Dynamic processes and boiling phenomena during droplet and hot surface interaction

47-086836 Uddin Mohammad Mezbah

Supervisor: Professor Dr. Koji Okamoto

When a liquid drop contacts a surface, the liquid spreads over the solid to minimize the total surface energy. Here we identify that the spreading diameter decreases with increasing surface roughness for lower drop velocity but the surface roughness effect is almost negligible at higher drop velocity. Considering boiling phenomena, the smooth & rough surface showed almost identical boiling phenomena in the film boiling regime but there are few differences in case of nucleate and transition boiling regime. Droplet and hot surface interaction at reduced pressure differs a lot considering atmospheric pressure. Strong evaporation and boiling phenomena are observed at early temperature and 2 kPa pressure whereas no boiling is observed at 100 kPa pressure. At 140⁰C temperature, a 'depinning jump' of droplet is observed at 2 kPa pressure. The cause of early 'depinning jump' and strong boiling is excess superheat temperature and subcooling effect at reduced pressure environment.

Key words: Surface roughness, drop velocity, drop spreading diameter, superheat temperature, subcooling effect

1 Introduction

In water-cooled nuclear reactors, the heat removal rate from the fuel element during a loss of coolant accident (LOCA) is managed using emergency core cooling system (ECCS). In certain types of water-cooled reactors, this emergency cooling water is sprayed into each fuel bundle from a pipe situated in the centre of the bundle. When a jet of emergency cooling water impinges on a hot fuel element, stable film boiling occurs [1].

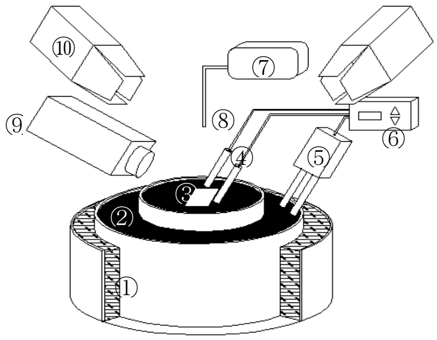
Regarding this purpose many researches are already performed considering bulk fluid flow. But researches to observe the drop dynamics between droplet and hot surface interaction are very few [2, 3].

The main goal of this research is to identify drop dynamics between droplet and hot surface interaction considering surface roughness, temperatures, drop velocity and sub-atmospheric pressures. And also find out the optimum parameters which can improve the heat transfer between droplet and hot surface during the LOCA condition.

2 Experiment

2.1 Set Up

Figure 1 shows the schematic of the experimental setup. The heated specimen plate is a SUS304 plate, kept on liquid metal (U-alloy of Ti, Cd, In & Sb, MP =138⁰ C). The liquid metal was heated by an electric heater (500 W) and the temperature was controlled with a controller connected with the heater and a thermocouple. A micro syringe pump was used to generate droplet. The drop diameter for all cases was about 2 to 3 mm. The other information of the set up is shown in Fig. 1.



1: Insulator 2: U-Alloy 3: Test piece 4: Thermocouple 5: Heater 6: Temperature controller 7: Micro syringe pump 8: Nozzle 9: High speed camera 10: Light source

Fig. 1 Experimental apparatus

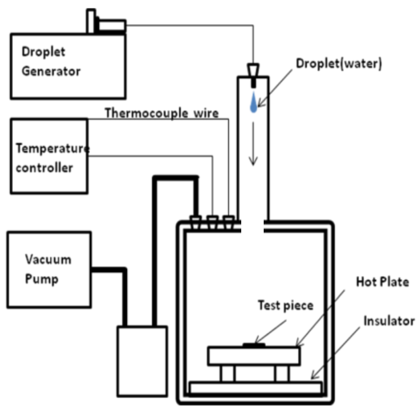


Fig. 2 Vacuum experimental apparatus

Figure 2 shows the schematic of the vacuum experimental set up. The vacuum box is an acrylic plastic box connected with vacuum system, temperature controller and drop generator. Hot plate is placed inside the vacuum box. Drop generation, lighting system and movie capturing method are similar to Fig.1.

The drop spreading dynamics are captured at 30,000 frames per second using a Photron High Speed Camera. Image processing and the corresponding data analysis are accomplished using Photron High Speed Camera software.

