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## Original Article

# Modeling of Hydrodynamic Processes at a Large Leak of Water into Sodium in the Fast Reactor Coolant Circuit

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## ABSTRACT

In this paper, we describe a physicomathematical model of the processes that occur in a sodium circuit with a variable flow cross-section in the case of a water leak into sodium. The application area for this technique includes the possibility of analyzing consequences of this leak as applied to sodium–water steam generators in fast neutron reactors. Hydrodynamic processes that occur in sodium circuits in the event of a water leak are described within the framework of a one-dimensional thermally nonequilibrium three-component gas–liquid flow model (sodium–hydrogen–sodium hydroxide). Consideration is given to the results of a mathematical modeling of experiments involving steam injection into the sodium loop of a circulation test facility. That was done by means of the computer code in which the proposed model had been implemented.

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## 1. Introduction

Different types of steam generators are used in the second circuit of fast sodium-cooled reactors. Damage to the heat exchange surface of a steam generator results in the leakage of water into sodium. Sodium reacts violently with water (vapor). The reaction is accompanied by the release of energy and a significant rise in temperature. The general phenomena observed during the water–sodium reaction is systematically described in [1].

The task of analyzing the consequences of an accident caused by a sodium–water steam generator intercircuit leak is

relevant for the justification of steam generators safety. Of great concern is the potential pressure growth in the sodium circuit as a result of sodium–water reaction. Full-scale field research on the consequences of large water leaks in sodium for various types of steam generators is not always possible. Therefore, computer modeling is generally used.

A large water leak can lead to unallowable loads on the circuit elements until their destruction. In order to model large leak effects reliably in a fast reactor sodium circuit, at least three principal factors must be determined: the parameters in the sodium–water reaction area; hydrodynamic parameters in the sodium circuit; and expansion tank

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parameters. Based on one of the approaches [2] a computer code was developed where the so-called piston model was implemented. In this model, the water–sodium reaction products form an expanding bubble that gradually displaces sodium from the circuit. In this case, gas parameters are determined within the framework of the model with lumped parameters, whereas the sodium flow in the circuit is considered as a one-dimensional (1-D) adiabatic transient flow of one-component incompressible fluid. A similar model was used to develop the well-known code SWAAM-LT [3], based on the 1-D incompressible single-phase flow model.

Simplifying assumptions made in the piston model narrow the area of the code applicability and reduce the accuracy of code predictions. The deficiencies of the simplified approach are revealed more vividly in the attempt to use the code with the piston model with the aim of analyzing the processes caused by water leaks in large-size heat-exchanging modules with big sodium flow cross-sections and significant sodium flow rates. Thus, the task of developing a physicomathematical model that eliminates the main deficiencies of the one-component piston model is becoming more topical. This problem was partially solved by SWAT-13/SWAT-13E codes [3], based on the 1-D two-phase flow model.

In the proposed improved approach, the sodium circuit is presented in the form of a combination of two models:

- a 1-D model with distributed parameters, that describes dynamics of the parameters in all the circuit elements (sodium–water reaction region included), with the exception of expansion tank volume; and
- an expansion tank model built as part of the model with lumped parameters.

These two models are cross-linked in the expansion tank inlet and outlet points. A 1-D one-velocity three-component model is suggested for the variable cross-section circuit to describe thermo-hydraulic processes in the circuit. Sodium, hydrogen, and sodium hydroxide are considered as components of this mixture. In this case, hydrogen is assumed to be an ideal gas and its solubility in sodium is taken into account. Consideration is also given to the dependence of sodium and sodium hydroxide on pressure and temperature.

## 2. The system of equations for the model to describe thermohydraulic processes in a 1-D circuit with a variable cross-section

The system of equations of the one-velocity three-component model of equal pressure includes the following differential equations.

Mass balance equation for each component:

$$(\varepsilon_1 \rho_1)_t + \frac{1}{S} (S \varepsilon_1 \rho_1 u)_x = \sigma_1^V + \sigma_2^{out}, \quad (1)$$

$$(\varepsilon_2 \rho_2)_t + \frac{1}{S} (S \varepsilon_2 \rho_2 u)_x = \sigma_2^V - \sigma_2^{out}, \quad (2)$$

$$(\varepsilon_3 \rho_3)_t + \frac{1}{S} (S \varepsilon_3 \rho_3 u)_x = \sigma_3^V \quad (3)$$

where indices 1, 2, and 3 refer to sodium, hydrogen and sodium hydroxide, respectively;  $\varepsilon_i$  = the  $i$ th component volume fraction;  $\rho_i$  is the  $i$ th component density;  $t$  = time;  $S$  = flow cross-section area of the channel;  $u$  = component mixture velocity; and  $x$  = length coordinate.

