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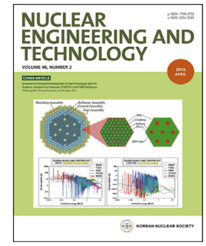

Original Article

A Numerical Design and Feasibility Study of Self-Wastage Experiment Using Simulant Material in a Sodium Fast Reactor

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ABSTRACT

A sodium–water reaction takes place when high-pressured water vapor leaks into sodium through a tiny defect on the surface of the heat transfer tube in a steam generator of the sodium-cooled fast reactor. The sodium–water reaction brings deterioration of the mechanical strength of the heat transfer tube at the initial leakage site. As a result, it damages the crack itself, which may eventually enlarge into a larger opening. This self-enlargement is called "self-wastage phenomenon." In this study, a simulant experiment was proposed to reproduce the self-enlargement of a crack and to evaluate the mechanism of the self-wastage. The damage on the surface of the crack was simulated by making the neutralization reaction with hydrochloric acid solution and sodium hydroxide solution. A numerical investigation was carried out to validate the feasibility of the approach and to determine experimental conditions. From the computation results, it is observed that when 5M HCl is injected into 5M of NaOH with 0.05 m/s inlet velocity, the temperature at the surface near the crack increased over 319.26 K. The computational results show that the self-wastage phenomenon is capable of being reproduced by the simulant experiment.

1. Introduction

In the steam generator of a sodium-cooled fast breeder reactor, liquid sodium and high-pressure water vapor pass through a thin heat transfer tube. If a tiny defect occurs at the surface of the heat transfer tube, the high-pressured water vapor will leak into the sodium side (outside of the tube) so that a sodium–water reaction (SWR) will take place. Erosion and corrosion caused by the SWR may bring about the deterioration of the mechanical strength of the heat transfer tube at the site of the initial crack. As a result of the SWR, the defect will be enlarged in size, and the leak rate will sharply increase. This enlargement of the crack is called the "self-wastage phenomenon."

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So far, self-wastage phenomenon has been studied by experimental approaches such as mock-up tests [1–5]. For example, Kuroha et al's [6] experimental result showed that even though the initial leak rate is very small (<0.05 g/s), the leak rate remains at a constant level for some time (from several minute to several days). The leak rate then sharply increases up to several grams per second, which could induce the secondary failure of the adjacent heat transfer tubes by target wastage. In addition, a small leakage is the most probable for steam generator operation and a large leakage, as a rule, is the consequence of subsequent failures of the heat exchange surface in the area of a small leak, and very seldom appears as an initial leakage.

Therefore, a quantification of self-wastage phenomena is important from the viewpoint of not only safety assessment but also the elucidation of the self-wastage mechanism in the steam generator.

However, it is hard to evaluate the self-wastage phenomena quantitatively due to experimental difficulties in treating liquid sodium, which possesses high chemical activity and opacity when in a liquid state.

As an alternative approach to assess the self-wastage phenomenon, an experiment using simulated material was devised. This new method focuses on reproducing the crack enlargement and its progression, which are caused by a chemical interaction between the SWR and the tube wall material.

Since the self-wastage phenomenon is attributed to a chemical reaction that takes place near the outside of the crack, we assumed that the damage on the surface of the crack can be evaluated by making the neutralization reaction with hydrochloric acid (HCl) solution and sodium hydroxide (NaOH) solution.

In this study, a numerical investigation was carried out to validate the feasibility of a new method and to decide on the conditions for the experiment. In the analysis, governing equations of concentrations of acid and alkali were implemented into a commercial Computational Fluid Dynamics (CFD) tool, Fluent version 6.3.26 by ANSYS Inc. The reaction rate is calculated based on the Arrhenius law.

2. Experimental methodology for simulating self-wastage phenomena using simulants

2.1. Schema of SWR

When pressurized water leaks from a heat transfer tube, it will vaporize immediately due to adiabatic expansion. Hence, it is expected that water reacts with sodium under a gas state in the SWR. With respect to sodium, it reacts with water vapor under a liquid state in an early stage of the SWR as shown in Eq. (1). According to the water-leakage test that models the steam generator of Japanese prototype fast breeder reactor "Monju", the maximum temperature measured in the reaction region was of 1,100–1,200 °C [7]. Thus, sodium vigorously evaporates, and the gas-phase sodium reacts with water vapor. At the second stage, the chemical interaction of products from the first stage (NaOH and hydrogen gas) takes place with an excessive sodium condition, as shown in Eqs. (2)–(4) [8].

$$2Na(l) + 2H_2O(g) \rightarrow 2NaOH(g) + H_2(g) \quad (1)$$

$$Na(g) + H_2O(g) \rightarrow NaOH(g) + H(g) \quad (2)$$

$$2Na(l) + H_2O(g) \rightarrow Na_2O(s) + H_2(g) \quad (3)$$

$$Na(l) + NaOH(s) \rightarrow Na_2O(s) + 1/2H_2(g) \quad (4)$$

It is expected that the wastage rate is related to the reaction rate. In the gas-phase reaction, the reaction rate is evaluated by the Arrhenius equation as follows:

Chemical reaction ($nA + mB \rightarrow C + D$)

$$\gamma = k(T)[A]^n[B]^m \quad (5)$$

$$k(T) = A_0(T)^{B_0} \exp\left(\frac{E_0}{T}\right) \quad (6)$$

Here, γ is a reaction rate, and the $k(T)$ is the rate constant. Eqs. (2)–(4) are considered as the gas-phase reaction. The rate constant can be derived experimentally and numerically.

The mechanism of self-wastage phenomena can be simplified by focusing on the following features. Firstly, the self-wastage phenomena contributed to an exothermic chemical reaction, and the of self-wastage rate is related to the reaction rate that is expressed by the Arrhenius reaction equation. To reproduce the enlargement of a crack from the interaction between the SWR and the tube-wall material, the following simulant experiment was designed.

2.2. Simulant material

When HCl solution and NaOH solution are mixed, the following neutralization reaction occurs, and the reaction heat is released [9].

$$HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_20 + \Delta H \quad (7)$$

In an aqueous solution, each reactant is dissociated fully so that the above reaction can be written in the following form:

$$H_3O^+ + OH^- \underset{k_B}{\overset{k_F}{\rightleftarrows}} 2H_2O \quad (8)$$

where k_F and k_B are the rate constants for the chemical reaction. The rate constant k is also expressed by the Arrhenius equation, as follows:

$$k_r = A_r e^{-E_a/RT} \quad (9)$$

where, A_r = pre-exponential factor (mol^{-1} m^3 s^{-1}); Ea = activation energy for the reaction ($J\ mol^{-1}$); and R = universal gas constant ($J\ mol^{-1}\ K^{-1}$)

In Eq. (8), the rate constant k_B is a few orders of magnitude smaller than k_F, therefore, the effect of backward reaction could be neglected.

One similarity exists in the reaction mechanism of the SWE and the neutralization reaction: the reaction rate is expressed by the Arrhenius equation. The reaction rate is closely related to the self-wastage phenomena.