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# Development of a Program for Predicting Flow Instability in a Once-through Sodium-Heated Steam Generator (III)

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## 1. Introduction

Two-phase flow systems can be subjected to several types of instability problems. Density-wave oscillation is the most common and important type of instability in boiling channels. Such instability results in difficulties in predictions of the system performance and system control, as well as component failure due to thermal fatigue. A computer program developed for predicting two-phase flow instability in a steam generator heated by liquid sodium was presented in previous works [1][2][3].

In this paper, the results of studies for several parameters are presented in detail.

## 2. Methods and Results

### *2.1 Governing equations*

For a homogenous two-phase, constant area, and one-dimensional channel flow, the mass, momentum, and energy conservation equations, as well as the equation of state, can be written as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} = 0$$

$$\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2)}{\partial x} + \frac{\partial p}{\partial x} + C_k \rho u^2 + \rho g = 0$$

$$\frac{\partial}{\partial t}\left[\rho\left(h + \frac{u^2}{2}\right)\right] + \frac{\partial}{\partial x}\left[\rho u\left(h + \frac{u^2}{2}\right)\right] + \rho u g = \frac{\partial p}{\partial t} + q_w$$

$$\rho = f(p, h)$$

To solve these equations, a novel solution scheme to the finite difference equations developed by Chatoorgoon [4] was used.

The energy conservation equations for the sodium side and water/steam side are coupled through the following relationship between heat sources. The heat balance equation for the tube metal is as follows:

$$\rho C_p V \frac{dT_M}{dt} = Q_s - Q_p$$

The axial conduction of heat is neglected, and $T_M$ represents the metal temperature at the mid-point in the tube wall.

### *2.2 Auxiliary variables*

The dependent variables (u, p, h) are calculated from the solution of the governing equations. Other flow variables are calculated from the thermodynamic and empirical relations and referred to as the auxiliary variables. They are the mixture density, static quality, and void fraction for a two-phase region, which are expressed as follows.

$$\rho = \left\{\frac{1}{\rho_l} + \left(\frac{1}{\rho_g} - \frac{1}{\rho_l}\right) x\right\}^{-1}$$

$$\mathrm{x} = \frac{h - h_l}{h_g - h_l}$$

$$\mathrm{r} = \mathrm{x}\,\frac{\rho}{\rho_g}$$

### *2.3 Empirical correlations*

The frictional and heat transfer resistances are calculated with the aid of empirical correlations for each flow region. The flow regions of the water/steam sides are divided into three regions, which are sub-cooled, saturated, and super-heated regions. It is well known that friction and heat transfer coefficients are discontinuous at boiling boundaries, and can lead to numerical instabilities. To overcome this problem, a two-phase friction multiplier and boiling heat transfer coefficient are smoothed using the following spline fit. The current values are static quality at departure from boiling, $x_{db}$=0.75, and void fraction, $r_{gs}$ =0.95 [5]. Figs. 1 and 2 show variations of two-phase multiplier values and boiling heat transfer coefficient values.

$$\emptyset = 1 + \left(\emptyset' - 1\right)\frac{(1 - \mathrm{x})}{(1 - x_s)}$$

$$x_s = \frac{r_{gs}\rho_g}{\left(r_{gs}\rho_g + (1 - r_{gs})\rho_l\right)}$$

$$h = h_{super\ heat} + (h_{boiling} - h_{super\ heat})\frac{(1-x)}{(1-x_{departure\ \ from\ \ boiling})}$$

