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NUMERICAL APPROACH OF SELF-WASTAGE PHENOMENA IN STEAM GENERATOR OF SODIUM-COOLED FAST REACTOR

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ABSTRACT

In the steam generator of sodium-cooled fast reactor (SFR), self-wastage phenomenon is a crack enlargement on the heat transfer tube itself caused by sodium-water reaction (SWR), which is triggered by the leakage of steam/water from the initial micro-crack. Therefore, a quantification of the self-wastage phenomenon is of importance from the viewpoint of safety assessment in the steam generator. In this study, we propose a numerical approach to evaluate the self-wastage phenomena and investigate an enlargement of the crack using a multi-dimensional-SWR code "SERAPHIM". In the analysis, two-dimensional initial crack is assumed based on SWAT-4 experiment carried out by Japan Atomic Energy Agency (JAEA). The wastage rate was estimated by Arrhenius type of the hypothetical equation, and remeshing arrangement was performed by changing solid-cells to fluid-cells with the estimated wastage amount on the heat exchanger tube in the initial (or former) model. After simulated again using the remeshing models, the resulting SWR products were distributed not only circumferential direction but also radial direction. The wastage region was formed invert triangle shape as the similar with experimental observation.

1. INTRODUCTION

When a small crack penetrates to a heat transfer tube wall in a steam generator of sodium-cooled fast reactor, steam/water inside the tube will leak into liquid sodium at the shell side resulting in sodium-water reaction (SWR). At an early stage of the leakage when the leak rate is too small that the reaction jet due to the SWR does not reach to a neighbor heat transfer tube, it is known that the size of crack is being enlarged gradually and the leakage rate increases because of corrosive effects caused by the SWR. This is referred to as a "self-wastage" phenomenon. After the reaction jet region develops and it reaches to the neighbor tube, a target wastage, where the surface of the neighbor tube is damaged by the reaction jet, will take place and it has a possible that a secondary failure of heat transfer tube happens. Experimental examination of micro leak test has been studied by using several steels with the artificial crack (Sandusky, 1976; Green, 1976; Kozlov *et al.*, 1976; Kuroha *et al.*, 1982; Jeong *et al*, 2009). Among these results, the 2.25Cr-1Mo steel gives the average leak rate of 10^{-2} to 10^{-5} g/sec orders until leak hole enlarged on SWAT-4 experiment (Kuroha *et al.*, 1982). The maximum leak rate after enlargement of a crack has become more than 1g/sec order. This leak rate would induce target wastage, and the time course to enlargement of a crack is 10^5sec order. On the other hand, Sandusky explained about self-wastage that the corrosion started from the sodium side and the leak rate stays almost unchanged until the thin edge is removed based on sudden rapid increase of the leak rate as shown in Fig. 1 (Sandusky, 1976). However, it was hard to evaluate quantitative analysis of the self-wastage due to experimental difficulty with treating liquid sodium, which possesses high chemical activity and opacity in liquid state. Accordingly a quantification of the self-wastage phenomenon is important from the viewpoint of not only safety assessment but also elucidation of the self-wastage mechanism in the steam generator. In this study, we propose a numerical approach to evaluate the self-wastage phenomena and investigate an enlargement of the crack using a multi-dimensional-SWR code "SERAPHIM" (Takata *et al.*, 2003, 2009). The SERAPHIM code consists of compressible three-fluid and one-pressure model, and two chemical reaction modes. This code calculates the multi-phase flow with chemical reaction. In the analysis, two-

dimensional initial crack is assumed based on the results of SWAT-4 experiment (Kuroha *et al.*, 1982) carried out by Japan Atomic Energy Agency (JAEA). The wastage rate was estimated by Arrhenius type of the hypothetical equation, and remeshing arrangement was performed by changing solid-cells to fluid-cells with the estimated wastage amount on the heat exchanger tube in the initial (or former) model.

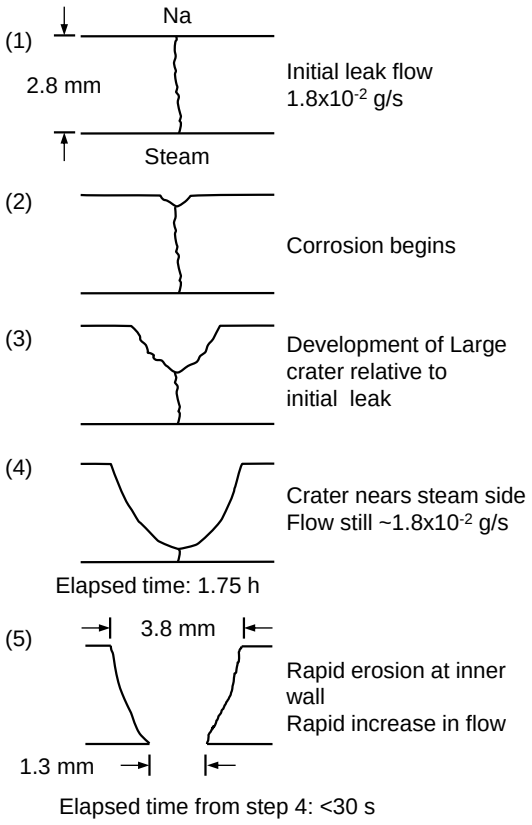


Fig. 1 Process of crack enlargement by self-wastage

2. SELF-WASTAGE ANALYSIS METHODOLOGY

Consideration for the self-wastage analysis methodology is necessary to consider the following roughly separated, (a) construction of the analytical models (b) wastage rate evaluation by local physical amount around the initial crack on the heat transfer tube. Here, properties around the crack are expected to be evaluated from the self-wastage model to be constructed and the numerical results followed by the remeshing based on corrosion amount calculated from the wastage rate.

