Modeling of hydrodynamic processes at a large leak of water into sodium in the fast reactor coolant circuit

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A description is given of a physico-mathematical model of the processes that occur in a sodium circuit with a variable flow cross-section in case of a water leak into sodium. The application area for this technique includes a possibility to analyze consequences of this leak as applied to sodium-water steam generators in fast neutron reactors.

Hydrodynamic processes that occur in the sodium circuit in the event of a water leak are described within the framework of a 1-D thermally-nonequilibrium three-component gas-liquid flow model (sodium-hydrogen-sodium hydroxide).

Consideration is given to the results of mathematical modeling of experiments with 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.

1. Introduction

The task of analyzing consequences of an accident caused by a sodium-water steam generator intercircuit leak is very relevant for the justification of steam generators safety. First of all, of great concern is a potential pressure growth in the sodium circuit as a result of sodium-water reaction. Large water leak can lead to unallowable loads on the circuit elements, until their destruction. In order to perform reliable modeling of large leak effects in the fast reactor sodium circuit, at least three principal tasks must be solved, namely to determine: the parameters in the sodium-water reaction area, hydrodynamic parameters in the sodium circuit as well as expansion tank parameters. Based on one of the techniques [1], which includes the solution of all the three tasks, 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 is gradually displacing 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 1D adiabatic transient flow of one-component incompressible fluid.

Simplifying assumptions made in the "piston" model narrow the area of the code applicability and reduce the degree of estimation fidelity. The deficiencies of the simplified approach are revealed more vividly at the attempt to use the code with the "piston" model with the aim to analyze 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 to develop a physico-mathematical model that eliminates the main deficiencies of one-component "piston" model is getting very topical. At the same time, this model should presuppose a rather simple and correct solution by means of the known numerical methods and allow a higher level of mathematical analysis fidelity.

In the proposed improved approach the sodium circuit is presented in the form of 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;
- 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 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:

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

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

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

where:
indices 1, 2, 3 –refer to sodium, hydrogen and sodium hydroxide, respectively;
ε_i – the i-th component volume fraction;
ρ_i – the i-th component density;
t – time;
S – flow cross-section area of the channel;
u – component mixture velocity;
x – length coordinate.

The source terms σ_1^V, σ_2^V, σ_3^V on right-hand site of equations (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 σ_2^{out} term describes hydrogen solubility in sodium.

Mixture momentum balance equation:

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

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;
ρ – average mixture density that is calculated by the formula:

$$\rho = \rho_1\varepsilon_1 + \rho_2\varepsilon_2 + \rho_3\varepsilon_3 \tag{5}$$

The pump head is modeled at the junction of channels with different cross-section. It can change depending on the time and consumption of sodium. The presence of a significant

amount of the gas component in the pump is not considered, since the circuit does not create for this purpose.

Energy balance equation for each component:

$$c_1\left(\varepsilon_1\rho_1T_1\right)_t+\frac{1}{S}\ c_1\left(S\,\varepsilon_1\rho_1\,u\,T_1\right)_x+p\left[\left(\varepsilon_1\right)_t+\frac{1}{S}\ \left(S\,\varepsilon_1\,u\right)_x\right]=$$

$$=Q_1^S+Q_{1\leftrightarrow W}+Q_{1\leftrightarrow 2}+Q_{1\leftrightarrow 3}+p\frac{\sigma_1^V}{\rho_1}+Q_2^{out}\ , \tag{6}$$

$$c_2\left(\varepsilon_2\rho_2T_2\right)_t+\frac{1}{S}\ c_2\left(S\,\varepsilon_2\rho_2\,u\,T_2\right)_x+p\left[\left(\varepsilon_2\right)_t+\frac{1}{S}\ \left(S\,\varepsilon_2\,u\right)_x\right]=$$

$$=Q_2^S+Q_{2\leftrightarrow W}-Q_{1\leftrightarrow 2}+Q_{2\leftrightarrow 3}+p\frac{\sigma_2^V}{\rho_2}-Q_2^{out}\ , \tag{7}$$

$$c_3\left(\varepsilon_3\rho_3T_3\right)_t+\frac{1}{S}c_3\left(S\,\varepsilon_3\rho_3\,u\,T_3\right)_x+p\left[\left(\varepsilon_3\right)_t+\frac{1}{S}\ \left(S\,\varepsilon_3u\right)_x\right]=$$

$$=Q_3^S+Q_{3\leftrightarrow W}-Q_{1\leftrightarrow 3}-Q_{2\leftrightarrow 3}+p\frac{\sigma_3^V}{\rho_3} \tag{8}$$

where:

c_i – isochoric heat capacity of the i-th component;

T_i – i-th component temperature;

p – component mixture pressure.

The source terms Q_1^S, Q_2^S, Q_3^S in right-hand parts of equations (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 equations (6)–(8).

