Nuclear Engineering and Design 313 (2017) 118–128

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Parametric investigation on transient boiling heat transfer of metal rod cooled rapidly in water pool

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HIGHLIGHTS

- Effects of liquid subcooling, surface coating, material property, and surface oxidation are examined.
- Liquid subcooling affects remarkably the quenching phenomena.
- Cr-coated surfaces for ATF might extend the quenching duration.
- Solids with low heat capacity shorten the quenching duration.
- Surface oxidation can affect strongly the film boiling heat transfer and MFB point.

ARTICLE INFO

Article history:
Received 1 September 2016
Received in revised form 2 December 2016
Accepted 3 December 2016

Keywords:
Transient pool boiling
Quenching
Film boiling heat transfer
Minimum film boiling point
Inverse heat transfer analysis

ABSTRACT

In this work, the effects of liquid subcooling, surface coating, material property, and surface oxidation on transient pool boiling heat transfer were investigated experimentally using the vertical metal rod and quenching method. The change in rod temperature was measured with time during quenching, and the visualization of boiling around the test specimen was performed using the high-speed video camera. As the test materials, the zircaloy (Zry), stainless steel (SS), niobium (Nb), and copper (Cu) were tested. In addition, the chromium-coated niobium (Cr-Nb) and chromium-coated stainless steel (Cr-SS) were prepared for accident tolerant fuel (ATF) application. Low liquid subcooling and Cr-coating shifted the quenching curve to the right, which indicates a prolongation of quenching duration. On the other hand, the material with small heat capacity and surface oxidation caused the quenching curve to move to the left. To examine the influence of the material property and surface oxidation on the film boiling heat transfer performance and minimum film boiling (MFB) point in more detail, the wall temperature and heat flux were calculated from the present transient temperature profile using the inverse heat transfer analysis, and then the curves of wall temperature and heat flux in the film boiling regime were obtained. In the present experimental conditions, the effect of material property on the film boiling heat transfer performance and MFB point seemed to be minor. On the other hand, based on the experimental results of the Cu test specimen, the surface oxidation had great impact on them. As compared with the as-received Cu test specimen, the pre-oxidized one showed the higher film boiling heat transfer performance and MFB heat flux, but it had the lower MFB temperature.

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1. Introduction

From a typical boiling curve of a solid in liquid pool at constant pressure, one can observe four different heat transfer regimes: single-phase natural convection, nucleate boiling, transition boiling, and film boiling (Kim et al., 2009; Bolukbasi and Ciloglu, 2007). These heat transfer regimes in the boiling curve are generally expressed by the heat flux and excess temperature (the temperature excess of the solid surface immersed in the liquid pool of the saturation temperature) also called wall superheat (i.e., $\Delta T_w = T_w - T_{sat}$, where ΔT_w, T_w, and T_{sat} are the wall superheat, wall temperature of solid, and saturation temperature of liquid, respectively). As the wall superheat is increased gradually from 0 °C, the four heat transfer regimes will appear in the order of single-phase natural convection, nucleate boiling, transition boiling, and film boiling. Transitions of boiling regimes in the opposite order will be observed when lowering the temperature of the solid from above the minimum film boiling (MFB) point, i.e., cooling of the solid surface.

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http://dx.doi.org/10.1016/j.nucengdes.2016.12.005
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Nomenclature

A	area (m^2)
c_p	specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)
D	diameter of test specimen (m)
g	gravitational acceleration constant (=9.81 $m \cdot s^{-2}$)
h_{lv}	latent heat of vaporization ($J \cdot kg^{-1}$)
k	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
L	length of test specimen (m)
q''	heat flux ($W \cdot m^{-2}$)
R	radius of test specimen (m)
r	radial coordinate
T	temperature (°C)
ΔT	temperature difference (°C)
ΔT_w	wall superheat (°C)
t	time (s)
Δt	time step (s)
V	volume (m^3)

Greek letters

α	thermal diffusivity ($m^2 \cdot s^{-1}$)
δ	coating thickness (μm)
μ	viscosity (Pa·s)
ρ	density ($kg \cdot m^{-3}$)
σ	surface tension ($N \cdot m^{-1}$)

Subscripts

B	Berenson (1961) correlation
c	rod center temperature
cr	chromium coating
H	Henry (1974) correlation
i	*i*th discrete time
l	liquid
MFB	minimum film boiling
s	solid
sat	saturation temperature
ts	test specimen
v	vapor
w	wall