2.1 Numerical procedure

It is difficult to simulate the whole time progress of the self-wastage phenomenon because it continuously takes much time until heat transfer tube enlargement occurs since the micro-leak has been started. Thus, we consider that a series of all events do not analyze by the numerical simulation at one time. Instead, the amount of wastage is evaluated from the results after elapse of the calculation time as the metastable state, and then a new analytical mesh model is re-constructed. Figure 2 shows the numerical procedure of the self-wastage phenomenon. The specific method is mentioned below.

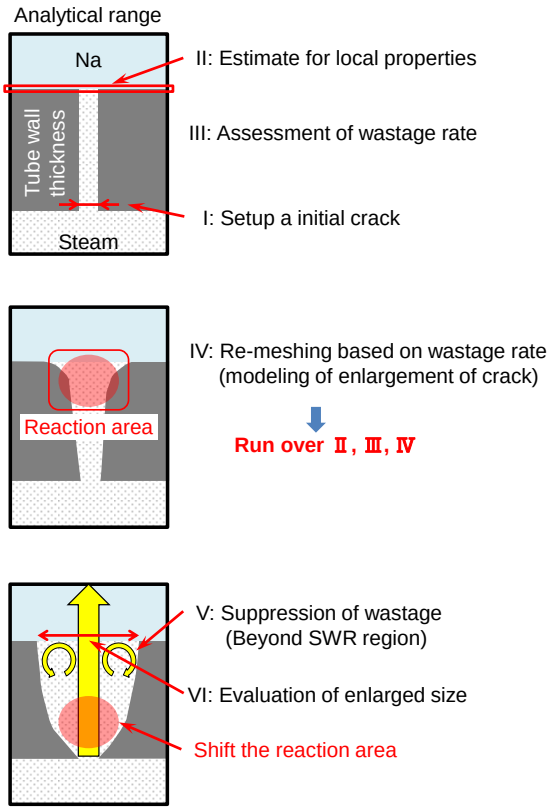


Fig. 2 Numerical procedure for the self-wastage analysis

(I) Setup of an initial crack size on the analytical mesh:
When the self-wastage occurs, it is difficult to practically model the initial crack shape. However the shape is expected to be the crevasse type because the crack progresses according to the crystal face of the material in case of micro-crack in general. Since the aspect ratio of a crevasse type crack is large, the reproduction of the phenomenon is expected for two-dimensional analysis around the crack center. So two-dimensional SWR is assumed as the analytical model and the crack form is single width.
(II) Numerical simulation of the SWR to obtain local thermal-hydraulics properties:
Two-dimensional SWR analysis by SERAPHIM code is carried out using the above input data.
(III) Assessment of wastage rates:
The wastage rate in each crack neighboring position is evaluated by using the physical properties (gas temperature, sodium hydroxide concentration, etc.) on the wall tube surface obtained by (II) according to the local part wastage rate evaluation model.
(IV) Remeshing based on wastage rate:
The following crack shape is predicted after the constant time course based on the wastage rate in each crack neighboring position obtained by (III), and the obtained crack shape is used as input data.
(V) Suppression of wastage (beyond SWR region):
The reaction area shifts to the center in the heat transfer tube with enlargement of the crack and the self-wastage might be suppressed. The enlarged size of the crack at sodium side, the size is almost same between Fig. 1(4)

and (5). This implies when the crack form becomes large, the reaction jet (high gas temperature and alkali corrosion environment) does not reach to the crack surface.
(VI) Evaluation of enlarged size:
Repeat (II), (III) and (IV), then the final maximum size of crack enlargement is presumed.

This procedure is also used to evaluate the amount of water leak for target wastage which is the next step of the SWR by judging the maximum enlarged crack size as the final.