Component balance equation:

$$\varepsilon_1+\varepsilon_2+\varepsilon_3=1 \tag{9}$$

Equation of state for each component

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

$$\rho_1=\rho_1\left(p,T_1\right) \tag{10}$$

$$\rho_2=\rho_2\left(p,T_2\right)=\frac{p\,\mu_2}{RT_2} \tag{11}$$

$$\rho_3=\rho_3\left(p,T_3\right) \tag{12}$$

where:

R – universal gas constant;

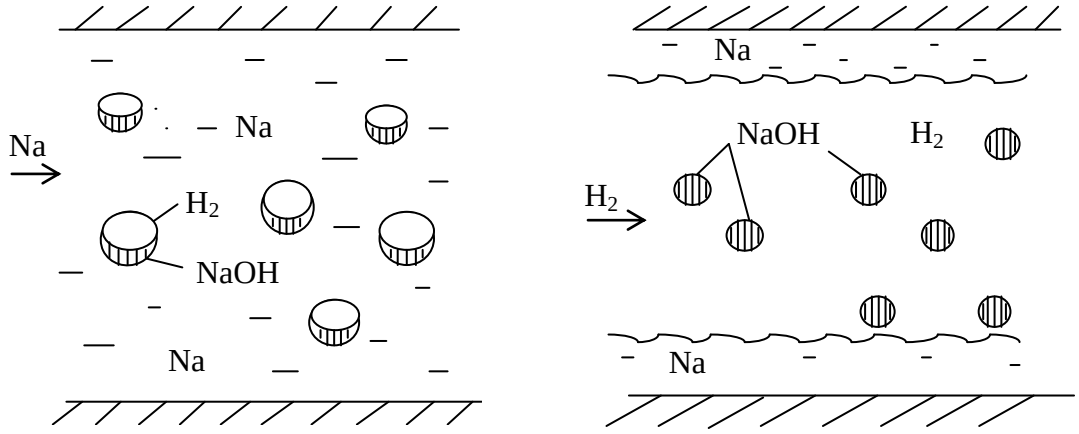
μ_2 – hydrogen molar weight.

So, the system of equations (1)–(12) proposed for description of thermohydraulic processes in the sodium circuit of fast reactors comprises 12 equations for 12 unknowns: u, p, T_1, T_2, T_3, ε_1, $\varepsilon_2, \varepsilon_3, \rho_1, \rho_2, \rho_3, \rho$. In order to close the system, it is necessary to

complement it with adequate expressions for the source terms on the right hand site of mass and energy balance equations and with correlations in the right part of the *momentum balance equation* to determine friction losses and pump head source.

In order to calculate heat transfer among the components, it is proposed that the following three-component flow-pattern diagram be used. It is assumed that at relatively low concentrations of sodium-water reaction products in the sodium flow, $(\varepsilon_2 + \varepsilon_3) \le \varepsilon_b$, ($\varepsilon_b$ – the top boundary of the bubble flow, figure 1 a)) the bubble flow takes place when the main carrying medium is sodium, and foreign particulates represent hydrogen bubbles that in their turn are partially filled with sodium hydroxide. In this mode, the heat exchange is interconnected between all three components. Subsequently, with the growth of volume fraction filled with bubbles, these particulates start to coagulate and at $\varepsilon_r \le (\varepsilon_2 + \varepsilon_3)$ the so-called annular-dispersed flow (figure 1 b)) sets in (ε_r – the bottom boundary of the annular-dispersed flow). In this case, sodium forms an annular film on the channel wall and sodium hydroxide moves as separate drops in the hydrogen flow. Heat transfer in this mode is carried out between hydrogen and hydroxide and between hydrogen and sodium, in the case of sufficient presence of sodium.

In the transient area, when $\varepsilon_b < (\varepsilon_2 + \varepsilon_3) < \varepsilon_r$, the expressions for flows are estimated through interpolation between the values calculated for hydrogen and hydroxide fractions at the bubble flow interface and the values calculated at the annular-dispersed flow interface.



a) bubble flow $0 < (\varepsilon_2 + \varepsilon_3) \le \varepsilon_b$ b) annular-dispersed flow $\varepsilon_r \le (\varepsilon_2 + \varepsilon_3) < 1$

FIG. 1. Three-component flow-pattern diagram

3. Thermal model of sodium-water reaction area. Source terms of the system of physico-mathematical model equations

In the course of the development of the model of processes that occur in large leaks of water into sodium, a first-order chemical reaction of sodium-water interaction is assumed to be considered:

$$Na + H_2O \rightarrow NaOH + \frac{1}{2} H_2 \uparrow + Q \qquad (13)$$

where Q stands for reaction heat.

In the proposed model, consideration is also given to the hydrogen gas-sodium reaction:

$$2Na + H_2 = 2NaH\,, \qquad (14)$$

However, the reaction heat (14) is not taken into account as it is negligible.

The chemical sodium hydroxide-sodium reaction is also neglected due to its insignificant effect on the main process parameters.