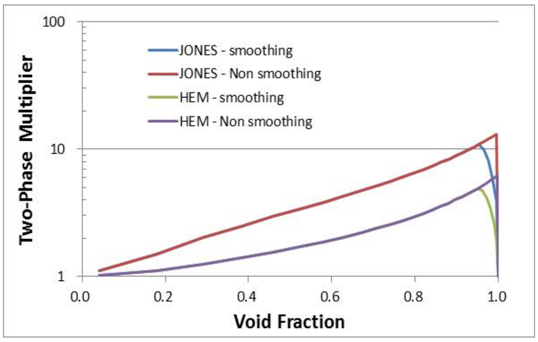


Fig. 1. Variations of two-phase multiplier values

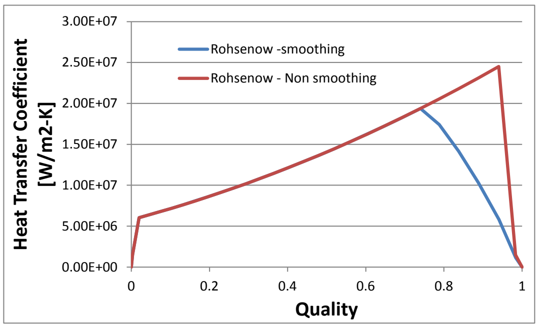


Fig. 2. Variations of boiling heat transfer coefficient values

### *2.4 Results of Analysis*

To demonstrate the ability of the program, experimental results of the tests, which were performed by JAEA [6], [7], are compared with the calculation results. The specifications of the 1 MW DWT-SG are given in Table 1.

Table 2 shows the test data of unstable conditions at 100% power. Figs. 3 shows that an instability occurs at an increased sodium flow by 17% of the test sodium flow data. A total of 151 nodes and a time step of 0.01 s are used for the calculations. The inlet flow rate and outlet flow rate diverge and eventually reach the limit cycle. The amplitude of the inlet flow rate is larger than that of the outlet flow rate. The amplitude of the inlet flow rate is about 25% of the nominal value during the limit cycle, and the period is about 2.7 s. Fig. 4 shows the weight factors of phases within the boiling boundary node. The weight factors are derived using the saturation enthalpy in the boiling boundary nodes. They are used to correct the heat transfer coefficient and friction factor of the boiling boundary node. The amplitude of the phase change location oscillation within the boiling-to-vapor boundary node is larger than that of the liquid-to-boiling boundary node. This shows that two boiling-to-vapor boundaries pass through a mesh boundary during the limit cycle. Fig. 5 shows the pressure drops of the liquid, boiling, and vapor regions. The phase of oscillation between the vapor and liquid is different. The summation of three pressure drops is constant due to the boundary condition imposed by the inlet and outlet plenum. Fig. 6 shows the heat addition into the liquid, boiling, and vapor regions. The heat addition is almost invariant in the boiling region. There are oscillations in the liquid and vapor regions, but the phase is different. Fig. 7 shows the sodium and steam temperature at the tube exit. They are invariant.

Table 1. Specifications of DWT-SG [6], [7]

| | |
|---|---|
| Heat transfer capacity | 1 MW |
| Number of tubes | 10 |
| Outer dia. of tube | 19 mm |
| Inner dia. of tube | 11.4 mm |
| Length of tube | 18 m |
| Tube material | Mod.9Cr-1Mo |
| Tube pitch | 36 mm |
| Tube arrangement | Equi.-triangular |
| Tube type | Straight, Double wall tube |
| Orifice coefficient | 120, 260, 400 |
| Gap conductance | $3.5 \times 10^4$W/(m2-K) |

Table 2. Test data at 100% power

| | |
|---|---|
| Sodium inlet temperature | 537.6 °C |
| Sodium outlet temperature | 339.7 °C |
| Sodium flow rate | 4.172 kg/s |
| Feed water temperature | 238.1 °C |
| Steam temperature | 523 °C |
| Feed water flow rate | 0.45 kg/s |
| Feed water pressure | 14.87 MPa |
| Orifice coefficient | 120 |

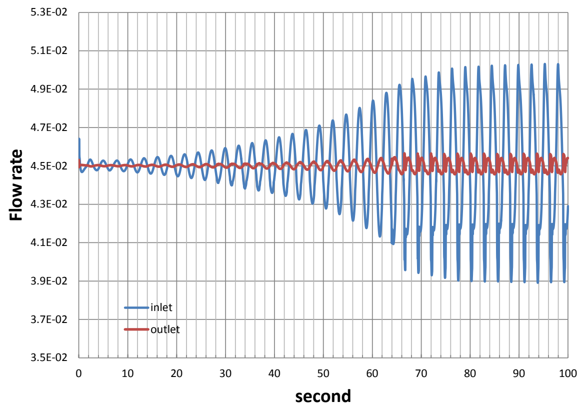


Fig. 3. Inlet and outlet flow rates for the condition of Table 2 at a sodium flow rate of 4.881 kg/s