2.2 Wastage model

2.2.1 How to determine the wastage rate

The self-wastage phenomenon is a continuous event for a long time in general. Therefore it is extremely difficult to analyze all events by using numerical approach. In this study, we adopt the assessment for self-wastage phenomenon after elapse of the calculation time as the meta-stable state (Fig. 2). The wastage rate is estimated from the physical amounts of tube surface around crack which are evaluated from the numerical results after the elapse of a certain period of the calculation time. When the wastage rate is experimentally estimated, the following proportional equation is commonly used as related temperature with Eq. (1).

$$W_R \propto \exp(K_1 - \frac{K_2}{T}) \qquad (1)$$

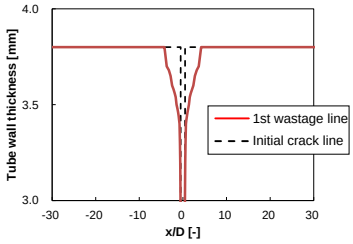
where W_R is wastage rate, K_1 and K_2 are constants and T is the absolute temperature of sodium and/or water/steam (Hori, 1980). The physical amounts related between SWR and wastage rate are to be gas temperature, sodium hydroxide (NaOH) concentration. Na_2O is also the physical amount as a secondary reaction product of the SWR (Hori, 1980). In the preliminary analysis, we focus on the influence of primary reaction in the SWR. Therefore, we assume the following wastage rate in association with Eq. (1) and Arrhenius equation as Eq. (2).

$$W_R = \mathrm{A}[NaOH]^B \exp(-\frac{\mathrm{C}}{\mathrm{T}}) \qquad (2)$$

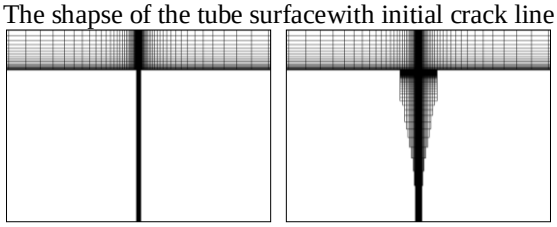
where W_R is wastage rate [m/s], [NaOH] is sodium hydroxide concentration [kg/m^3], T is gas temperature [K] and A, B and C are constants. Constant number A in Eq. (2) is related to the continuous time progress. Since the self-wastage is evaluated for each state in a period of time (Fig. 2). Thus, A is disregarded in this study. Instead, the amount of the maximum wastage is assumed to be 10% of the tube thickness. Moreover, for the corrosion of the heat transfer tube, it is expected that the wastage rate might be changed by NaOH concentration or gas temperature. So if the wastage proceeds by depending on the NaOH concentration (sodium hydroxide dominant process: SHDP), B=1 and C=1 are used as the constant number. While if the wastage proceeds by depending on the gas temperature (gas temperature dominant process: GTDP), B=1 and C=25000 are used as the constant number.

2.2.2 How to construct of the wastage mesh model

After the physical amounts are estimated, the shape of tube surface is illustrated in a diagram. Figure 3 shows the examples of a shape of tube surface after wastage analysis, initial and wastage mesh model. Remeshing model is constructed based on the diagram by changing solid-cells to fluid-cells with the estimated wastage amounts on the heat exchanger tube in the initial (or former) model.



The shapse of the tube surfacewith initial crack line



Initial model Remeshing model

Fig. 3 Construction of wastage remeshing model

3. PRELIMINARY ANALYSIS

3.1 Analytical conditions

Kuroha group has assessed experimental self-wastage phenomena using the artificial crack as a crevasse type which is made mechanically pressed the pinhole of the material (Kuroha *et al.*, 1982). Analytical condition is used for 2.25Cr-1Mo steel as the tube material in 3.84mm wall thickness. Steam and sodium temperature are 470°C, and steam pressure is 130 kg/cm^{2}G. Table 1 shows Kuroha group experimental conditions. Initial leak rate is ten times higher than average leak rate. This distinction of the rate implies self-plug might be occurred (Sandusky, 1976). In addition, the leak rate is almost same until crater nears steam side as shown in Fig. 1(IV). Hence, average leak rate (2.35×10^{-5}g/s) is adopted the initial rate for the analytical condition as the small leak rate.

Table 1 Experimental conditions

Tube material	2.25Cr-1Mo
Tube thickness	3.84 mm
Sodium temperature	470 ºC
Sodium pressure	1.47×10^{-1} MPa
Steam temperature	470 ºC
Steam pressure	12.8MPa
Initial crack width	15 μm
Initial leak rate	3.40×10^{-4} g/s
Average leak rate	2.35×10^{-5} g/s

3.2 Initial model

In the numerical simulation, two-dimensional SWR is conducted using SERAPHIM code with experimental results as the boundary condition. The initial crack width is 15μm, which is simply measured by Kuroha's sample (Kuroha *et al.*, 1982; sample number 2022), and the tube wall thickness is 3.84mm. Liquid sodium domain is determined by based on Dumm's empirical equation for the distance affected by the jet from the nozzle (Dumm, 1974). The maximum distance affected by the jet is calculated approximately 7mm for the analytical condition on SWAT-4 experiment. Therefore, the model size of sodium domain is approximately three times longer than the jet distance as 20.0mm (width) and 22.1mm (height), respectively. Figure 4 shows the mesh arrangement and model scaling. Equally-spaced meshes divided into 15 (1.0μm interval) cells in the initial crack and geometry-spaced divided into 121 (I) × 127 (K) cells are arranged to liquid sodium domain. The analytical boundary conditions are shown in Fig. 5. The inlet boundary is constant flow rate (2.35×10^{-5}g/s), and the outlet boundary is constant pressure (1.47×10^{5}Pa). The side walls of sodium region are free-slip condition, and adiabatic boundary is used as the surface of heat exchange tube and crack inside with non-slip condition. The time step is 1.0×10^{-10}s from the viewpoint of numerical calculation stability.