The principal assumptions in the physical modeling of the sodium-water reaction area are the following:

– an isochoric-isothermal model of sodium-water reaction is considered;

– the reaction is instant;

– generated hydrogen is assumed to be an ideal gas;

– the screening effect of the generated reaction products (that slows down the reaction) on the sodium-water interaction pattern is not taken into account.

In order to calculate the density of the component mass sources, σ_1^V, σ_2^V, σ_3^V, the following formulas are used:

$$\sigma_1^V = -\alpha_1 \cdot \frac{1}{S} \cdot G_{H_2O}^{\Delta x} \tag{15}$$

$$\sigma_2^V = \alpha_2 \cdot \frac{1}{S} \cdot G_{H_2O}^{\Delta x} \tag{16}$$

$$\sigma_3^V = \alpha_3 \cdot \frac{1}{S} \cdot G_{H_2O}^{\Delta x} \tag{17}$$

where: $G_{H_2O}^{\Delta x}$ – water source linear power.

In order to determine the values of the source terms Q_2^S and Q_3^S, it is assumed that all the heat generated in the reaction is used to increment the internal energy of the reaction products, with the reaction products heated from the temperature of primary reactants T_R to one and the same temperature T_K:

$$T_K = \frac{q_{V,T_0}}{\alpha_2 c_2 + \alpha_3 c_3} + T_R + (T_R - T_0)\left(1 - \frac{\alpha_1 c_1 + \alpha_{H_2O} c_{V_{H_2O}}}{\alpha_2 c_2 + \alpha_3 c_3}\right) \tag{18}$$

where:

q_{V,T_0} – standard thermal effect of isochoric-isothermal reaction (for the sodium-water reaction the standard thermal effect value is expressed in terms of water mass, $q_{V,T_0} = 8.695 \cdot 10^6\ J/kg$ at $T_0 = 298.15\ K$);

α_i, α_{H_2O} – stoichiometric numbers of reaction components (13);

$c_{V_{H_2O}}$ – isochoric heat capacity of water.

The calculated value of T_K is used to determine the specific values of source terms for the reaction products:

$$q_1^S = \alpha_1 c_1 T_1 \tag{19}$$

$$q_2^S = \alpha_2 c_2 T_K \tag{20}$$

$$q_3^S = \alpha_3 c_3 T_K \tag{21}$$

Accordingly, the formulas to calculate the density of the reaction product thermal energy sources will be as follows:

$$Q_1^S = -\frac{q_1^S}{S} \cdot G_{H_2O}^{\Delta x} \tag{22}$$

$$Q_2^S = \frac{q_2^S}{S} \cdot G_{H_2O}^{\Delta x} \tag{23}$$

$$Q_3^S = \frac{q_3^S}{S} \cdot G_{H_2O}^{\Delta x} \tag{24}$$

4. Consideration of hydrogen solubility in sodium

The model assumes that hydrogen dissolves in sodium, with the mass of hydrogen dissolved in sodium (in a unit volume per unit time) $\sigma_2^{out} = f(\varepsilon_2)$ depending on the hydrogen volume fraction.

In order to calculate hydrogen solubility in sodium, the same flow-pattern diagram as the one used to calculate heat transfer among the components is used. The model of hydrogen gas solubility in sodium is developed with account for the available empiric values of hydrogen-sodium reaction rate constants [2, 3].

The amount of outgoing thermal energy of hydrogen is determined by the following formula:

$$Q_2^{\text{out}} = \sigma_2^{\text{out}} \cdot c_2 \cdot T_2 \tag{25}$$

Sodium circuit numerical modeling technique

The technique is developed for a general case when the circuit cross-section depends on the spatial coordinate and this dependence is described by the piecewise constant function.

Calculation of hydrodynamic parameters of the mixture in the expansion tank

Parameters of the mixture components (pressure, temperature, volume fraction) in the expansion tank are considered to be only functions of time. To calculate these parameters we use the component (sodium, hydrogen, sodium hydroxide) mass and thermal energy balance ratios in the mixture area, as well as the component (argon, hydrogen) mass and thermal energy balance rations in the expansion tank gas. Intercomponent heat transfer in the mixture area and in the gaseous cavity, as well as heat transfer on the compensation tank interface surface, are taken into account.

The obtained system of ordinary differential equations is solved using the iterative method.

The suggested model and mathematical technique [4, 5] were realized in the form of a computer code.

5. Testing the code on experimental data

Studies of parameter dynamics inside the sodium loop upon water steam injection at various steam flow values were performed on the experimental sodium circulation facility "MT" (Institute for Physics and Power Engineering, Obninsk, Russian Federation) in1993.

General view of the experimental facility sodium loop is shown in Figure 2.