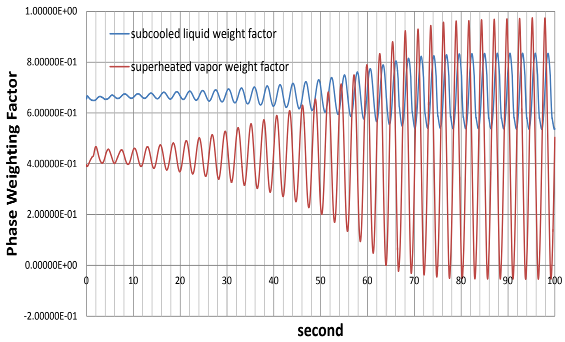


Fig.4. Weight factors of phases within the boiling boundary node

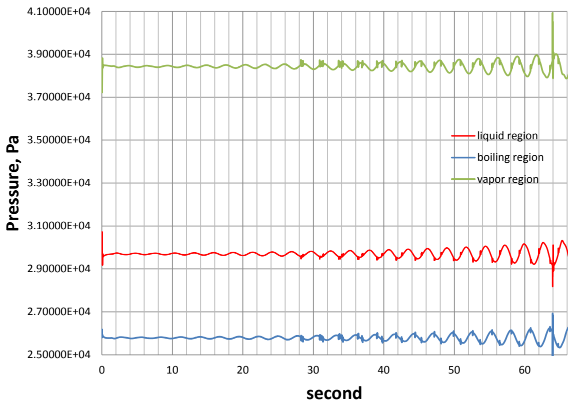


Fig.5. Pressure drop of each regions

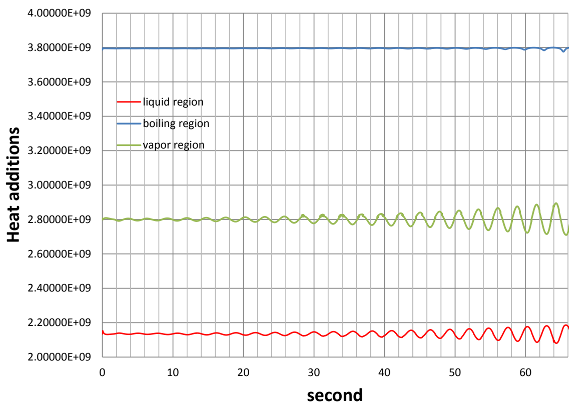


Fig.6. Heat addition of each region

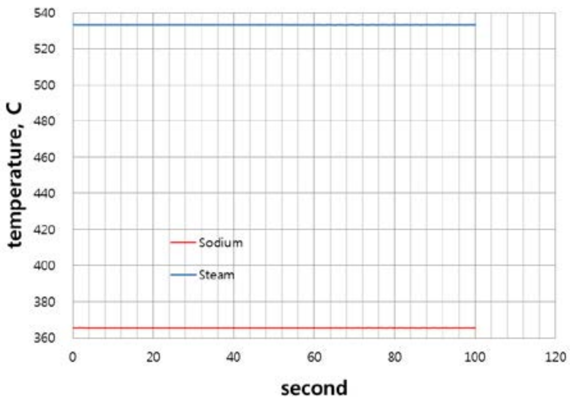


Fig.7. Sodium and steam temperature at tube exit

## 3. Conclusions

The limit cycle was predicted even in a fixed node system. The amplitude of the inlet flow rate is larger than that of the outlet flow rate. The amplitude of the phase change location oscillation within the boiling-to-vapor boundary node is larger than that of the liquid-to-boiling boundary node. The sodium and steam temperatures are invariant at the tube exit.

## ACKNOWLEDGEMENT

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