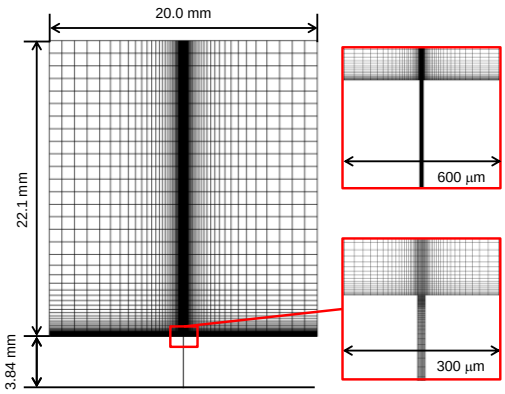


Fig. 4 Initial mesh model

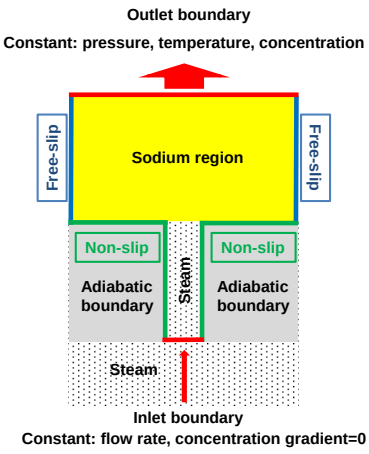
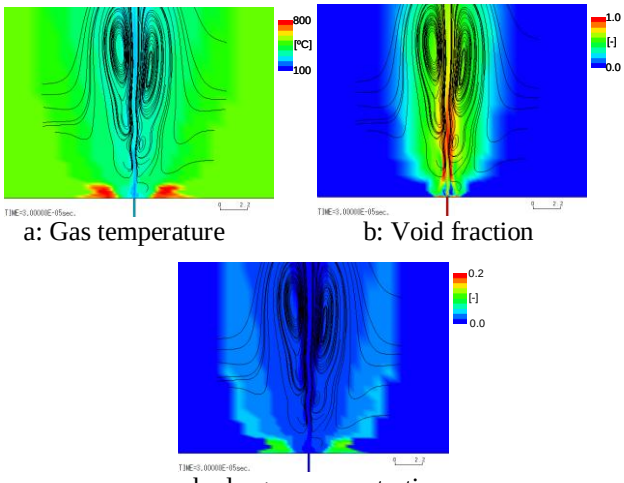


Fig.5 Analytical boundary conditions

3.3 Result and discussion

3.3.1 Analysis of the initial model

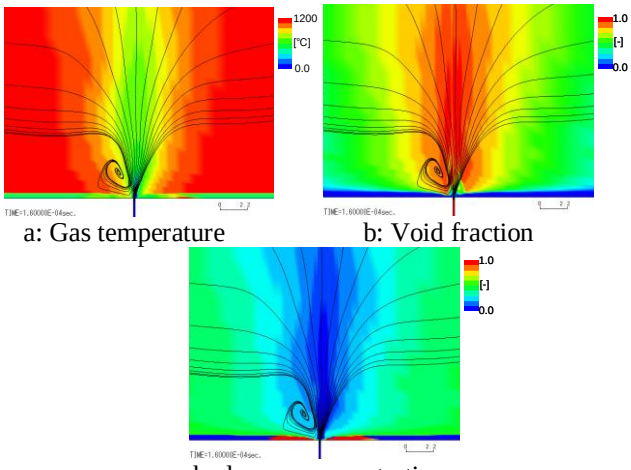
Figures 6 and 7 show the results of analysis of the initial model at 3.0×10^{-5}s and 1.6×10^{-4}s, respectively. The streamline is depicted based on gas phase velocity. High temperature gas phase region (~800 ºC) is located slightly far from the initial crack on the tube surface in Fig. 6a. Void fraction indicates the high temperature region is liquid phase (Fig. 6b) and hydrogen, which is one of the SWR products, is placed this region (Fig. 6c). On the other hand, there is no outstanding temperature difference (~1000 ºC) on the tube surface as high temperature region in Fig. 7a. However, sodium (liquid phase) is thinly covered on the tube surface as shown in Fig.7b. Hydrogen concentration is increasing at the crack neighborhood in liquid phase. This region would be corrosive domain because sodium hydroxide (NaOH) is also concentrated this domain. Figure 8 shows heat quantity of a surface reaction (SWR) at 1.6×10^{-4}s. The SWR has already stopped at high temperature region, and the streamline indicates the gas phase is rolling through reaction area to the tube surface. The concentration of SWR products on the tube surface might be carried by this gas phase rolling.