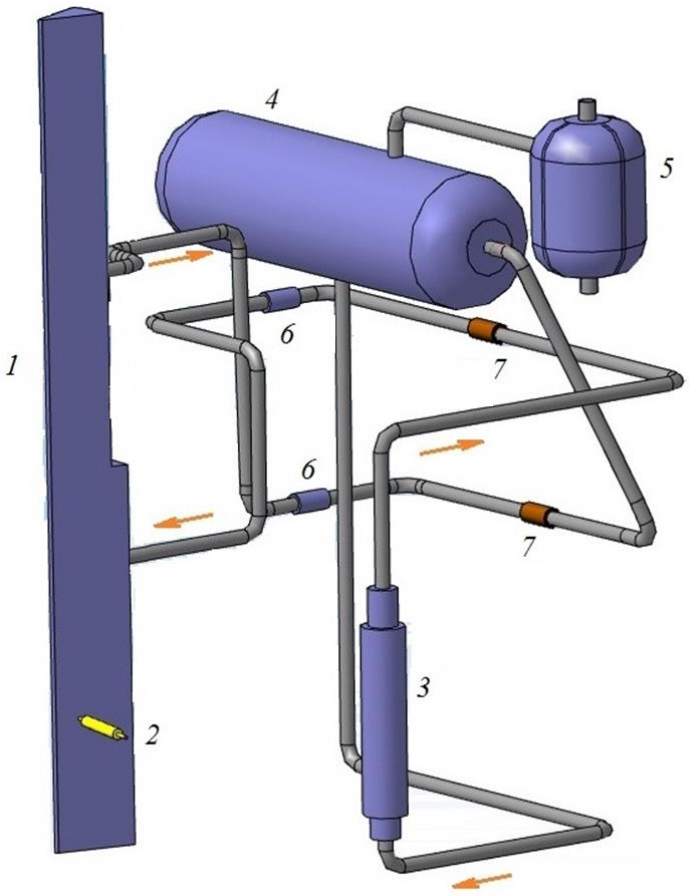


FIG. 2. General view of the experimental facility sodium loop

The facility represents an isothermal sodium loop designed to comprehensively study and test the elements and subsystems of a fast reactor NPP (BN-600 type) steam generator automatic protection system, as well as to study the processes of sodium-water interaction and reaction product spread in the sodium circuit.

The facility sodium circulation loop comprises:

- sector model of steam generator (1);
- steam injection device (2);
- electromagnetic pump (3);
- 0.9 m^3 expansion tank (4);
- 0.2 m^3 separator tank (5);
- magnetic flowmeters (6);
- DN70 pipelines with shut-off valves (7).

The facility is equipped with necessary technological systems and means of technological parameters control.

Main parameters of the facility:

- coolant: sodium;
- sodium temperature: up to 450°C;
- sodium volume in the loop: up to 1.5 m^3;
- sodium flow rate: up to 13.9×10^{-3} m^3/s;
- operating pressure: 0.6×10^6 Pa;
- steam temperature: up to 500°C;
- steam (gas) pressure: up to 14×10^6 Pa.

Facility experiments were performed by injecting superheated steam prepared in a special system into the sodium using an injecting device which was set up in the lower part of the steam generator sector model. Sodium flow rates in supply and discharge DN70 pipe lines were registered using magnetic flow meters (6). Pressure alteration in the expansion tank gas and steam preparation system was also registered.

Table 1 shows the initial parameters characterizing the facility condition before the injection for four various tests. The tests differed in the supplied steam flow rate and total amount of steam fed into the loop during the experiment.

TABLE 1:– INITIAL PARAMETERS OF THE FACILITY BEFORE THE EXPERIMENTS WITH WATER INJECTION TO SODIUM AND THE TOTAL AMOUNT OF STEAM FED INTO THE LOOP DURING THE EXPERIMENT.

№	Sodium temperature, °C	Sodium flow rate, kg/s	Gas pressure in expansion tank, $Pa \times 10^{-3}$	Steam temperature, °C	Steam pressure, $Pa \times 10^{-3}$	Steam mass, kg
1	392.1	8.56	58.8	379.4	8207.3	0.151
2	427.9	7.46	60.8	444.5	7893.2	0.069
3	409.7	9.54	40.5	391.8	8268.1	0.090

Figures 3–5 show the comparison of calculations performed using the developed technique with the experimental data. In addition, Figure 2 shows calculation data without considering hydrogen solubility as well as calculation results using the "piston" model. Figure 3 (positions a and b) suggests that the "piston" model adequately describes only the initial stage of the process, greatly overestimating pressure inside facility elements in the latter stages. It can also be seen in the same figure that neglecting hydrogen solubility also results in pressure overestimation.

Comparison of calculation data with other experiments (Figures 4–5) indicates that the suggested technique adequately reflects long-term processes at various steam flow rates into the loop.

A rather good agreement between calculations and experimental data for the pressure in the gas cavity of BE (position b) is shown. Calculations of flow rates in the inlet pipeline and in the outlet pipeline of a steam generator model (positions c and d) reproduce experimental data qualitatively, and in some time points, quantitatively.