The source terms  $\sigma_1^V$ ,  $\sigma_2^V$ ,  $\sigma_3^V$  on the right-hand side of Eqs. (1)–(3), describe sodium loss as a result of sodium–water reaction and hydrogen and sodium hydroxide ingress into the circuit at the leak point, and the  $\sigma_2^{out}$  term describes hydrogen solubility in sodium.

Mixture momentum balance equation:

$$(u\rho)_t + \frac{1}{S} (S\rho u^2)_x + p_x = -F_{TR} + F_{pump} - \rho g \sin \beta, \quad (4)$$

where:  $F_{TR}$  = friction losses in the channel;  $F_{pump}$  = pump head source;  $\sin \beta$  = current slope of the circuit axis relative to horizontal;  $g$  = gravity factor; and  $\rho$  = average mixture density that is calculated by the formula:

$$\rho = \rho_1 \varepsilon_1 + \rho_2 \varepsilon_2 + \rho_3 \varepsilon_3 \quad (5)$$

Energy balance equation for each component:

$$\begin{aligned} c_1(\varepsilon_1 \rho_1 T_1)_t + \frac{1}{S} c_1 (S \varepsilon_1 \rho_1 u T_1)_x + p \left[ (\varepsilon_1)_t + \frac{1}{S} (S \varepsilon_1 u)_x \right] \\ = Q_1^S + Q_{1 \leftrightarrow W} + Q_{1 \leftrightarrow 2} + Q_{1 \leftrightarrow 3} + p \frac{\sigma_1^V}{\rho_1} + Q_2^{out}, \end{aligned} \quad (6)$$

$$\begin{aligned} c_2(\varepsilon_2 \rho_2 T_2)_t + \frac{1}{S} c_2 (S \varepsilon_2 \rho_2 u T_2)_x + p \left[ (\varepsilon_2)_t + \frac{1}{S} (S \varepsilon_2 u)_x \right] \\ = Q_2^S + Q_{2 \leftrightarrow W} - Q_{1 \leftrightarrow 2} + Q_{2 \leftrightarrow 3} + p \frac{\sigma_2^V}{\rho_2} - Q_2^{out}, \end{aligned} \quad (7)$$

$$\begin{aligned} c_3(\varepsilon_3 \rho_3 T_3)_t + \frac{1}{S} c_3 (S \varepsilon_3 \rho_3 u T_3)_x + p \left[ (\varepsilon_3)_t + \frac{1}{S} (S \varepsilon_3 u)_x \right] \\ = Q_3^S + Q_{3 \leftrightarrow W} - Q_{1 \leftrightarrow 3} - Q_{2 \leftrightarrow 3} + p \frac{\sigma_3^V}{\rho_3} \end{aligned} \quad (8)$$

where  $c_i$  = isochoric heat capacity of the  $i$ th component;  $T_i$  =  $i$ th component temperature; and  $p$  = component mixture pressure.

The source terms  $Q_1^S$ ,  $Q_2^S$ ,  $Q_3^S$  on the right-hand side of Eqs. (6)–(8) describe energy inflow and outflow at the leak point of the circuit as a result of sodium–water reaction, and the  $Q_2^{out}$  term describes hydrogen-sodium energy exchange as a result of hydrogen solubility in sodium.

Heat transfer among the components is described by the terms  $Q_{1 \leftrightarrow 2}$ ,  $Q_{1 \leftrightarrow 3}$ ,  $Q_{2 \leftrightarrow 3}$ , and heat exchange with a pipeline wall, by the terms  $Q_{1 \leftrightarrow W}$ ,  $Q_{2 \leftrightarrow W}$ ,  $Q_{3 \leftrightarrow W}$  in Eqs. (6)–(8).

Component balance equation

$$\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 1 \quad (9)$$

Equation of state for each component

The properties of the compressibility and temperature expansion of sodium and sodium hydroxide are described in linear approximation. It is assumed that hydrogen behaves as an ideal gas.

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