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Quenching heat transfer analysis of accident tolerant coated fuel cladding

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ABSTRACT

Transient boiling heat transfer during quenching of the candidate Accident tolerant fuel (ATF) claddings on vertical rodlets is studied experimentally. The candidate ATF material (Chromium, FeCrAl, and Molybdenum) are applied on Zircaloy-4 rodlets. The vertical solid rodlets are heated to 600 and 1000 °C and are quenched in a saturated pool of water. The temperature variation during the quenching of rodlets was recorded online with synchronized visualization of boiling regimes over the test specimen using a high-speed video camera. The quench performance of the ATF coatings is analyzed based on the examination of various surface parameters supported by microscopic images analysis and contact surface profilometry. In order to obtain a more realistic picture of the candidate performance during the emergency cooling reflood phase in a nuclear reactor, the coated rodlets are also oxidized in an autoclave before quenching. The performance of the candidate claddings after oxidation is also analyzed along with their surface characterization. It was observed from the analysis that the surface characteristics and oxidation had a significant impact on the quench performance of ATF coatings which varied between different coating materials.

1. Introduction

Development of accident tolerant fuels (ATF) for light water reactors (LWRs) came into focus for the nuclear engineering community after the accidents at Fukushima-Daiichi. In the subsequent year, the U.S. Congress guided the US Department of Energy (DOE) to develop nuclear fuels and claddings with improved accident tolerance (Carmack et al., 2013). The DOE funds multiple teams across national laboratories, universities, and the nuclear industry for the development and testing of ATFs. The primary focus of the ATF program is to identify alternative fuel and cladding technologies that may provide enhanced safety, competitiveness, and economics. The new fuel design must also be compatible with present-day LWR design. Other countries such as France, Russia, Republic of Korea, China and India also are engaged in unique programs focusing on the development of ATFs. An ATF deployment timeline depends on its development stage. For near-term applications, coatings on the nominal Zirconium-based cladding material and other metallic materials are being considered to improve the corrosion resistance and reduce the generation of hydrogen at high temperatures (Zinkle et al., 2014). Thermal-fluids characteristics are pivotal for a robust testing of ATF concepts as the proposed candidates may have an entirely different thermal-hydraulic behavior when compared to Zircaloy-4. ATF coatings may display very different boiling characteristics, as a result, different microstructures and surface characteristics (Brown et al., 2016). Major ATF coating choices under consideration include Chromium as a coating (Park et al., 2015), FeCrAl as cladding (Snead et al., 2014) and Molybdenum as one layer of cladding (Cheng et al., 2016) which have demonstrated better mechanical and oxidation behavior during the experimental testing.

Evaluation of quench performance is critical in the development process of ATF surfaces. During a loss of coolant accident (LOCA), the fuel cladding gets overheated and the cooling is established with the emergency cooling system (Duffey and Porthouse, 1973). The coolability of the claddings during the reflood phase is governed by its quenching characteristics. Quenching is defined as the rapid cooling of a solid initially at a very high operating temperature (Yeh, 1975). The heat transfer coefficient on the cladding surface during the initial phase of quenching is very low as a result of film boiling. In the film boiling regime, a stable vapor film covers the surface of the cladding thus reducing the contact between the coolant and the surface (Murao and Sugimoto, 1981). The large thermal resistance created between the heated surface and the coolant reduces the coolant rate by an order of magnitude when compared to the subsequent nucleate boiling regime. Nucleate boiling occurs at a lower temperatures in which the film collapses and vapor bubbles are formed at the heated surface which provides an efficient means for heat transfer (Bankoff and Mehra, 1962). The transition point from the film boiling to nucleate boiling regime is known as Minimum Film Boiling (MFB) or Leidenfrost

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temperature (Gottfried et al., 1966). The Leidenfrost temperature and nucleate boiling heat transfer coefficient depends on the material thermal conductivity and surface properties such as wettability, surface roughness and porosity (Kruse et al., 2013).

Evaluation of quenching phenomenon in vertical rods is important as its synonymous to the quenching of nuclear fuel rods after a LOCA. Many works have focused on establishing the governing mechanisms affecting the transient boiling during quenching in vertical rods. The experiments of Elliott and Rose (1970) are one among the pioneering works to study the falling film over stainless steel and Zircaloy tubes. They concluded that low thermal capacity of Zircaloy had a positive impact on the quenching velocity when compared to stainless steel, the potential choice of fuel cladding for operations at high temperature. Few results also demonstrated similar behavior under subcooled conditions (Piggott et al., 1976). The lateral conduction is the dominating phenomenon that influences the quench front velocity and the Leidenfrost temperature. Experiments performed at UCLA (Drucker et al., 1980; Tung et al., 1986) aimed at the development of a mechanistic model to account for the effect of lateral conduction. Subsequently, Dhir et al. (1981). Derived a semi-empirical model to explain the quenching phenomenon in Zircaloy rod bundles based on the experiments to present a more useful picture of the nuclear fuel rod behavior

