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Quenching characteristics of a continuously-heated rod in natural sea water

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ABSTRACT

This study explores the quenching of a cylindrical rod with an internal heater in deionized water and natural sea water with pool temperature from 30 °C to 95 °C. An initial temperature of the testing rod ranges from 600 °C to 700 °C. Natural sea water may be used as emergency cooling water in a nuclear power plant near sea coast. The internal heater may be used to simulate the decay heat generated by the nuclear fuel rod after the power plant shutdown. The results demonstrate that film boiling occurs for the quenching in deionized water at any pool temperature investigated in the present study while it is absent when natural sea water is used with pool temperature below 70 °C. The maximal CHF of the non-continuously-heated case (or continuously-heated case) takes place in sea water at 30 °C, which reaches 2104 kW/m^2 (or 1936 kW/m^2), about 132% (or 136%) of that in deionized water. The Leidenfrost temperatures in sea water, if the film boiling is present, are considerably higher than that in deionized water resulting in much shorter quenching time in sea water than that in deionized water. The Leidenfrost temperature decreases as the pool temperature is increased, and the internal heat generation in the testing substance during the quenching process shows insignificant effect on it. In addition, the Leidenfrost temperature can be correlated as the function of the pool subcooling. In conclusion, this study demonstrates the enhancements of the quenching performance and CHF by using sea water as the coolant, instead of deionized water, which further indicates the beneficial sides of using natural sea water as emergency cooling water in a nuclear power plant.

1. Introduction

Quenching is an efficient way to cool a high-temperature substance by exposing it to a low-temperature coolant (also called quenchant), and is frequently used in several engineering applications, such as metallurgy and nuclear industries. The behavior of quenching process is generally influenced by many parameters, such as the surface properties of the substance, thermal–hydraulic properties of the coolant, and temperatures of the substance and coolant. The boiling behavior, surface cooling rate, heat transfer coefficient, critical heat flux (CHF), and Leidenfrost temperature (i.e., the minimal temperature for maintaining the film boiling condition) as well as boiling visualization, during the quenching of various materials and coolants have been widely investigated in recent years. One of the most typically used coolants is water in the literature. For example, Vakarelski et al. [1] explored the effect of surface wettability on the quenching of stainless steel spheres in water. Four types of surface wettability of sphere, namely superhydrophilic (contact angle < 10°), hydrophilic (contact angle < 30°), hydrophobic (contact angle ~100°), and superhydrophobic (contact angle > 160°), were tested. In their experiments, the maximal surface temperature of the hydrophobic (or superhydrophobic) sphere was 700 °C and that of the hydrophilic (or superhydrophilic) was 400 °C. Their results demonstrated that the sphere temperature decreased rapidly to the pool temperature during the quenching of the superhydrophilic sphere, and no film boiling was observed. The Leidenfrost temperatures of about 420 °C and 210 °C, respectively, were clearly identified for the quenching of the hydrophilic and hydrophobic spheres. However, film boiling was maintained during the entire quenching process of the superhydrophobic sphere. Fan et al. [2] studied the quenching behavior of stainless steel spheres with modified surface wettability from superhydrophilic to superhydrophobic in water. Their results

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revealed that the acceleration of the quenching process and the enhancement of the CHF were observed by increasing the surface hydrophilicity. In addition, for the superhydrophobic case the vapor film was stabilized and retained even at a very small wall superheat, as reported by Vakarelski et al. [1].

In recent years, the effects of nanofluids used as the coolant on the quenching behaviors have been studied extensively in the literature. For example, Kim et al. [3] explored the quenching behavior of steel and zircaloy spheres in pure water and water-based nanofluids with low-concentration of alumina, silica, and diamond nanoparticles. The initial temperatures of the testing spheres were controlled to be as high as 1030 °C. They found that the quenching processes of water-based nanofluids were almost the same with that of pure water in the first run of the test. However, in subsequent quenching tests, they observed that some nanoparticles deposited on the surface of the testing sphere which significantly shortened the duration of the film boiling and increased the CHF. They argued that the deposition of nanoparticles on the sphere (i.e., increase of surface roughness and wettability) might disrupt the film boiling, resulting in increasing the Leidenfrost temperature, especially in alumina and silica nanofluids. The effect of nanoparticle deposition on the quenching behavior of a metallic rod in water-based nanofluids was further demonstrated by Kim et al. [4], and Ciloglu and Bolukbasi [5].

Khoshmehr et al. [6] studied the effects of surface roughness and coolant (i.e., deionized water and carbon-nano-tube (CNT) nanofluids) on the quenching behavior of a silver rod with an initial temperature of 650 °C. The results demonstrated that the quenching time for the rough surface was shorter than that for the smooth one. In addition, they found that the nanofluids with lower concentrations shortened the quenching time but that with higher concentrations increased the quenching time as compared to deionized water. However, the CHFs in nanofluids were smaller than that in deionized water and decreased with an increase in the nanoparticle concentration. Their results also showed that the quenching time in both deionized water and nanofluids was decreased with increasing the test run, as reported in [4,5]. Another study, reported by Babu and Prasanna Kumar [7], demonstrated that the preparation process of CNT nanofluids significantly influenced the heat transfer characteristics during the quenching of a stainless steel rod. They found that CNT nanofluids prepared with surfactants reduced the peak heat flux by 24.9% but prepared without surfactants enhanced the peak heat flux by 37.5% during the quenching process as compared to that of water.

