On the formation of vapor film during quenching in de-ionized water and elimination of film boiling during quenching in natural sea water

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A B S T R A C T

The present study explores the quenching of two metallic spheres, i.e., stainless steel 304 and zircaloy-702, respectively, in natural sea water, compared with that in de-ionized water. The diameters of the spheres are 17.5 mm. In this study, the superiority of sea water compared to deionized water for nuclear power plant quenching was established. By visualization using a high-speed video camera, it was observed that when deionized water was used for quenching, the formation of a stable vapor film around the metallic quenching test spheres was not immediate as traditionally thought, but occurred through the coalescence of nucleated bubbles at ultra-high temperatures. Conversely, sea water was observed to enable much more rapid quenching through the prevention of stable film boiling due to a zeta-potential effect and quenching starting with transition boiling characterized with moderate bubble nucleation sites and possible burst out of bubble clusters.

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1. Introduction

Quenching, which is the process of rapidly cooling a hot object by exposing it to a much cooler liquid, is critical to the nuclear industry, especially regarding the safety of a nuclear power plant (NPP). In the event of a loss-of-coolant accident (LOCA), the temperature of the fuel rods in the core of an NPP could rise to over 1000 °C [1]. To ameliorate the situation, the emergency core cooling system of the plant pumps water into the core to cool the fuel rods containing decay heat. However, if the temperature of the rods is too high, the heat transfer rate may be limited by film boiling, wherein a stable vapor film blankets the hot surface, resulting in high thermal resistance. Such might have occurred during the Fukushima Daiich NPP accident, resulting in ineffective cooling and eventual core damage due to overheating. Sea water was subsequently used to cool the very hot fuel rods and melts of the plant. Based on the lessons learned from the accident, the so-called Ultimate Response Guideline (URG) was recently proposed [2]. Owing to the large potential supply of sea water to NPPs located on sea coasts, it was recommended for use in emergency cooling during Fukushima-like accidents. It is therefore of great importance to the further enhancement of nuclear power safety to

establish the physical mechanism of the quenching of very hot objects in a liquid, especially natural sea water.

Studies on film boiling and the Leidenfrost temperature, which is the minimum temperature required for the sustenance of film boiling, are very abundant in the literature. The mechanism of film boiling heat transfer is reasonably well understood and there are well-established models. Bromley's model [3] for vertical surfaces and horizontal cylinders and Berenson's model [4] for horizontal surfaces are two classical examples. In these two classical models, it was assumed that heat diffused through the vapor film by conduction to the vapor–liquid interface providing entirely the latent heat of evaporation there. The convective effects and liquid subcooling were not considered. Koh [5] and Sparrow and Cess [6] adopted a laminar boundary layer type approach for film boiling on vertical surface to treat the convective effect with some simplifying assumptions at the interface. Sakurai et al. [7] based on the boundary layer theory, developed a comprehensive model for pool film boiling from a horizontal cylinder including the contribution of liquid subcooling and radiation from the heating surface. Numerical solutions for the set of non-linear ordinary differential equations derived were reported and compared well with experimental data. Sakurai et al. also developed a simplified model, neglecting convective effects, but considering heat diffusion through the subcooled liquid boundary layer from the vapor liquid interface. A very complicated equation for heat transfer coefficient of film boiling was reported with liquid subcooling effect included.

The film boiling heat transfer coefficient increased with increasing liquid subcooling. Although the heat transfer mechanism of film boiling is well understood and theory is well-established, the real mechanism of the formation of the vapor film remains unclear. It is commonly accepted that film boiling is characterized by the immediate formation of a thin vapor film between the heated surface and the bulk liquid.

The vapor film of film boiling may become unstable if the surface temperature becomes too low, and the process would no longer be sustainable. The minimum temperature required for film boiling is referred to as the minimum film boiling temperature or the Leidenfrost temperature as pointed out earlier. Although the process is not well understood, several propositions have been made as reviewed in Bernardin and Mudawar [8], including the hydrodynamic instability hypothesis, metastable liquid (homogeneous or heterogeneous) nucleation hypothesis, thermomechanical effect hypothesis, and wettability hypothesis. Such different propositions result in significant different equations for the Leidenfrost temperature.