2.2 Experimental Parameters

The first step in our experiments was to prepare SUS304 surface of variable roughness using variety of emery papers (#240, 600, 1000). Experiments were conducted for four different drop velocities (0.32, 0.49, 0.71 and 4.47 m/s), different absolute pressures (2, 5, 10 and 100 kPa), different surface temperatures (23 to 300^{0}C) and water was used as liquid. The Leiden frost temperature of SUS304 surface is about 240^{0}C.

2.3 Droplet Shape Measurement

The main parameters used in this experiment are drop spreading diameter (drop width) and drop height as shown in Fig. 3. The two parameters are variable with time and calculated for different surface roughness, drop velocity and surface temperatures.

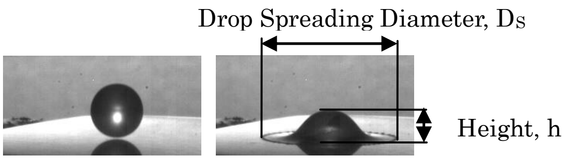


Fig. 3 Drop Spreading Diameter & Drop Height

3 Results & Discussions

3.1 Effects of surface roughness and temperatures on drop spreading diameter

Figure 4 shows comparison of drop spreading diameter for smooth and most rough SUS304 surface considering different surface temperatures. It is to be mentioned that in Fig. 4 'SS' refers to smooth SUS304 surface and 'EP#240' refers treated SUS304 surface using emery paper (#240). From Fig. 4 it is observed that smooth surface spreading diameter is higher at all temperatures comparing rough surface.

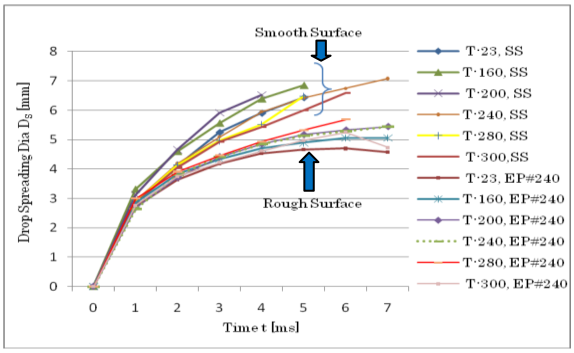


Fig. 4 Comparison of drop spreading diameter for smooth and rough surface for different temperatures (Drop velocity 0.49 m/s)

Figure 5 shows spreading diameter dependency on temperatures for two surfaces after 3 ms of drop contact. In case of smooth surface, the spreading diameter decreased at 240^{0}C. Since the Leidenfrost temperature is 240^{0}C, film boiling affects on the droplet dynamics, causing the spreading speed to be decreased. While, in case of rough surface, the spreading diameter has few effects on film boiling regime.

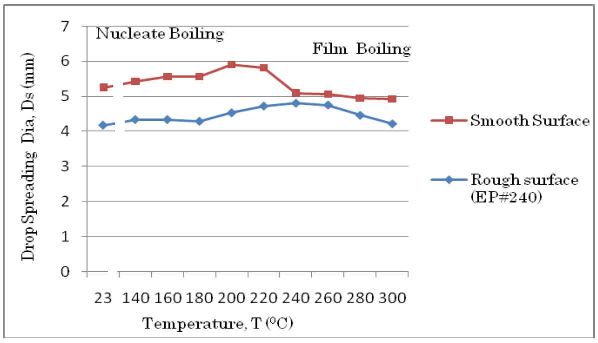


Fig. 5 Comparison of drop spreading diameter (Ds) after 3 ms of drop contact considering different temperatures & surfaces.

3.2 Effects of drop velocity on drop spreading diameter & height

Figure 6 shows comparison of drop height and spreading diameter for rough surface (#240) at two different drop velocities. It is observed that spreading diameter and height changes smoothly for lower drop velocity but for higher drop velocity spreading diameter increases abruptly.

