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Critical heat flux for SiC- and Cr-coated plates under atmospheric condition

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ABSTRACT

Hydrogen gas released by Zircaloy's oxidative reaction can lead to disastrous results, as observed in the Fukushima accident. SiC and Cr, however, have low potential for a hydrogen explosion. This paper is focused on measuring the critical heat flux (CHF) for SiC and Cr surfaces, which are known to have favorable properties such as oxidation resistance of a bulk material in atmospheres containing steam or a high vapor fraction. SiC also has a low neutron absorption cross-section, which is one of the required characteristics for cladding of light water reactors (LWRs).

Regarding their application, SiC and Cr materials can potentially be used to design coatings for the Zircaloy cladding that is used at present. We suggest that SiC coating can be achieved through a PVD (physical vapor deposition)-sputtering and Cr coating can be achieved through an electroplating process on the surface of the Zircaloy cladding. After coating, reaction between the Zircaloy cladding and steam will be reduced. In this study, coatings were achieved on the stainless steel plate to assess the surface effects on CHF. Two groups of experiments were conducted to assess the heat transfer performance of the SiC and Cr surfaces. The experiments were carried out under pool boiling condition of saturated de-ionized (DI) water to assess the SiC- and Cr-coated surfaces. SiC and Cr coatings with two levels of thickness were prepared and evaluated. The SiC-coated surfaces showed improved CHF compared with the other surfaces used in our experiments. Test sections with thicker coatings showed higher CHF results than the thinner ones. The enhanced performance was due to improved surface wettability. On the other hand, Cr-coated surfaces have shown lower CHF results compared with other surfaces regardless of the thickness used in our experiment.

1. Introduction

During severe accidents or LOCA (loss-of-coolant accident) situation when coolant is not properly provided, claddings are often exposed to steam. Under such condition, the integrity of the cladding can be threatened by accelerated embrittlement through hydriding and active oxidation. If hydrogen is not properly eliminated, explosions can occur which may threaten the integrity of the containment. The Fukushima accident in Japan demonstrates the potential danger of actively produced hydrogen not properly eliminated and exothermic reaction between the zirconium-based alloy and steam. Fukushima accident provoked interest in materials and structures that minimize oxidation, even at a high temperature. As a candidate, SiC has been regarded as a strong candidate material because it undergoes less oxidation than the Zircaloy claddings that are used at present. SiC also has a low neutron absorption cross-section, which is a necessary property for LWR claddings. Also, Cr is a well-known corrosion-resistant material at high temperatures and commonly used in industries. Corrosion-resistant materials such as SiC and Cr reduce oxidation by way of forming protective oxide layer on the surface which inhibits further oxidation. Historically, SiC has been used under high temperature conditions such as in fusion reactors and other very high temperature reactors due to its excellent properties at high temperatures. In addition, SiC monoliths and SiC/SiC composites have been investigated for use in LWRs (Carpenter, 2006; Feinroth et al., 2009; Jung et al., 2012; Kim et al., 2012). According to Feinroth et al. (2009), triplex specimens have the same hoop strength as unirradiated samples within 2 standard deviations after exposure to typical PWR operating conditions, including fast neutron irradiation. Furthermore, their study showed that the addition of an outer composite layer with a unique fiber architecture and an outer

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environmental barrier layer can provide additional pressure retention capacity. Kim et al. (2012) discussed overall trends and future studies regarding the applicability of SiC for LWR fuel. Jung et al. (2012) introduced metal-ceramic hybrid cladding consisting of an inner zirconium tube and an outer SiC fiber-matrix made from SiC ceramic composite. This study attempted to resolve the problems associated with fission gas confinement and the joining of end caps. In the study by Carpenter (2006), SiC duplex was proposed as a fuel cladding. In this study, the behavior of SiC cladding was compared to that of conventional Zircaloy cladding to demonstrate that SiC has superior resistance to creep and mechanical degradation due to radiation or oxidation. Cr has also been widely used as a corrosion-resistant material since it forms protective oxide layer on the surface. Not just under the air and water (steam) conditions, chromium oxide is also stable in alkaline solutions. Many studies have confirmed the effect of Cr-added alloys and the amount of Cr addition to the bulk materials. In many industrial areas, Cr is included in alloy or is used as a coating material to protect the bulk material from corrosion and wear. According to Viswanathan et al. (2006), up to 40% Cr is recommended for highly corrosive environments. According to Rohr (2005), one possible way to minimize the corrosion phenomena is Cr coating on the surface, and the bulk material will give mechanical properties like creep resistance at the same time. Kim et al. (2013) have carried out stainless steel oxidation experiments with different Cr contents under 900 °C steam condition up to 200 h. The results have shown that specimen of high Cr content formed protective layer and prevented further oxidation. They suggested minimum Cr content of 18–20 wt% is required to act as an oxidation barrier.