Movement of gaseous hydrogen (considerable decreases and pulsations of a mass flow rate in the outlet pipe), separation of gaseous hydrogen in BE (lack of pulsations of a mass flow rate in the inlet pipeline) are well modeled and calculated data reach the steady state after the sodium-water reaction was stopped.

The results of comparison on dynamics of pressure in BE and the sodium flow rate in a sodium circuit allows us to assume that calculated values of equilibrium pressure in a sodium-water reaction zone correctly reflect real values of pressure. Nevertheless, further improvement of the developed technique and validation of the code by means of the available experimental data is planned.

To summarize, it is fair to say that the suggested one-dimensional model makes it possible to make a more precise description of long-term thermohydraulic processes in

sodium loops during steam inflow, including the pressure estimation. The latter is particularly important as the pressure inside the sodium loop is one of the main parameters used to draw conclusion about its integrity maintenance in case of a big water leak into sodium in the steam generator.

6. Conclusion

A physico-mathematical model was developed for numerical simulation of hydrodynamic processes (within the model of a one-dimensional thermally non-equilibrium three-component gas-liquid stream) that occur in sodium circuits that have a variable flow cross-section in the case of a water leak into sodium.

The mesh-characteristic method was chosen (inverse fixed-mesh method of characteristics), as it is one of the most effective and economic methods of numerical modeling for hyperbolic quasilinear differential equation systems.

The proposed model and calculation technique have been realized in the form of a computer code.¶

A computer code was tested on experimental data obtained from the injection of water vapor into sodium at the Russian sodium loop named “MT” facility.

Results gained from a comparison of calculations with experimental data, lead us to conclude that the proposed technique adequately reflects the transient behavior of the relevant parameters during the hydrodynamic processes that occur in sodium-water interaction in a sodium circuit.¶

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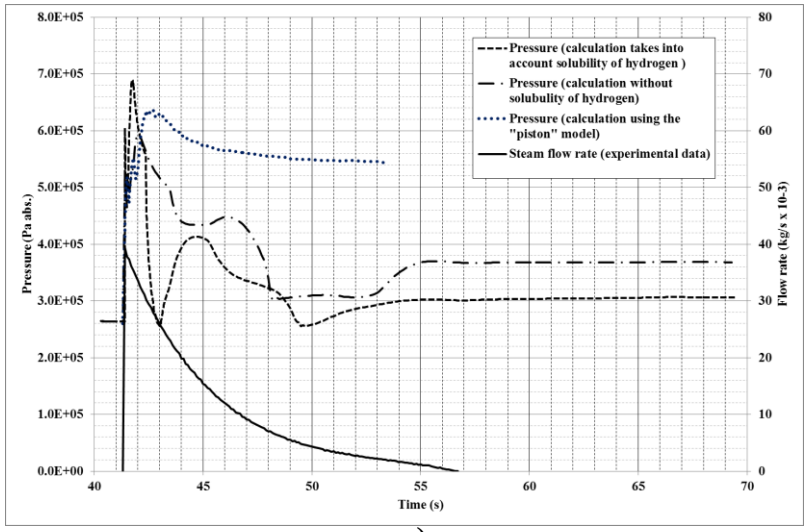

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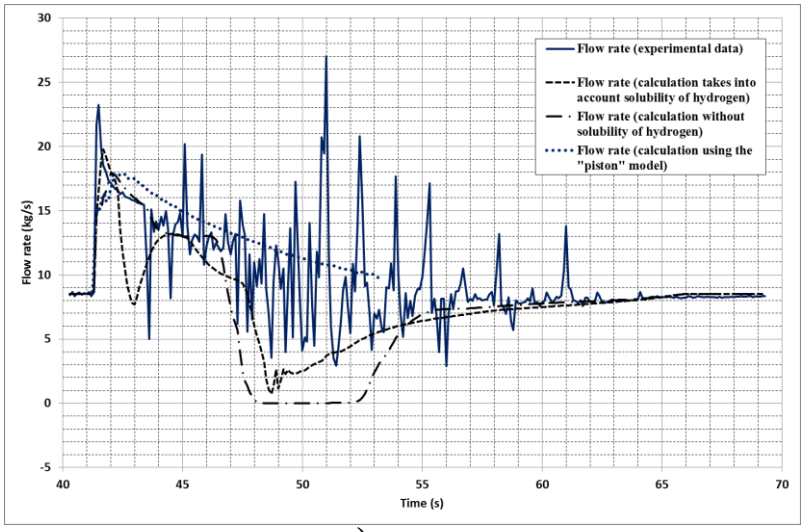