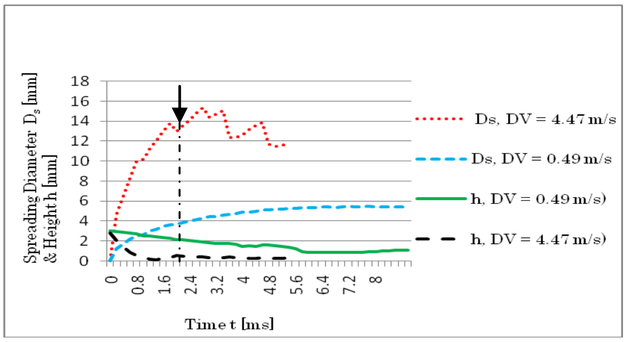
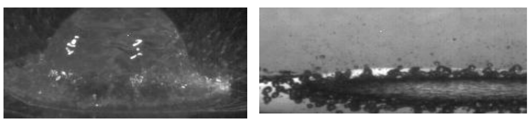


Fig. 6 Comparison of drop height (h) & spreading diameter (Ds) for rough SUS304 surface (#240).
(T= 200^{0}C, Drop Velocity (DV) = 0.49 &4.47 m/s)

Figure 7 shows images of two drops instant for lower and higher drop velocity which are occurred after 2 ms, i.e. arrow in Fig. 6.



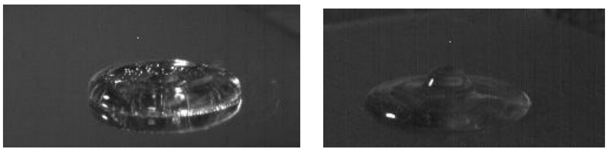
(a) DV=0.49 m/s (b) DV=4.47m/s

Fig. 7 Comparison of droplet shape (T=200^{0}C, EP#240, the 2nd image shows half of droplet).

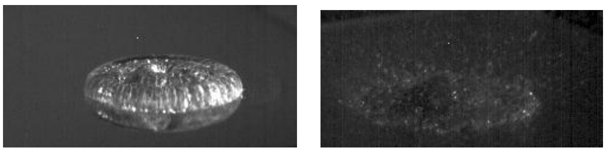
From Fig. 7 it is observed that boiling phenomena are strongly influenced by the dynamics of droplet. In addition, it is observed that drop height affected drastically in case of higher drop velocity.

3.3 Effects of drop velocity & temperature on boiling phenomena considering surface roughness

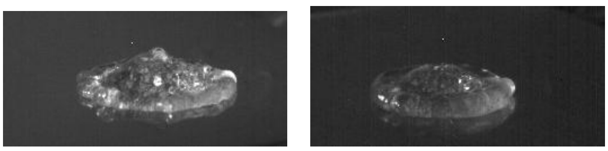
Two different values of wall roughness were used to analyze the boiling phenomena. One was smooth SUS304 surface and another was treated SUS304 surface with emery paper (#240). For the nucleate boiling regime the morphology of the impact is practically influenced by the wall roughness as it can be appreciated from Fig. 8. For lower drop velocity strong bubbles occurred in case of smooth surface whereas bubble nucleation density is very low in case of rough surface. In the transition boiling regime, strong splashing occurred for rough surface whereas no splashing occurred for smooth surface. In the film boiling regime, the smooth & rough surface showed almost identical boiling phenomena.



T-140^{0}C, SS, 5.0 ms　　T-140^{0}C, EP#240, 5.0 ms



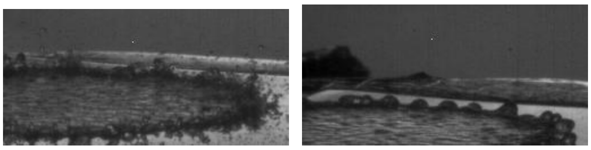
T-200^{0}C, SS, 5.0 ms　　T-200^{0}C, EP#240, 5.0 ms



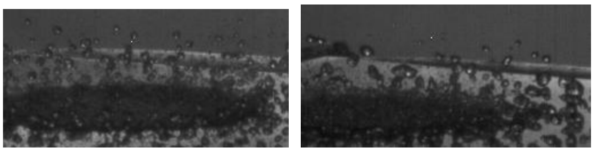
T-280^{0}C, SS, 5.0 ms　　T-280^{0}C, EP#240, 5.0 ms

Fig. 8 Comparison of boiling phenomena for smooth and rough surface for different temperatures (140, 200 & 280^{0}C) after 5 ms of droplet contact and 0.49 m/s velocity