a: Gas temperature b: Void fraction

c: hydrogen concentration

Fig. 6 Results of the initial model at 3.0×10^{-5}s



a: Gas temperature b: Void fraction

c: hydrogen concentration

Fig. 7 Results of the initial model at 1.6×10^{-4}s

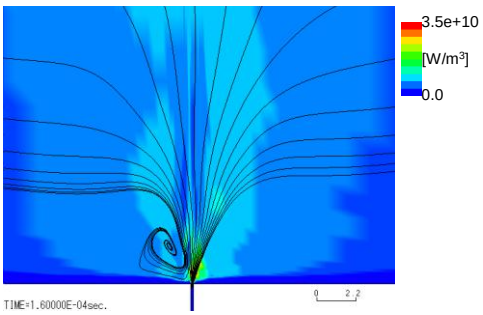
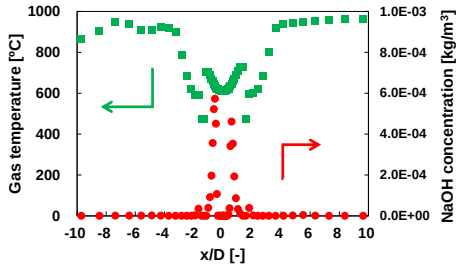


Fig. 8 Heat generation of a surface reaction at 1.6×10^{-4}s

Figure 9 shows the relationship between gas temperature, NaOH concentration and the tube surface length at 8.0×10^{-4}s. The x-axis means normalized horizontal distance by the initial crack width (15μm) from the center of the crack. The distribution of both gas temperature and NaOH concentration in Fig. 9 is slightly asymmetry. This point indicates elapse of the calculation time is not enough as a metastable state. However the time step is used 1.0×10^{-10}s, the numerical stability is going down to calculation failure. Therefore we try to assess the wastage rate using the data at 8.0×10^{-4}s. NaOH, which is the SWR product, exists around the tube surface close to the crack with high gas temperature.



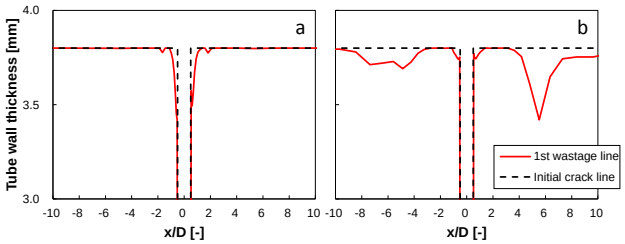
Gas temperature and NaOH concentration on tube surface

Fig. 9 Result of the initial model at 8.0×10^{-4}s

3.3.2 Construction of remeshing model

First wastage model

Physical amounts such as gas temperature and NaOH concentration from the results at 8.0×10^{-4}s data are turned into Eq. (2), and the shapes of the tube surface are depicted in Fig. 10. As mentioned above §2.2.1, an assessment of wastage is performed under the conditions of both SHDP and GTDP, which are changed the constant number B and C in Eq. (2). In the case of SHDP, the corrosion occurs at just the crack neighborhood (Fig. 10a). On the other hand, the corrosion occurs not only at crack neighborhood but also at away from the crack as the case of GTDP (Fig. 10b). Although the shapes of both tube surfaces (Fig. 10a and 10b) are not symmetry, the asymmetry of Fig. 10b is emphasized by the large constant number C (25000).



a: SHDP b: GTDP

Fig. 10 The shapes of the tube surface after first self-wastage anlalysis

Figures 11 and 12 show the first wastage remeshing models constructed based on Fig. 10 a and 10b data, respectively. These mesh models are used to the next numerical calculation.

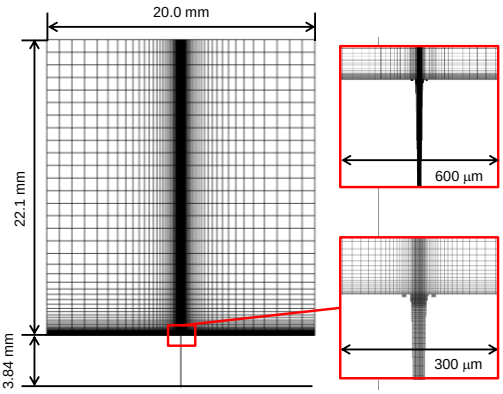


Fig. 11 The first remeshing model for SHDP

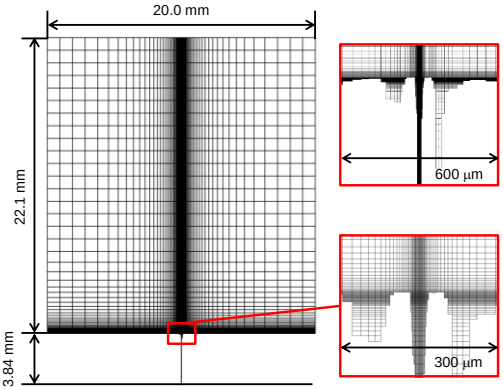


Fig. 12 The first wastage remeshing model for GTDP

Second wastage model

Figures 13 (SHDP) and 14 (GTDP) show the relationship between gas temperature and NaOH concentration in cases of 6.4×10^{-4}s and 8.0×10^{-4}s of the tube surface length, respectively. The numerical calculation is performed as the same condition as the initial model. The inside of deformed initial crack is placed steam as the same condition before, and the corrosion parts on the tube surface are replaced solid cell with fluid cell as liquid sodium region for the treatment of new mesh model.

