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Towards understanding the effects of irradiation on quenching heat transfer

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ABSTRACT

Quench and rewet characteristics at low pressure depends on the heated sample surface characteristics. The rate of decrease in the maximum temperature during the quench of heated specimen depends on its surface, material, and the quenching environment. The effect of irradiation on the quench heat transfer, particularly gamma irradiation has been investigated previously for metallic rodlet specimens. Some of the previous studies demonstrated an improvement in wettability and Leidenfrost temperature in oxide surfaces as a result of exposure to gamma irradiation. However, the mechanism behind such improvements has not been studied in detail. The present work reports the experiments carried out to understand the wettability and quench performance of Zircaloy-4, the nominal fuel cladding material for nuclear energy, and chrome-coated Zircaloy rodlets, proposed coating material to increase Zircaloy's accident tolerance in response to Fukushima disaster, under gamma irradiation. The goals of the experiments were to delineate the effect of radiation on the transient pool boiling behavior during the quenching of the surfaces and assist the development of a mechanistic model. The results of water quenching and contact angle studies showed a higher Leidenfrost temperature and wettability in both samples exposed to gamma irradiation. Further, to understand the effects of gamma irradiation, independent studies with ultraviolet ozone treatment were performed and microscopic images of the gamma irradiated samples were analyzed. It was found that formation of oxide micropores in the samples exposed to gamma irradiation was the primary mechanism for enhanced wettability as well as higher Leidenfrost temperature.

1. Introduction

Quenching [1] or chill down refers to the rapid cooling of hot objects contacted by a much cooler fluid. It has many applications in various industrial and energy production processes such as cryogenic cooling systems. Cryogenic startup systems require efficient chill down during their startup for stable operation [2]. Similarly, in a light water nuclear reactors (LWR), the fuel rods (made up of fuel pellets surrounded by the cladding, are quenched by flooding the core with emergency water during certain limiting accident conditions. The heat removal from the fuel rods during quenching is severely restricted by the occurrence of film boiling, in which a stable vapor film surrounds the surface of the cladding [3]. The vapor film creates a large thermal resistance between the heated surface and the coolant, thus reducing the cooling rate by an order of magnitude when compared to the subsequent nucleate boiling occurring at low temperatures after the vapor film collapses. The transition point from film boiling to nucleate boiling regime is known as Minimum Film Boiling (MFB) or Leidenfrost temperature [4]. The Leidenfrost temperature and nucleate boiling cooling rate depend on the material thermal conductivity, volumetric heat capacity and surface properties such as wettability, surface roughness and porosity. It was found that increased wettability and porosity improves the capillary wicking leading to higher Leidenfrost temperature [5]. In the case of a nuclear reactor, the fuel rods are installed in vertical direction (for LWR's) which is parallel to the coolant water flow. Therefore, the evaluation of the quenching phenomenon in vertical rods becomes important. A substantial amount of work was done in the past four decades to establish the physical phenomenon affecting transient boiling during quenching in vertical rods. Elliot and Rose [6] were among the early ones to study the film collapse over stainless steel and Zircaloy tubes. They concluded that Zircaloy had a high quenching velocity compared to the stainless steel due to its low thermal heat capacity. Similar results were seen in the subcooled quenching experiments by Piggott et al. [7]. Few works followed on analyzing the effect of lateral conduction on quench front velocity and the transition from film boiling to nucleate boiling heat transfer [8]. A more realistic picture for nuclear applications was obtained from

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the experiments of Dhir [9]. Dhir [10] derived a semi-empirical model to explain the quenching phenomenon in Zircaloy rod bundles based on experiments. Since then, few works have studied the effect of conductivity, subcooling and gravity on the quench boiling performance of vertical rodlets [11,12].

Development of nanofluids led nuclear engineers to focus on analyzing the effect of surface properties on the quench boiling heat transfer. The major contributions were provided by the groups at Postech and MIT [13–15]. Kim et al. [13,14] performed experiments with different nanofluids and observed an increase in Leidenfrost temperature and quench front velocity as nanoparticles attached themselves to the quenched surface. 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. It was concluded that increase in hydrophilicity and surface roughness due to the deposition of nanoparticles was responsible for improved quench boiling heat transfer. After the Fukushima Daiichi incident, nuclear engineers started showing more focus on fabricating surfaces that improve CHF and quench characteristics. The Department of Energy, Office of Nuclear Energy (DOE-NE) is working closely with various universities and industries through its Advanced Fuels Campaign (AFC) on the development of potential accident tolerant fuels (ATF) for LWRs [16]. The coated cladding is found to have improved oxidation kinetics over existing zirconium-based alloy claddings [17]. Implementation of potential accident tolerant claddings requires a complete understanding of thermal-fluid characteristics of the coatings when exposed to the ionizing radiation within the cooling environment. In order to investigate the effect of oxidation occurring on the cladding surface, Lee et al. [18] carried out quench experiments on oxidized Zircaloy and chromium-coated samples. Zircaloy had better quench characteristics when compared to chromium. However, the analysis is incomplete without the study of the effect of gamma irradiation present in the reactor environment. The fission process results in the creation of strong gamma fields that remain present for decades via decay of the fission products. A few previous studies revealed the effect of gamma radiation-induced surface activation (RISA) on the wettability and quench performance of metal oxides. In the studies by Takamasa et al. [19,20], the contact angle was found to decrease in the case of gamma-irradiated metal oxide samples indicating an increase in surface energy for a period of time before the surface returned to its nominal condition. Application of gamma irradiation for an increase in wettability also has got several implications on non-nuclear industries including manufacturing and bio-medical industries where other techniques to improve wettability are difficult to implement [20].

