. Fig. 4 presents the delay time variation, which can be regarded as a parameter correlated with the LFP, versus wall super heat for atmospheric pressure and sub-atmospheric pressures. Red line represents the LFP (180 °C), which does not change much with Weber number, for a droplet impinging on a polished cupper plate with a Weber number of 20. The correlation between the LFP and delay time can be related to vapor layer formation and corresponding delay of boiling that evidenced with a minor peak in delay time at 80 °K in atmospheric pressure data.

No significant delay is observed for the case of sub-atmospheric pressure in between 0-60 °K super-heat regions, while a remarkable delay is detected under atmospheric pressure in the same range of superheat. Since the latent heat of saturated water at 50 kPa (2300 kJ/kg) higher than that of atmospheric pressure (2257 kJ/kg), apparently more heat energy is needed for the creation of vapor layer in sub-atmospheric pressure, hence, the reason of no delay in boiling around low super-heats is likely to be the lack of sufficiently thick vapor layer formation.

Under the sub-atmospheric pressures, we observed an intriguing sharp increase in delay time beginning earlier than those of atmospheric pressure case and rises up to elevated times at a super-heat temperature corresponding to LFP of atmospheric pressure. If we took into account solely the differences in latent heats of both cases and the time to reach a stable film boiling, the peak in boiling delay in sub-atmospheric pressures must have been developed at higher superheats and it must have not been much diverged from the atmospheric pressure. From this point of view, another factor must come into a crucial role and govern the film boiling regime by generating more stable blockage against heat transfer and prevents droplet’s wetting during the film boiling in sub-atmospheric pressures. Air bubble entrapment beneath the impinging droplets on solid surfaces in atmospheric pressures is known from some researches in the literature. Recently reported by Driscoll et al. that at sub-atmospheric pressures, a ring of highly populated microbubbles, differing from atmospheric pressure conditions, encircling a larger bubble are entrapped and their sizes grow with decreasing pressure. It can be hypothesized that larger delays caused by those microbubbles which are blocking the droplet wettability and blanketing conductive heat transfer to the droplet leading to larger delays. Even this is the case, quantification of this hypothesis is essential and yet to be performed.

Fig. 3 Stepwise change of contact angle.

Fig. 4 Delay time versus super-heat at atmospheric (We=5.8) and sub-atmospheric (We=6.4) pressures.

References