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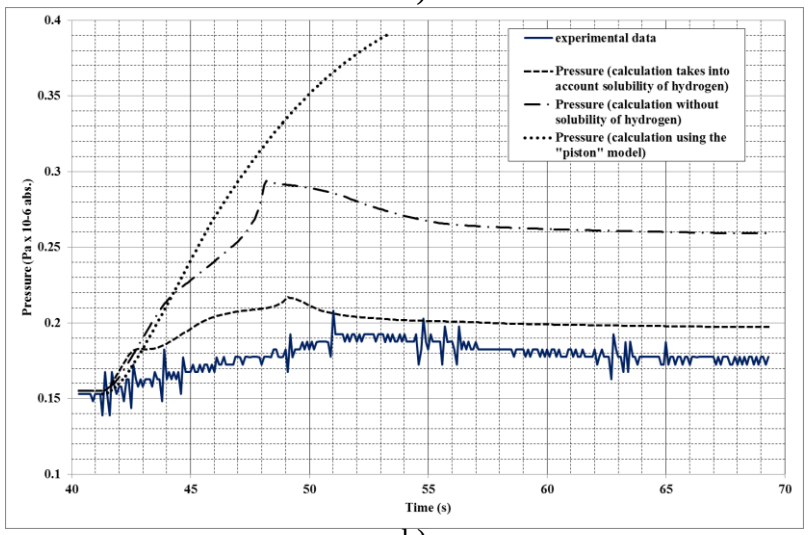

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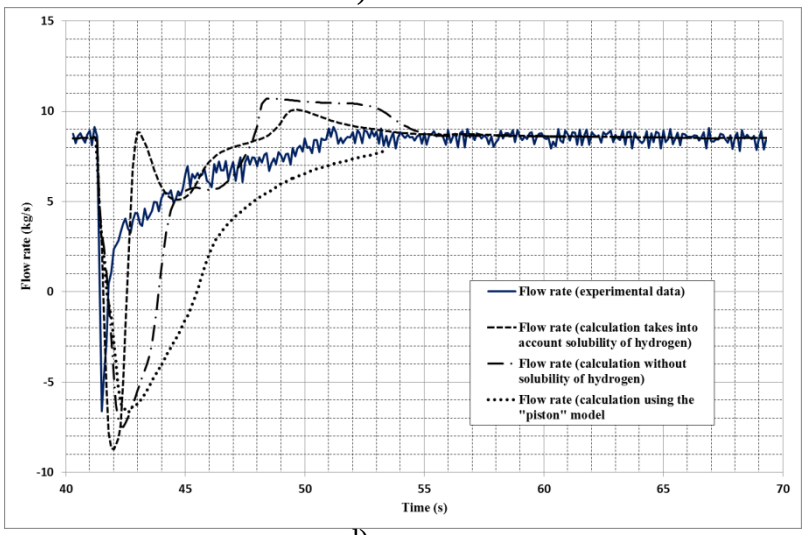

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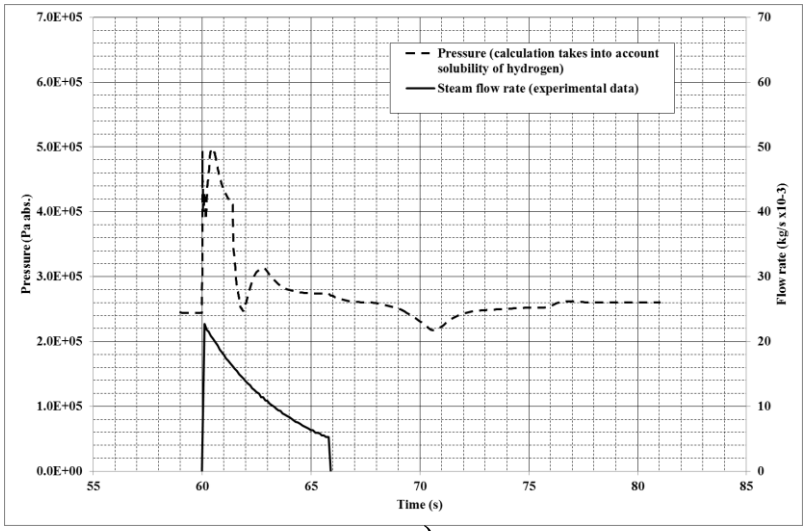
FIG. 3. Comparison of calculation results with data of experiment No. 1: a) pressure in the area of sodium-water reaction and steam mass flow into sodium; b) pressure in the expansion tank gas; c) sodium flow rate in the steam generator model discharge section; d) sodium flow rate in the steam generator model supply section.