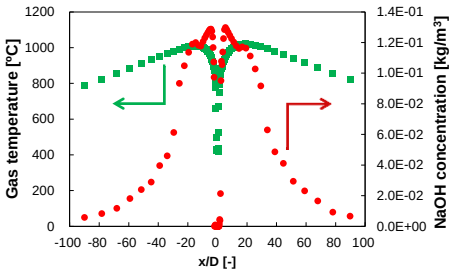


Fig. 13 Result of the first wastage model under SHDP at 6.4×10^{-4}s

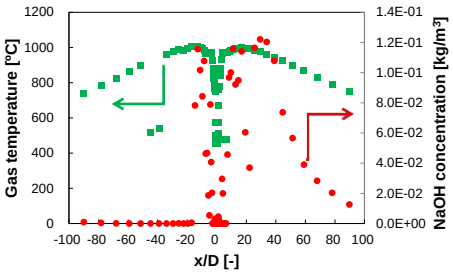


Fig. 14 Result of the first wastage model under SHDP at 8.0×10^{-4}s

In the case of SHDP, NaOH is distributed on the surface with higher gas temperature than the result of initial model (x/D=±20). On the other hand, GTDP case gives the high gas temperature but NaOH concentration is varied. Figure 15 shows the shape of the tube surface as the second wastage and the second remeshing model for SHDP. When the wastage proceeds under the SHDP, the corrosion is occurring grainy in a wide area on the tube surface (Fig. 15). On the other hand, if the wastage proceeds under the GTDP, the corrosion is occurring slightly narrow area but the wastage depth is the almost same compared with the SHDP case as shown in Fig. 16.

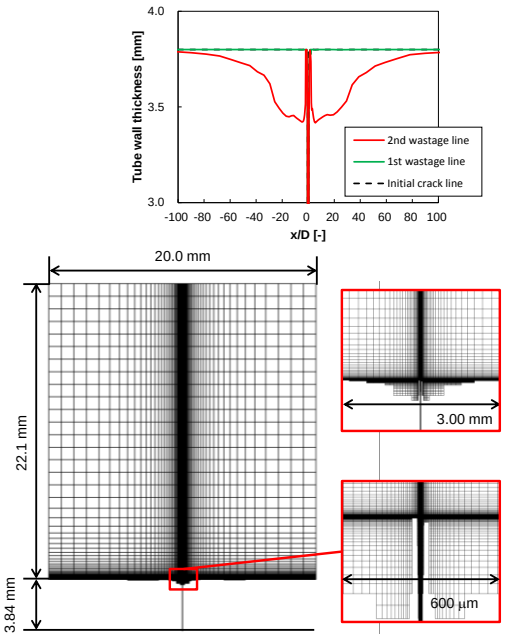


Fig. 15 The shape of the tube surface and the second remeshing model for SHDP

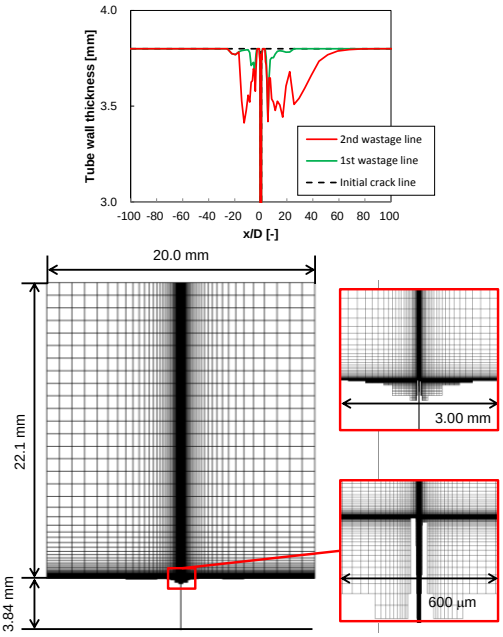


Fig. 16 The shape of the tube surface and the second remeshing model for GTDP

3.3.3 Comparison with the results of the crack enlarged model

Figures 17 and 18 show the results of the crack enlarged model started from the initial models at 1.6×10^{-4}s. In general, gas phase of the first wastage model has tended to divide and spread in liquid sodium region (Fig. 17b and 18b). The reason of this tendency is thought that the steam flows from the enlarged crack to liquid sodium region. In addition, NaOH is directly distributed on the tube surface with high temperature in comparison with the results of initial crack model which sodium (liquid phase) is thinly covered on the tube surface. Therefore the wastage region of the second model is larger than the first model. The high temperature gas phase (~ 1000°C) and NaOH flow toward the center of the crack depth direction in both cases (Fig. 17a, c and Fig. 18a, c). This tendency indicates the wall tube wastage proceeds to be maintained inverted triangle from. Figure 19 shows comparison of experimental observation and numerical results. The wastage region was formed inverted triangle as similar with the experimental observation.

4 CONCLUSIONS

In this study, numerical approach to investigate self-wastage phenomenon including enlargement of crack has been proposed, and preliminary numerical simulation has been carried out to examine applicability of SERAPHIM code.

