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Effect of change in surface condition induced by oxidation on transient pool boiling heat transfer of vertical stainless steel and copper rodlets

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ABSTRACT

In the present experimental study, the effect of change in surface condition induced by oxidation on the transient pool boiling heat transfer was investigated using vertical SS (Stainless Steel) and copper rodlets. The quenching method was applied, and pure water was used as a quenchant. Various kinds of surface characterizations (i.e., photograph, microscopic image, surface roughness, and water contact angle) together with boiling visualizations were provided and discussed in detail. The surface conditions of the copper test specimen were more sensitively influenced by the repeated quenching tests and 2 h-oxidation, as compared with those of a SS test specimen. The copper test specimen showed a shorter quenching duration than the SS test specimen, owing to its smaller heat capacity. Through a 2 h-oxidation of the test specimens, the surface conditions and quenching curves of the SS test specimen were not altered much. On the other hand, the copper had a very rough surface with unique feather-like structures, which considerably enhanced the quenching performance. This may be because the flaky feather-like structures kept disrupting the vapor film. This result implies that the transient pool boiling heat transfer can be improved and controlled by the functionally well-designed surface structure. Through the boiling visualizations of 2 h-oxidized SS and copper test specimens, the vapor film collapse modes were observed to be different. In SS, the propagative collapse mode was mainly observed. On the other hand, in copper, the vapor film seemed to begin to be collapsed through a coherent collapse mode. Based on this study, it was found that the quenching performance and vapor film collapse mode are strongly influenced by changes in the surface conditions induced by oxidation.

1. Introduction

The quenching process refers to the rapid cooling of a very hot solid object by exposure to a much cooler liquid, which is frequently encountered in a variety of engineering applications: cooling of the superconducting magnet, cryogenic technology, rocket engines, core safety of a nuclear light water reactor, and a rapid solidification process [1,2]. Generally, when a heated metal with a higher temperature than the Leidenfrost temperature is immersed in a liquid pool, it undergoes time-dependently film boiling, nucleate boiling, and single-phase natural convection heat transfer regimes [2].

Several studies on the transient pool boiling heat transfer during quenching have been conducted [2–9]: For example, Bolukbasi and Ciloglu [2] investigated the influence of the test specimen size on film boiling heat transfer during quenching using five kinds of vertical brass cylinders with different sizes. They reported that the test specimens having the same characteristic length, defined as the ratio of volume to surface area, exhibited the same film boiling heat transfer performance. Roy Chowdhury and Winterton [3] studied the surface effects (i.e., the surface roughness and contact angle) on the boiling heat transfer using a quenching technique with metal cylinders (e.g., aluminium and copper) immersed in saturated water and methanol. They mentioned that the contact angle has a very strong influence on the transition boiling, and that improved wetting (i.e., small contact angle) increases the heat flux at a given wall superheat. The roughening turned out to improve the nucleate boiling heat transfer in the experiments using methanol. Wu et al. [4] reported the experimental results of the surfactant (SLS; Sodium Lauryl Sulfate) effect on the pool boiling CHF (Critical Heat Flux) in a wide range of concentration using a quenching sphere. The experimental results showed that the CHF was decreased by the surfactant additive. Yamada et al. [5] carried out the quenching experiments to study the film boiling heat transfer around a vertical silver cylinder with water under atmospheric pressure condition. The analytical solutions for saturated and subcooled boiling were obtained by applying a two-phase boundary layer theory for a vapor film with a smooth interface.

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Nomenclature

A	area (m^2)
c	specific heat (J/kg K)
q''	heat flux (W/m^2)
R	surface roughness (μm)
T	temperature (K or °C)
ΔT	temperature difference (K or °C)
t	time (s)
V	volume (m^3)

Greek letters

ρ	density (kg/m^3)

Subscripts

a	surface roughness (arithmetic mean)
IRC	initial rod center temperature
RC	rod center temperature
z	surface roughness (average based on segment peaks and valleys)

Their proposed method predicted the experimental data within ±15%. Recently, quenching experiments using various kinds of nanofluids with different concentrations have been extensively carried out to achieve a high-performance boiling heat transfer [1,10–17]. The quenching behavior was strongly dependent on the kind of nanoparticles as well as their volume fraction. In most papers, some nanofluids were reported to be an effective way to enhance the boiling heat transfer (i.e., high critical heat flux, transition boiling heat transfer performance, minimum heat flux point, and fast quenching front velocity), which might be caused by a change in the surface characteristics (e.g., a decrease in the contact angle and/or an increase in the surface roughness) owing to the deposition of nanoparticles on the surface. Based on the previous researches, the surface condition can have a significant influence on the transient pool boiling heat transfer during rapid cooling, which should be performed further using different materials and surface conditions.