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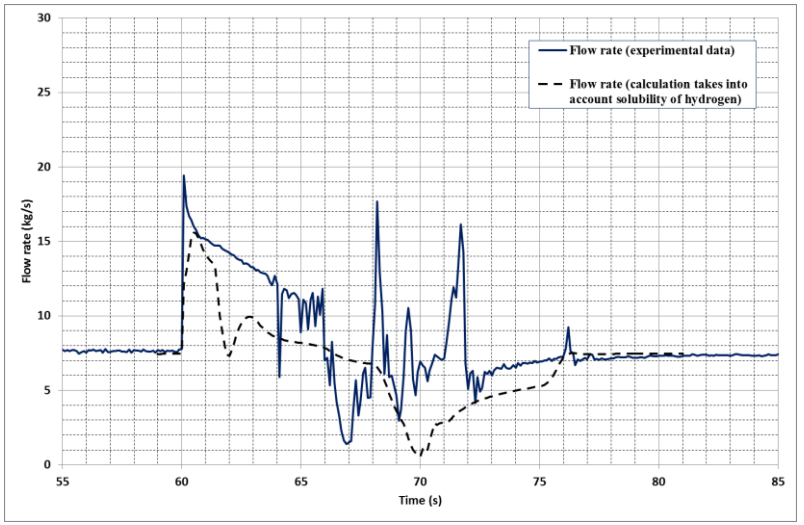

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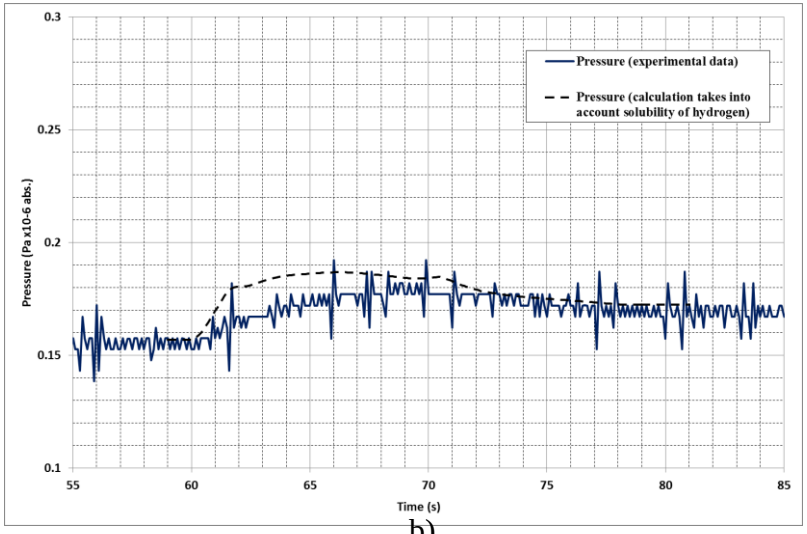

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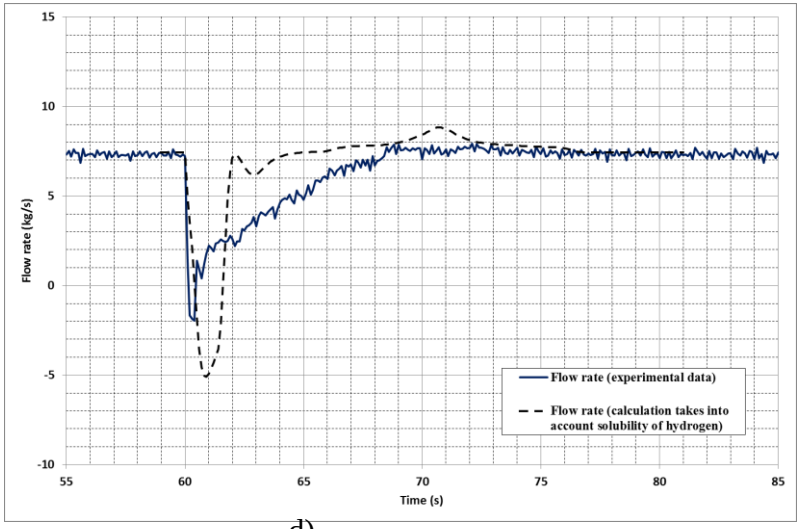

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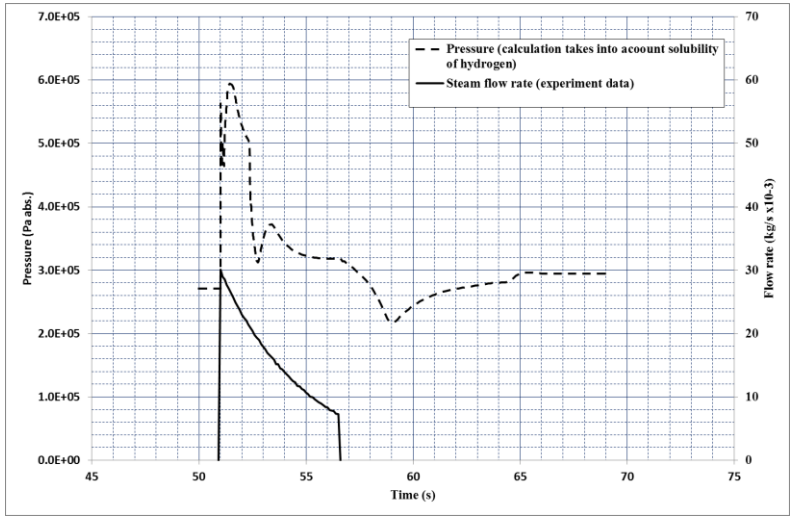
FIG. 4. Comparison of calculation results with data of experiment No. 2: a) pressure in the area of sodium-water reaction and steam mass flow into sodium; b) pressure in the expansion tank gas; c) sodium flow rate in the steam generator model discharge section; d) sodium flow rate in the steam generator model supply section.