As the result, sodium layer covered on the tube surface, and the SWR products concentrated close to the leakage with high gas temperature in the initial crack model. The wastage rate was calculated by using Arrhenius type equation (2) based on proportional equation (1). The wastage models were constructed by changing solid cells to fluid cells in the initial (or former) model according to wastage amounts.

Assessment of the wastage was carried out to consider the two types of dominant case as sodium concentration and gas temperature, respectively. Although there was a different form close to the leakage in the first wastage model, both became the form of inverted triangle with the same size in the second wastage model. The form was similar with the experimental observation. These results indicated self-wastage phenomena could be investigated numerically based on the present approach.

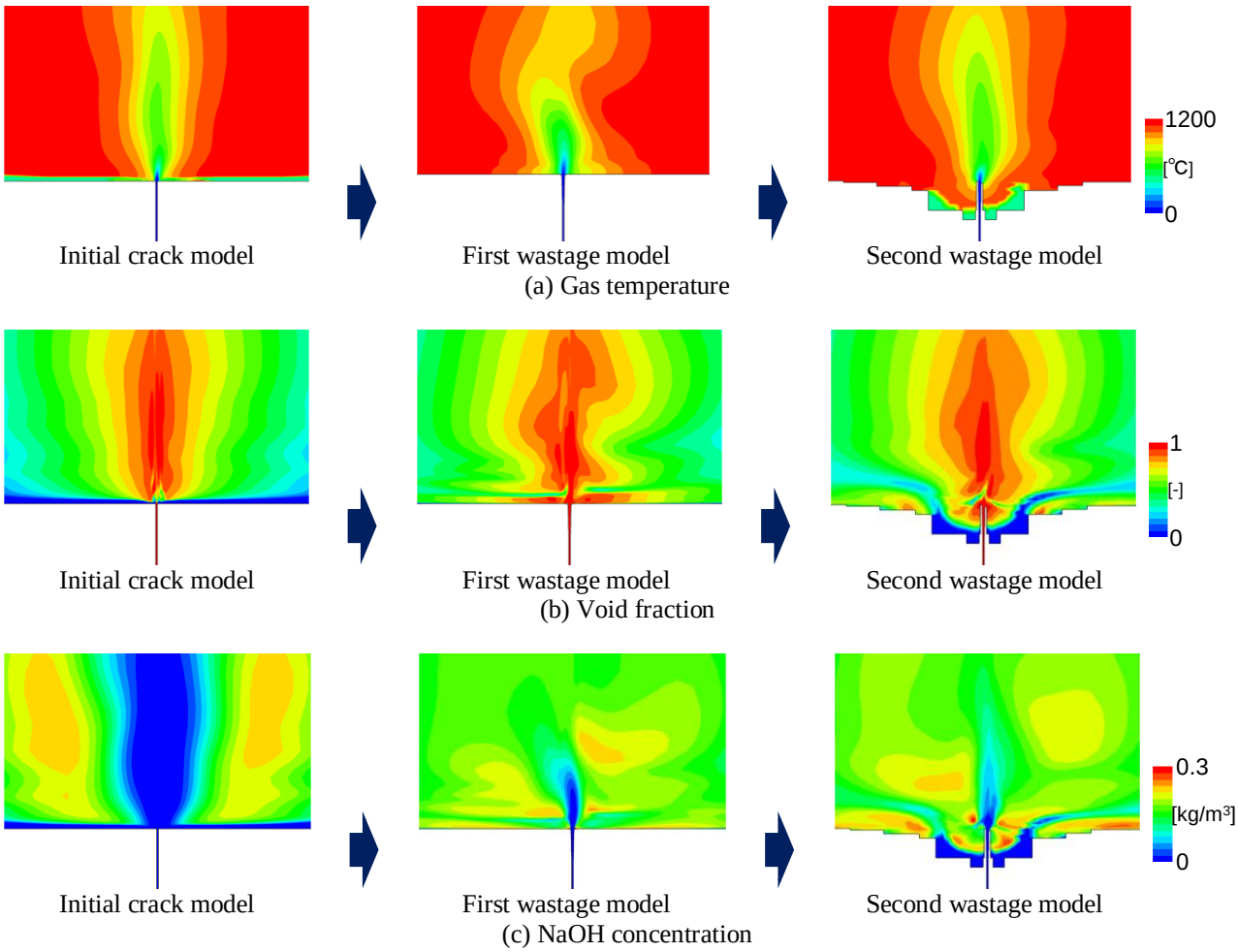


Fig. 17 Results of the crack enlargement model (SHDP)