Under nucleate boiling conditions, heat can be transferred into liquids efficiently with less superheating on the surface. However, as heat flux on the surface increases further, bubbles rapidly form and begin to merge with each other, inhibiting the motion of liquid near the wall. Slugs and vapor become more unstable with increasing surface temperature and begin to form local blankets. The proportion of film increases and the heat transfer coefficient (HTC) decreases with further increases in the surface temperature. At a certain point referred to as the CHF, the surface is completely covered by a vapor film. At this point, the temperature of the surface rises abruptly due to a sudden decrease in the HTC caused by the film layer. Above the CHF, an abrupt temperature increase can induce material failure. Therefore, the CHF is a very important value related to thermal hydraulic phenomena.

CHF is related to many factors including material properties and thickness. Many studies have shown that surface wettability is one of the most important factors that influence the CHF. According to Phan et al. (2009), wettability is an important factor in bubble growth. Kandlikar (2001) proposed a theoretical CHF model that used the dynamic contact angle to assess the effect of surface wettability. According to the experimental results of Jeong et al. (2008), the CHF is strongly affected by wettability, as determined by contact angle measurements. In the studies by Lee et al. (2012, 2013) magnetite nanoparticles deposited on a heated surface improved both wettability and CHF. According to other previous studies (Chun et al., 2011; Kim et al., 2006; Lee et al., 2012; Song et al., 2014), CHF was enhanced in nano-fluids due to the deposition of nano-particles on the surface during evaporation. Many other studies have verified this relationship between wettability and CHF, making it a major subject of study in the heat transfer characteristics of materials. In addition to wetting, thickness of the material also greatly affects heat transfer. According to Gogonin (2009), CHF depends substantially on the thickness of heated wall. This study has summarized based on many studies that heat generated on a thick-walled heater is dissipated both to coolant and heater itself by conduction. Tachibana et al. (1967) also showed that there exists great dependency of CHF on wall thickness introducing the newly defined parameter. But this and other studies showed that there is some saturated thickness from which thickness effect is negligible. Based on these studies, it is clear that changing the surface of claddings from Zircaloy to SiC or Cr will change the heat transfer properties. However, there is still a lack of information regarding the thermal hydraulic properties of SiC and Cr coatings. Therefore, the purpose of this study is to measure the CHF of SiC and Cr surfaces to assess their applicability as coatings for LWR claddings. CHF values of SiC- and Cr- coated surfaces were measured for two different coating thicknesses under pool boiling conditions. Furthermore, the contact angle, scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), atomic force microscopy (AFM), and X-ray diffraction (XRD) were used to evaluate heat transfer mechanisms and confirm the coating quality.

1.1. Preliminary calculation of neutron economy

Neutron economies were calculated for SiC- and Cr-coated Zircaloy cladding. For the purpose, MCNP calculation under assumption of infinite lattice was used. MCNP is abbreviation of Monte Carlo N-Particle code which is Monte Carlo transport code for several types of particles. Monte Carlo method can depict statistical reactions with given cross-section values from libraries like ENDF/B-VI and is useful for the complex calculations that is hard to be solved with deterministic methods. According to the calculation, SiC-coated Zircaloy cladding showed better result than that from the Cr-coated case. Chromium has relatively high neutron absorption cross section that chromium coatings on the Zircaloy surface will decrease the effective multiplication factor with increasing thicknesses more than the SiC coatings resulting in degraded neutron economy in LWR ($\sigma_{a,Cr} = 3.1$b, $\sigma_{a,Si} = 0.16$b, $\sigma_{a,C} = 0.0034$b at 0.0253 eV). The schematic structure used in our calculation is shown in Fig. 1. The relative deviation of the multiplication factor when SiC and Cr coatings are added on zirconium-based alloy cladding are represented in Fig. 2. Relative deviation of the multiplication factor was calculated by relative error based on the multiplication factor of the non-coated zirconium-based cladding (k_{ref}).

2. Experimental apparatus

2.1. Test pool and procedure

The pool boiling experiment was carried out with DI water, and the fluid was saturated under atmospheric conditions. The condenser transformed the vapor into liquid and kept the system

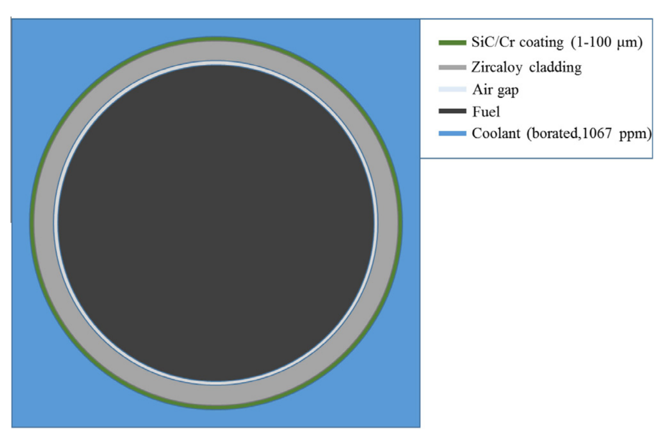

Fig. 1. The schematic description of the structures used in our calculation.