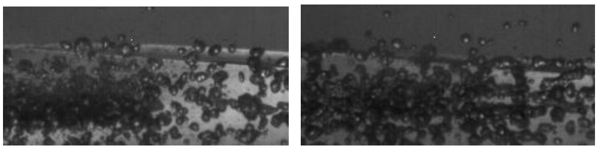
It is important to notice another feature that differentiates the boiling phenomena for different boiling regime at higher drop velocity (4.47 m/s). For the nucleate boiling case, the increase of impact velocity produces an increase of the spreading of the liquid lamella. Drop spreading periphery is early affected by heat in case of smooth surface at 160^{0}C whereas liquid accumulates in the periphery for rough surface. In the film boiling regime, boiling phenomena for smooth and rough surface are almost identical. The roughness effect for higher drop velocity case concluded that average secondary drop diameter is higher in case of rough surface compare to smooth surface. The direction of the secondary drop ejection is affected by the wall temperature at higher drop velocity. For nucleate boiling, the secondary drop direction is always mainly vertical, whereas for film boiling there is also an ejection in radial direction during the very fast impacting period. This phenomena is also observed by G.E. Cossali et al.[4].



T-160^{0}C, SS, 4.0 ms　　T-160^{0}C, EP#240, 4.0 ms



T-220^{0}C, SS, 4.0 ms　　T-220^{0}C, EP#240, 4.0 ms



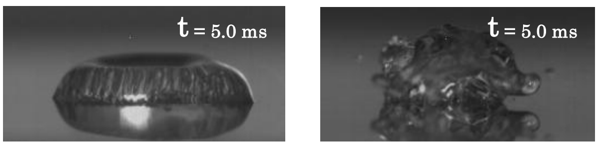
T-280^{0}C, SS, 4.0 ms　　T-280^{0}C, EP#240 4.0 ms

Fig. 9 Comparison of boiling phenomena for smooth and rough surface for different temperatures (160, 220 & 280^{0}C) after 4 ms of droplet contact at 4.47 m/s velocity

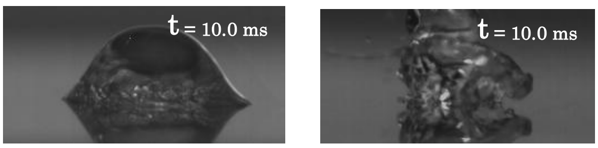
3.4 Droplet and hot surface interaction at reduced pressure environment

$\Delta T_{subcool}$ = 50.0^{0}C　　$\Delta T_{subcool}$ = -0.8^{0}C

P_a = 100 kPa, ΔT_{sh} = 40^{0}C　　P_a = 10 kPa, ΔT_{sh} = 93^{0}C



P_a = 100 kPa, ΔT_{sh} = 40^{0}C　　P_a = 10 kPa, ΔT_{sh} = 93^{0}C



P_a = 100 kPa, ΔT_{sh} = 40^{0}C　　P_a = 10 kPa, ΔT_{sh} = 93^{0}C

Fig. 10 Boiling phenomena for smooth SUS304 surface considering two different absolute pressures, 0.49 m/s drop velocity and 140^{0}C temperature

Fig. 10 shows the comparison of droplet and hot surface interaction for 100 kPa and 10 kPa absolute pressures and 140^{0}C temperature. From the photographs of 100 kPa pressure, it is observed that after 1 ms small bubbles are formed and it continues up to 10 ms. The generation of bubble is so smooth that it cannot agitate the whole droplet shape. But 10 kPa pressure condition is totally different because strong boiling started from impacting period. At 140^{0}C temperature a 'depinning jump' of droplet is observed after 33 ms of droplet contact. $\Delta T_{superheat}$ for 100 kPa and 10kPa are 40^{0}C, 93^{0}C and $\Delta T_{subcool}$ are 50^{0}C and -0.8^{0}C. The reason of 'depinning jump' at 140^{0}C temperature and 10 kPa pressure is excess superheat temperature compare to atmospheric condition.

Figure 11 shows the comparison of droplet and hot surface interaction for 10 kPa and 2 kPa absolute pressures considering higher drop velocity (4.47 m/s) and 125^{0}C temperature. From the photographs it is observed that after 10 ms droplet achieved Leidenfrost phenomena for both cases. But for atmospheric condition it occurs at higher temperature. It is also observed that droplet evaporation is very rapid at lower pressure (2 kPa). The cause of early Leidenfrost phenomena and rapid evaporation is due to higher superheat temperature, subcooling effect and higher impact velocity.