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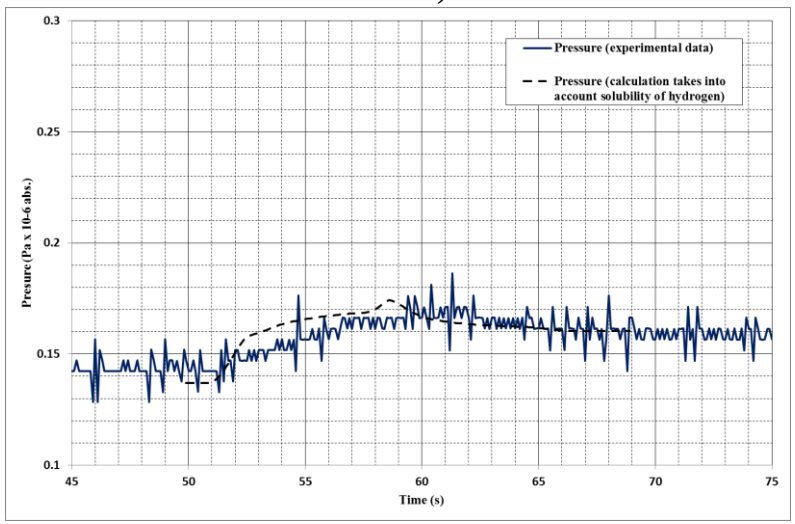

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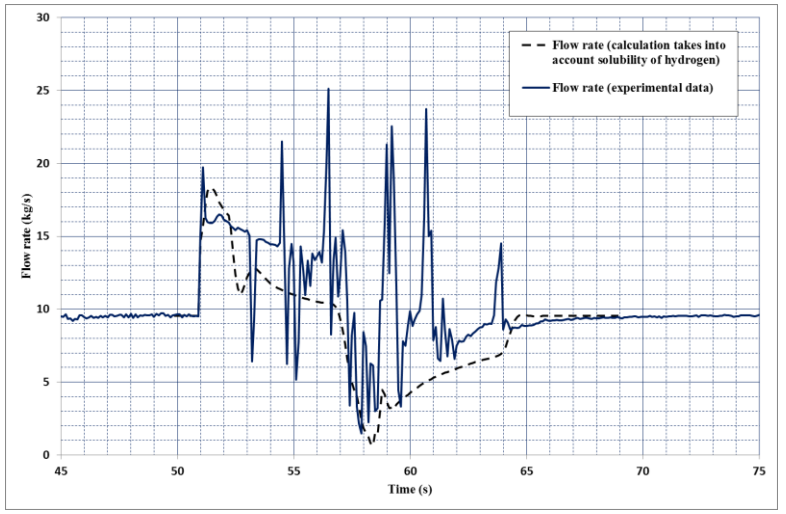

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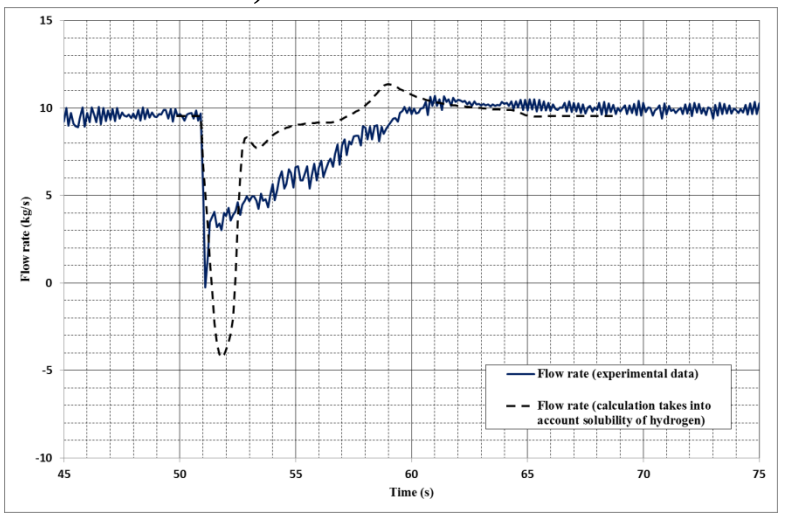

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FIG. 5. Comparison of calculation results with data of experiment No. 3: a) pressure in the area of sodium-water reaction and steam mass flow into sodium; b) pressure in the expansion tank gas; c) sodium flow rate in the steam generator model discharge section; d) sodium flow rate in the steam generator model supply section.