As a first step towards the analysis of quench and rewet performance of various non-oxidized cladding choices under irradiation, tests on wettability and quench performance were carried out by exposing the test samples to gamma irradiation. An attempt was also made to study the effects of Ultraviolet Ozone (UVO) treatment on the specimen and determine the difference in quench behavior observed in samples exposed to gamma irradiation and UVO. The rationale behind studying the effects of UVO is to verify the existing hypothesis on the effect of gamma irradiation in the removal of surface contaminants and increase in surface energy. UVO cleaning is a well-known technique, effective in removing the organic contaminants from the surface. Organic compounds are decomposed by strong UV waves of energy, stronger than the bond energy of the tested surface. Thus cleaning the surface with UVO increases its surface energy, leading to the increased wettability. This provides a way to verify the mechanism of gamma irradiation compared to another technique focused on improving the wettability by cleaning the surface and increasing the surface energy. Microscopic analysis of the irradiated and non-irradiated samples was done to understand the mechanism behind the effect of irradiation on the microstructure and its impact on the quench heat transfer for the first time.

2. Materials and methods

Fig. 1 shows the experimental setup for the quench tests. Tested samples are cylindrical rodlets made of Zircaloy-4 (Sample 1) and chromium spray coated on Zircaloy (Sample 2). The test sample is a cylindrical rodlet (test sample) of diameter 4.8 mm and height 50 mm. The radiant furnace powered with a DC power supply (25 V, 150 A) is used to achieve a maximum temperature of 1500 °C. The samples are heated using radiant furnace with air as the medium. The average ramping rate 2 °C/s and the sample was heated for a little over 300 s and is immediately dropped into the coolant using the pneumatic conveyor. In all the experiments, it was observed from the synchronized high speed imaging that the temperature at the instant the sample drop is in the coolant is 600 ± 5 °C. Pneumatic pressure (600 kPa) is used to displace the sample downward to the quench pool at a mean velocity of 0.5 m/s. The downward motion of the sample is actuated by a 4-way solenoid valve. The water in the quench pool is at saturation temperature (1 atm, 100 °C) and the temperature is controlled with the help of a hot plate and temperature controller. A K-type sheathed, thermocouple is used to measure the centerline temperature of the rodlet. A hole is drilled from the top side of the test sample along the axis such that the thermocouple can measure the centerline temperature as described in Fig. 2. The thermocouple is connected to HP Agilent 34980A data acquisition system for online measurement of temperature. The temperature data is recorded at a rate of 20 Hz. K-type sheathed, ungrounded thermocouple with the measurement uncertainty of ±1 °C [22] is inserted to the bottom of the hole and is held by friction. This technique ensures a good thermal contact and thus thermocouple response time is small (for the size of thermocouple: 0.8 mm) and this uncertainty is neglected. The calculated Biot number is less than 0.2 in the experiment and hence the temperature gradient within the rodlet is negligible. Hence the measured temperature is assumed to be closer to the

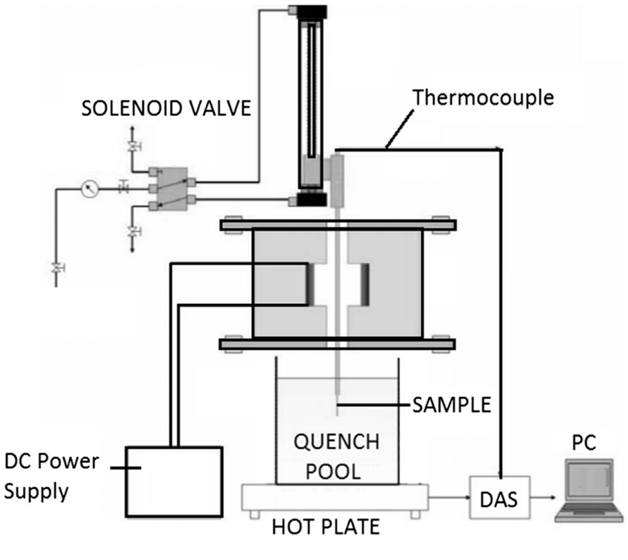

Fig. 1. Quench experimental setup.