For different industrial applications, oils, polymer solutions, and cryogenic fluids (such as liquid nitrogen) are used, as frequently as water, as the coolant in the quenching process. For example, Buczek and Telejko [8] investigated the heat transfer characteristics during the quenching of a rod, made of INCONEL 600, in two mineral oils and a polymer solution. In their study, the rod was heated to nearly 850 °C, and the results demonstrated that the heat transfer coefficients increased with the temperature of the coolant. Prasanna Kumar [9] studied the heat transfer behaviors during the quenching of two different types of steel rod (i.e., the low alloy steel and plain carbon steel) with an initial temperature of about 850 °C in a mineral oil and polymer solution. Their results demonstrated that the maximal cooling rates for the both steel rods occurred between 600 °C and 700 °C, which were also reported by Hasan et al. [10] for several steel rods with a variety of iron alloys at the same initial temperature (i.e., 850 °C), in both mineral oil and polymer solution. In addition, Prasanna Kumar [9] found that the surface heat flux in the mineral oil was slightly smaller than that in the polymer solution.

Recently, Hu et al. [11] used liquid nitrogen as a coolant to study the quenching behavior of an aluminum rod with a normal-polished or nanoporous surface. The temperatures of liquid nitrogen and the testing rod were 77.35 K (i.e., saturated temperature under atmospheric pressure) and 300 K (i.e., room temperature), respectively. Their results showed that the nanoporous surface improved the heat transfer performances in all three quenching regimes (i.e., film boiling, transition boiling, and nucleate boiling). Compared to the normal-polished surface case, the Leidenfrost temperature was increased by 32 K and the CHF was enhanced by 160% in the nanoporous surface case, resulting in a reduction of the cooling time by 20%. Ladizhensky et al. [12] investigated the heat transfer characteristics during the quenching of copper spheres with different surface coatings of crystalline materials (i.e., NaCl, $MgSO_4$, $CaCl_2{\cdot}2H_2O$, and $C_6H_5Na_3O_7{\cdot}2H_2O$) in liquid nitrogen. Their results demonstrated that the coated spheres considerably prevented the film boiling and shortened the transition boiling, resulting in a reduction of use of liquid nitrogen (also cooling time). The maximal heat flux for the best coated surface (i.e., $C_6H_5Na_3O_7{\cdot}2H_2O$) was 8.0 times higher than that for the uncoated surface. It is interesting to noted that the elements of materials (such as Na^+, Cl^-, Mg^{2+}, SO_4^{2-}, and Ca^{2+}) used in Ladizhensky et al. [12] are also the major species in natural sea water.

Another candidate of coolants for the quenching process is an aqueous solution (also namely electrolyte solution). For example, Lozano et al. [13] investigated the transient temperature distribution during the quenching process of a stainless steel rod with an initial temperature of 850–900 °C in pure water and sodium nitrite ($NaNO_2$) aqueous solution with concentrations of 1% and 9% (wt). The results demonstrated that the addition of $NaNO_2$ to water yielded a very high cooling rate (e.g., the maximal surface cooling rate was 1300 °C/s at a surface temperature of about 700 °C). Lee et al. [14] studied the quenching behavior of a long stainless steel tube (1.6 m) with an initial temperature of 620–720 °C in a 3.5% sea salt solution (close to the concentration of natural sea water). In their experiments, the reflood of the coolant was employed as a testing method rather than the immersion of the testing substance. They found that the quenching time of the tube in the sea salt solution was shortened by 10 s (8.4%) and the CHF was enhanced by 9.7% compared to those in water, resulting from the top quenching caused by the earlier condensation of vapor during the reflood of the sea salt solution.

Due to the large potential supply of sea water near a nuclear power plant, it could be recommended for use in emergency cooling, such as the actual use in the accident of the Fukushimas Daiich nuclear power plant (Japan, on March 11, 2011). To investigate the possible application of natural sea water for the emergency cooling of a very high temperature substance, such as a nuclear fuel rod, Hsu et al. [15] conducted an experimental study on the quenching of stainless steel and zircaloy spheres at the temperature of about 1000 °C in both natural sea and deionized water with the pool temperature of 33 °C. The quenching curves (i.e., temperature vs. time) and visualization results of their study demonstrated that the film boiling was clearly observed in deionized water but not occurred in sea water. The formation of vapor film in water was through the coalescence of bubbles nucleated at a very high temperature ($\sim$1000 °C). More rapid quenching was revealed in sea water due to the quenching process starting with transition boiling and the absence of film boiling. They further explained this phenomenon by the zeta-potential effect between the sea water and sphere and other forces between bubbles and dissolved salts. In addition, the rapid bubble nucleation at the surface temperature of nearly 1000 °C was demonstrated by visualization, which is much higher than the classical homogeneous or heterogeneous temperature of bubble nucleation.

To approach the more real condition of the quenching of nuclear fuel rods in a nuclear power plant, the focus of the present study is to investigate the quenching of a rod in natural sea water and compared with that in deionized water reported by Ho et al.