From the heat transfer point of view, the quenching is the rapid cooling of a solid at a high temperature by exposure to a liquid at a much lower temperature. This process plays a critical role in the safety of nuclear power plants (Lee et al., 2012). The fuel rods in nuclear power plants can overheat during a loss-of-coolant accident. The supply of cold water by the emergency cooling system to the overheated fuel rods is represented by quenching process. Recently, the quenching experiments using the sea water have been reported for the application of nuclear power plant accident (Fu et al., 2016; Hsu et al., 2015; Lee et al., 2013). The effectiveness of the cooling will depend on the boiling heat transfer regime. If the temperature of the fuel rods excesses the MFB point, the cooling of fuel rods can be hindered by the vapor barrier during film boiling. Under such a circumstance, the heat transfer rate in the film boiling regime is generally lower by order of magnitude than that in the nucleate boiling regime, which is the reason that film boiling is considered an undesirable form of heat transfer and to be avoided in the engineering designs. In other words, since the heat transfer performance in the film boiling regime becomes to be remarkably degraded, the predictions of the change in the heat transfer regime from the film boiling to the transition boiling and nucleate boiling regimes (i.e., MFB point) and the film boiling heat transfer performance can be the important subjects in the various kinds of industrial applications related to the quenching process. Hence, the investigations on them under the diverse conditions should be performed.

Meanwhile, the nuclear fuel rods in the nuclear reactor are installed parallel to the coolant water flow. Therefore, considering the nuclear fuel application, it is meaningful to carry out the quenching experiments using the vertical rod-typed test specimen made of zircaloy widely used as the nuclear fuel cladding. Lately, after the Fukushima nuclear accident, the research activities on the accident tolerant fuel (ATF) have been highlighted for the nuclear reactor safety. One of research objectives in ATF is to decrease the hydrogen generation induced by the nuclear fuel cladding oxidation under the high-temperature condition (Kim et al., 2014). To reduce the large amount of hydrogen generation, the chromium-coated zircaloy cladding is considered to be a candidate for ATF. Lee et al. (2016) conducted preliminarily the transient heat transfer experiment using the chromium-coated metal test specimen. However, the further investigations through the additional experiments are necessary for ATF application.

There have been many studies to investigate the transient pool boiling by means of quenching experiments. Three decades ago, Roy Chowdhury and Winterton (1985) pioneered the importance of the surface roughness and surface wettability on pool boiling heat transfer. Their quenching experiments with aluminum and copper cylinders showed a significant correlation between the surface wettability and heat transfer during transition boiling when immersed in saturated liquid water and methanol. The heat flux was increased with surfaces having higher wettability. Their conclusions also included the enhancement in nucleate boiling heat transfer on roughened surfaces. Recently, more refined studies have been conducted to closely look at the role of surface effects. For example, Kim et al. (2009) reported that nanofluids work in favor of enhancing the critical heat flux (CHF). They argued a mechanism that the surface roughness increase and wettability enhancement caused by the nanoparticle deposition on the surface of steel or zircaloy sphere affects the heat transfer during quenching. Various research groups examined the quenching behavior using the different kinds of nanofluids with various concentrations (Kim et al., 2009; Lee et al., 2012; Bolukbasi and Ciloglu, 2011; Ciloglu and Bolukbasi, 2011; Kim et al., 2010; Chun et al., 2011; Zhang et al., 2014; Babu and Prasanna, 2011). The common conclusion is that the rapid cooling process is influenced by some nanofluids. The increased roughness and wettability by the nanoparticle deposition may be responsible for increased heat transfer during the transient boiling heat transfer. One of most recent reports (Kang et al., 2016) investigated the effect of a completely wettable surface on film boiling heat transfer. The completely wettable surface was prepared using the anodizing technique of zirconium rod, which exhibited the capillary-wicking into nano-scale, needle-shaped structures on the surface. They compared it with a bare surface, and showed superior heat transfer performance during film boiling on the completely wettable surface with an increase in the minimum heat flux of 158%. Fan et al. (2014) investigated the influence of surface wettability on transient pool boiling heat transfer using the nanostructure-coated spheres. They reported that the surface wettability affected significantly the CHF, MFB point, average surface heat transfer coefficient, and equivalent vapor film thickness.

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