Recently, the effects of heating surface properties, including wettability, structure, and material, on film boiling and the Leidenfrost temperature have been intensively reported in the literature, e.g. Refs. [9–12]. Vakarelski et al. [9] demonstrated the significant effect of surface wettability on the quenching of 20-mm-diameter stainless steel spheres. They modified the surfaces of the spheres to be superhydrophilic (contact angle < 10°), hydrophilic (contact angle < 30°), hydrophobic (contact angle ≈ 100°), and superhydrophobic (contact angle > 160°). They demonstrated that the temperature dropped rapidly to the pool temperature during the cooling of the superhydrophilic sphere. The cooling of the hydrophilic and hydrophobic spheres began with film boiling, and the Leidenfrost temperatures were about 420 °C and 210 °C, respectively. In the case of the superhydrophobic sphere, film boiling was maintained throughout the cooling down to the pool temperature, without the collapse of the vapor layer. Lee et al. [10] investigated the effect of surface condition induced by 2 h-oxidation procedure and repeated quenching of stainless steel and copper rodlet in water. They found that the surface morphology and roughness of copper rodlet were significantly changed by 2 h-oxidation. They also reported that the quenching duration time was significantly shorten due to unique feather-like structure on the copper surface. However, there was no remarkable influence on quenching performance of stainless steel rodlet resulting from 2 h-oxidation. Thus, they concluded that the quench cooling might be improved and controlled by a surface structure design. Kruse et al. [11] demonstrated the shift of the Leidenfrost temperature from stainless steel surface with multiscale macro/nano structures by the evaporation of a single water droplet on a heated surface. They found that the Leidenfrost temperature of surface with multiscale macro/nano structures was 175 °C higher than that of the polished surface. This shift could be attributed to the reductions in contact angle and substantial capillary wicking resulting from nanoporosity during intermittent contacts by the droplet. Sher et al. [12] investigated that the quenching of spheres with different sizes made by aluminum, copper or steel in subcooled liquid. They reported the dependence of the quenching temperature on the liquid subcooling and material of spheres and increase in the Leidenfrost temperature with the size of spheres.

The effects of coolant additives including nanoparticles and dissolved salt on film boiling and the Leidenfrost temperature have also been conducted intensively in the literature. For example, Kim et al. [13] investigated the quenching of steel and zircaloy spheres using pure water and water-based nanofluids containing low concentrations of alumina, silica, and diamond nanoparticles. They found that the first run quenching in a nanofluid was nearly the same as that in pure water. However, subsequent quenching of the same spheres was significantly accelerated in water containing alumina or silica nanoparticles. The critical heat flux (CHF) and minimum film boiling temperature (MFBT) (i.e., the Leidenfrost temperature) were significantly increased. The minimum film boiling temperature determined from the boiling curve obtained by their lumped capacitance model was as high as 400 °C, which is about 150 °C higher than that for quenching in pure water. Kim et al. attributed the elevated CHF and MFBT and the accelerated quenching effect to the deposition of nanoparticles on the surface of the sphere, which increased the surface roughness and wettability. This apparently destabilized the vapor film as proposed by Park el al. [14] and Takata el al. [15]. Kim et al. also reported that subsequent quenching in water containing diamond nanoparticles was very much the same as that in pure water, although the deposit of the diamond nanoparticles significantly increased the surface roughness and wettability. They therefore suspected some other non-negligible effects. Chun et al. [16] conducted quench experiments of the bare Pt wires and Si/SiC nanoparticle-coated Pt wires in water and nanofluids containing Si and SiC, respectively. They found that for the bare Pt wires there was no significant influence on boiling curve between water, Si and SiC nanofluids. However, a rapid cooling without stable film boiling for nanoparticle-coated Pt wires was demonstrated. They also indicated that this phenomenon depended strongly on the macrostructure and the thickness of nanoparticle deposition layer. Ciloglu and Bolukbasi [17] investigated the quenching behavior of spheres in water-based nanofluids containing various volume fractions of Al_2O_3, SiO_2, TiO_2 and CuO nanoparticles. The heat fluxes in film boiling regime were found to be similar to that of pure water in the first run for all nanofluids. However, a porous layer depending on volume fraction and type of nanofluids was observed during repeated tests. An enhancement of CHF and increase in the Leidenfrost temperature, which was attributed to the porous layer resulting from the deposition of nanoparticles, was reported.

Recently, Lee et al. [18] conducted a quenching experiment to investigate the cooling performance of 35o/oo sea salt solution in reflood heat transfer through a long vertical tube. They found that the cooling performance of the sea salt solution was nearly tenfold that of freshwater, and the CHF was enhanced by 9.7%. Based on microscopic examination, they concluded that the enhancements were not due to the superior wettability produced by the sea salt deposition, but the top quenching caused by the earlier condensation of vapor during the reflood of the sea salt solution. Conversely, Huang and Carey [19] found that the dissolved salt increased the Leidenfrost temperature owing to the evaporation of a liquid drop from a surface heated by the formation of nucleation cavities. They reported that the Leidenfrost temperature was about 10–33 °C higher than that for distilled water, and attributed this to the suppression of bubble coalescence by the dissolved salt, salt deposition during the initial contact of the deposition, and earlier collapse of the vapor film due to increasing salt concentration at the liquid–vapor interface. Indeed, recently, it has been extensively studied in the literature that dissolved salt may suppress bubble coalescence possibly due to colloidal forces, gas solubility, Gibbs–Marangoni effect, surface rheology and ion-specific [20]. However, the inhibiting effect of salts on bubble coalescence is not yet well understood [20]. Abdalrahman et al. [21] investigated the spray cooling of an aluminum alloy using dissolved single salt solution and salt mixtures. In their work, it was proposed to use electrical conductivity instead of concentration to explain the dissolved salt effect on the boiling phenomena. They indicated that the Leidenfrost temperature, the temperature corresponding to the departure form nucleate boiling, maximum heat flux and heat transfer coefficient all increased with increasing electrical conductivity. Furthermore, the effect resulted from salt mixtures was found to be stronger than that of single salt solution.