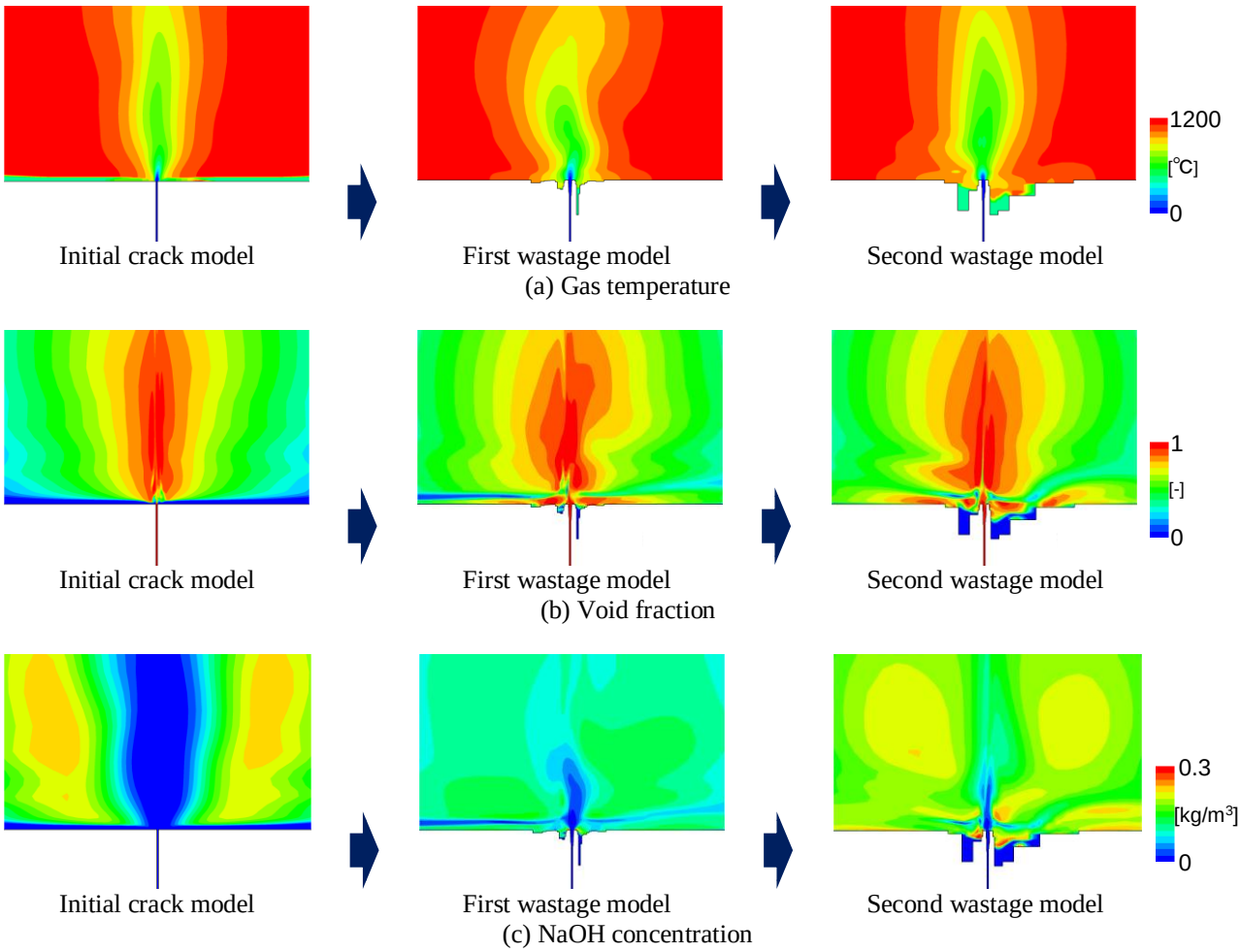
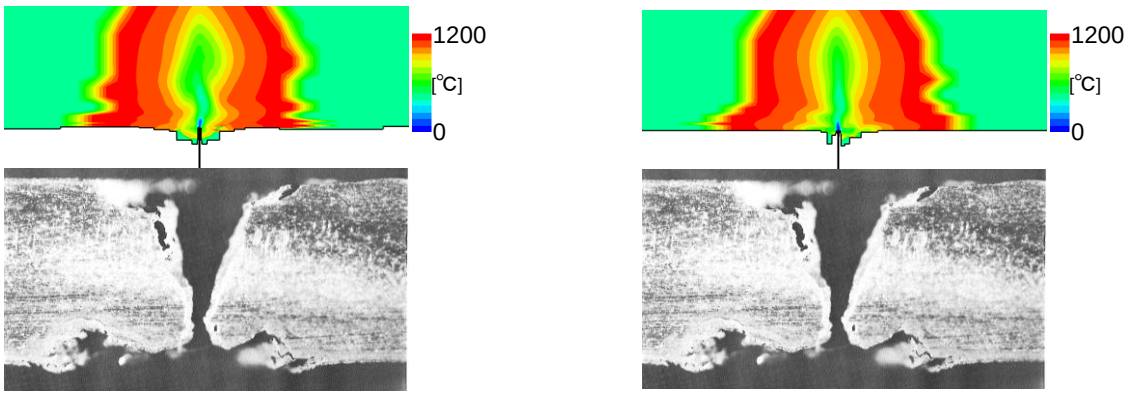


Fig. 18 Results of the crack enlargement model (GTDP)



SHDP case **GTDP case**

Fig. 19 Comparison of the experimental observation (Gas temperature)

ACKNOWLEDGEMENTS

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