Meanwhile, from a practical viewpoint, the surface oxidation may be not desired, but is an inevitable phenomenon to be considered as an important parameter to determine the performance of an industrial thermal energy system. A few researches on the surface oxidation effect on boiling under steady-state and transient conditions are available as follows: Sinha et al. [18] carried out experiments on transient pool boiling heat transfer for nuclear fuel application using an instrumented nuclear fuel rod simulator manufactured with a combination of cladding and filler. In their experimental data, the oxidation had a strong effect on the minimum film boiling temperature, quench phenomenon, and boiling curve. The thicker oxide layer resulted in a significant increase in the minimum film boiling temperature. Coursey and Kim [19] performed CHF tests under a steady-state condition using a copper heater surface with five different surface oxidation levels. They reported that the oxidized copper surface decreased the water contact angle, and clearly exhibited higher CHF values. The well-oxidized surface enhanced the CHF by about 41%. Lee and Chang [20] examined a water pool boiling CHF under the steady-state condition using an SA508 test heater, which is the material of the reactor pressure vessel in a nuclear power plant. They reported that SA508 showed a higher CHF value, which was due to the change in the surface. In other words, corrosion occurred on the surface of the test heater, which was analyzed to be magnetite (Fe_3O_4). Our research group [21] has examined the surface oxidation of zircaloy on CHF under steady-state conditions for nuclear fuel cladding application, and reported that the oxidized zircaloy surface achieved a higher CHF than a non-treated surface. Based on the previous studies [18–21], the investigations on the influence of surface oxidation on transient pool boiling heat transfer are still very limited and insufficient. Moreover, considering the industrial heat transfer applications, the SS (Stainless Steel) and copper materials, widely and popularly used in a thermal energy system, should be targeted and tested. Therefore, studies on transient pool boiling heat transfer using SS and copper materials should be conducted.

In this work, the transient pool boiling heat transfer during rapid cooling is investigated using vertical SS and copper rodlets. Various kinds of surface characterizations (i.e., photograph, microscopic image, surface roughness, and water contact angle) are carried out and provided in detail. Quenching experiments using as-received and 2 h-oxidized test specimens are performed, and their behaviors are examined and discussed together with the results of surface characterization and boiling visualization. Our belief is that this effort can be quite a useful and meaningful contribution to understand the relationship between metal surface oxidation and transient pool boiling heat transfer.

2. Experimental

2.1. Facility for quenching

In Fig. 1, an image and schematic of the experimental facility for a quenching test are shown. A furnace to radiantly heat up the test specimen is 320 mm in diameter and 350 mm in height, which provides a maximum temperature of around 1000 °C. In the furnace, four K-type sheathed thermocouples are installed: One is to set and control the furnace temperature, and the others are to monitor it. As the test specimen, SS (Type 304) and copper are used. The test specimen has a vertical cylinder shape with a hemispherical shaped bottom, and its dimension is 10 mm in diameter and 60 mm in length. To measure and check the center temperature of the test specimen, a K-type ungrounded sheathed thermocouple (Watlow) of 0.5 mm in diameter and 1500 mm in length is tightly inserted into the hole of about 30 mm in depth precisely drilled at the center of the test specimen. The response time of the thermocouple is below 0.02 s, as the specification provided by the manufacturer, and the uncertainties of temperature measurement are estimated to be within $\sim$2% for 100 °C and $\sim$1% for 300 °C using the field metrology well (FLUKE 9143). The test specimens with a thermocouple are connected to a SS tube of 3.175 mm (1/8 in) in diameter and 50 mm in length, which is connected to a SS tube of 12.7 mm (1/2 in) in diameter and 700 mm in length using the compression fitting. Finally, this assembly is fixed to the moving holder. The moving holder is operated vertically up and down using an airslide, and its working distance from the center of the furnace to the quenchant pool is set to about 350 mm. The average downward moving velocity of the test specimen is about 0.3–0.4 m/s. As the quenchant, pure water is used. For the quenchant pool, a glass beaker is used for visualization, which is 100 mm in diameter and 150 mm in height. The quenchant pool is placed on a hotplate to generate the desired pool temperature. To measure the quenchant pool temperature, a T-type sheathed thermocouple is installed. The temperatures of the furnace, quenchant pool, and center of the test specimen are monitored and stored using a data acquisition system (Data Translation, DT9828).