A few works later discussed in detail the effect of conductivity, subcooling, and gravity on the quench boiling performance of vertical rodlets (Mozumder et al., 2007; Westbye et al., 1995). In the latter part of the last decade, nuclear engineers began exploring the possibility of using nanofluids as a possible coolant for normal and post-LOCA operations (Buongiorno, 2006; Kim et al., 2007). Kim et al. (2009a,b) performed experiments with different nanofluids and observed an increase in Leidenfrost temperature and quench front velocity. It was noted that the nanoparticles stuck to the surfaces of the rodlet, thereby increasing the surface roughness and porosity. The analysis was also done to study the separate effect of porosity, surface roughness and wettability on the Leidenfrost temperature and the quench front velocity (Kim et al., 2011). It was concluded that the increase in hydrophilicity and surface roughness due to the deposition of nanoparticles was responsible for improved quench boiling heat transfer. Later few models were proposed based on capillary wicking and early evaporation of microlayer as result of varied surface roughness and porosity which, explained the physics behind the influence of surface characteristics on the boiling heat transfer (Ahn et al., 2012; Kim and Kim, 2007; Son et al., 2017). As the focus shifted to the development of ATF claddings, researchers began investigating the performance of various ATF coatings and alternate cladding materials. Lee et al. (2016) carried out quench experiments on Zircaloy and chromium-coated samples and it was seen that Zircaloy had better quench characteristics when compared to chromium. In a subsequent work (Lee and Kim, 2017), the parametric influence of surface characteristics and subcooling was documented for the chrome coated cladding. More recently, Kang et al. (2018) published the work demonstrating the quenching behavior of FeCrAl and SiC cladding material and compared it with the nominal cladding material. Zircaloy-4. The analysis was also done on the oxidized claddings and it was observed the oxidation of claddings lead to a significant difference in the quench characteristics as a result of a change in wettability.

The objective of the present work is to present the report of the experimental findings on the performance coated claddings such as chromium, FeCrAl and Molybdenum applied on Zircaloy-4. Quench and wettability tests are carried out before and after oxidation of the samples and a detailed characterization is presented supported with high-speed camera results and microscopic image analysis. Though a few works have tried to bring out the differences observed in the quenching characteristics of chromium and zircaloy (Lee et al., 2016; Lee and Kim, 2017), so far no results are published with the FeCrAl coating. The analysis was made with the solid FeCrAl in Kang et al. (2018) but, the variation in specific heat capacity resulted in very different quench characteristics. The present work aims to bridge this gap by using the same parent material (zircaloy) with the FeCrAl coating applied on the surface thus, comparing the two materials with similar heat capacity. Similarly, the present work is novel in the analysis of Molybdenum as a possible accident tolerant fuel cladding. Molybdenum with protective layers has been investigated as an ATF candidate because of its high melting temperature and high-strength properties at elevated temperatures (Cheng et al., 2016).

Though an analysis was presented in (Lee and Kim, 2017) on the effect of surface oxidation in the quenching characteristics, the effect of contact angle, surface roughness and porosity is not considered in detail. Furthermore, the oxide samples display an interesting time-dependent trend in their wettability as a result of hydrophobic recovery which is vital in deciding the performance of the fuel cladding and has not been dealt with so far in detail for nuclear materials. In this work, the wettability of the samples was measured immediately after oxidation, and periodic measurements were henceforth taken to quantify the hydrophobic recover. Apart from this, the role of emissivity has been neglected in existing literature which could have a strong impact on the film boiling heat transfer affecting the peak cladding temperature as well as the coolability of the cladding during a postulated LOCA. Emissivity variations in the oxidized and non-oxidized samples are considered in the current work and the impact on the cooling curve is presented. Finally, the potential effect of the quenching characteristics (quench front velocity and film boiling rate) of the present work on the peak cladding temperature is also discussed.

2. Materials and methods

Fig. 1(a) shows the experimental setup for the quench tests. Tested samples are cylindrical rodlets made of Zircaloy-4 (Sample 1), chromium coated on Zircaloy, Low Alloy FeCrAl (10 Cr, 6 Al, Bal. Fe) coated on Zircaloy (Sample 3) and Molybdenum coated on Zircaloy (Sample 4). The test sample is a cylindrical solid rodlet (test sample) of diameter 4.8 mm and height of 50 mm. The coating thickness of all the coated samples is 100 ± 5 μm and thus the expected change in thermal conductivity and specific heat capacity is negligible for the small thickness of the coating compared to the rodlet thickness. The radiant furnace is used to achieve a maximum temperature of 1000 °C which is powered with a DC power supply (25 V, 150 A). Pneumatic pressure (600 kPa) is used to displace the sample from the furnace downward to the quench pool at a mean velocity of 0.5 m/s (As measured). The downward

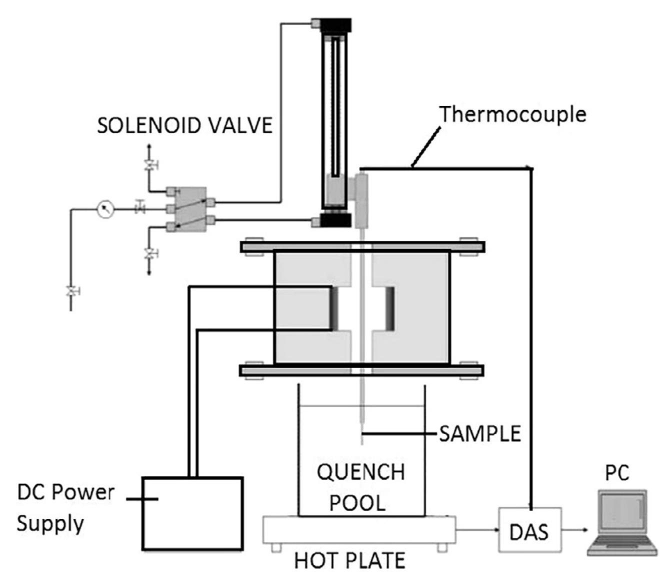

Fig. 1. (a) Quench experimental setup. (b) Thermocouple attachment to the rodlet.