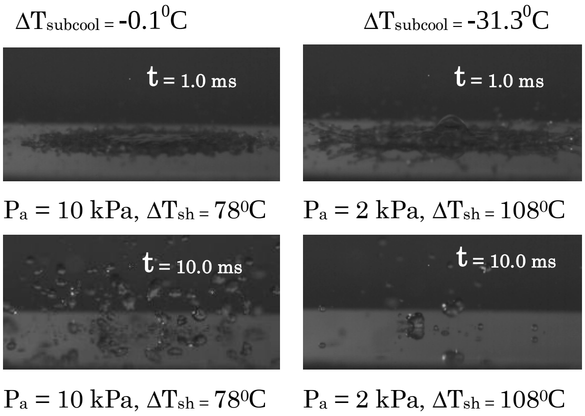


Fig. 11 Comparison of boiling phenomena for smooth SUS304 surface and 125^{0}C considering two different absolute pressures and 4.47 m/s velocity

3.5 Droplet and hot surface interaction at similar superheat but different sub-cooled temperatures

Fig.12 shows the comparison of droplet and hot surface interaction for smooth SUS304 surface considering similar superheat but different sub-cooled temperatures and higher drop velocity (4.47 m/s).

From the photographs it is observed that after 1 ms droplet boiling phenomena differs a lot. It is to be mentioned that super heat temperature is almost similar for both cases but $\Delta T_{subcool}$ differs a lot for two cases. The cause of strong boiling and rapid evaporation at 2 kPa pressure is due to very low subcooled temperature. As $\Delta T_{subcool}$ is very low for 2 kPa pressure, the droplet needs very little amount of heat compare to atmospheric one, consequently strong boiling occurs at early period of time for 2 kPa pressure.

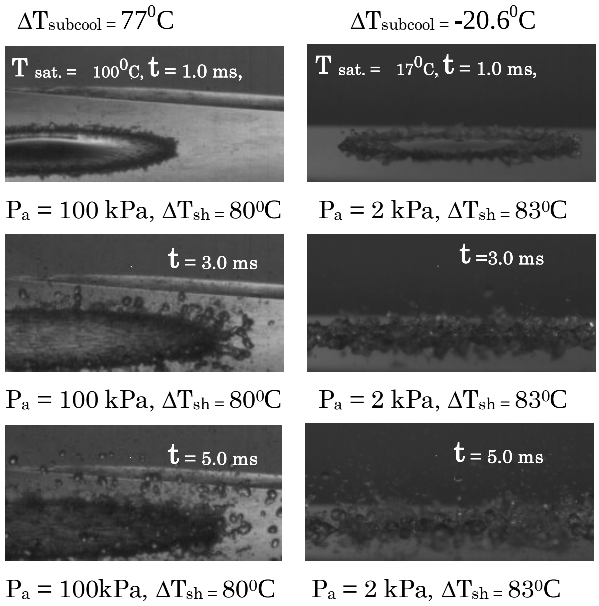


Fig. 12 Comparison of boiling phenomena for smooth SUS304 surface considering similar superheat but different sub-cooled temperatures

4 Conclusion

The surface roughness has strong effect on droplet spreading diameter at lower drop velocity but at higher drop velocity it is negligible. Effect of surface roughness on boiling phenomena is negligible in the film boiling regime but it has few effects in the nucleate and transition boiling regime. The effect of reduced pressure on droplet and hot surface interaction is prominent. The evaporation and boiling process are strongly enhanced at reduced pressure environment and early temperatures. This is due to the superheat and subcooling effect on droplet and hot surface interaction at reduced pressure.

References

1) R.G. Owen, D.J. Pulling, Reactor Safety, Applications, vol. 2, Clean Energy Research Institute, University of Miami, 1979, pp. 639–669.
2) G.E. Cossali, M.Marengo & M. Santini, Expt. Thermal & Fluid Science, 29 (2005) 937-946.
3) H. Chaves, A.M. Kubitzek, F. Obermeier, Intl. J. of Heat and Fluid Flow 20 (1999)470-476.
4) G.E. Cossali, M.Marengo, International Journal of Heat and Fluid Flow 29 (2008) 167–177.