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

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1. Introduction

A SG selected for PGSFR is of a once-through integrated type. It is a vertical counter flow shell and tube heat exchanger with sodium on the shell side and water-steam in the tubes. The phenomenon of two-phase flow instability has been observed in many industrial domains such as boiling systems and steam generators. Since the oscillations induced by two-phase flow instability can cause many problems such as thermal cycling at the dryout location of the tube and the upper tubesheet, and flow mal-distribution among the tubes, it is necessary to develop a design tool to predict the thresholds of flow instability. In this paper, a computer program developed for predicting two-phase flow instability in a steam generator under axial non-uniform heat flux is presented, and analysis results for verification are presented.

2. Methods and Results

Flow instability has been studied by solving the time dependent mass, momentum, and energy conservation equations representing the system. Chatoorgoon [1] developed a novel solution to the finite difference equations to study the system instability. The method avoids many of approximations, the use of property derivatives, and matrix inversion. It also permits large time-step as well as small time-step. The method was used for investigating two-phase flow instability under constant heat flux conditions, which is the preliminary work of a present work. [2]

2.1 Governing equations for fluids

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

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

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

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

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

, where ρ, u, p, h, C_k, q_w are the fluid density, velocity, pressure, enthalpy, friction constant and applied heat per unit volume of flow, respectively.

2.2 Auxiliary variables

The dependent variables (u, p, h) are calculated from the solution of governing equations in section 2.1. Other flow variables are calculated from the thermodynamic and empirical relations and referred as the auxiliary variables. They are mixture density, static quality, and void fraction for two-phase region, which are expressed as following.

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

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

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

, where ρ, x, r, l, g are mixture density, static quality, and void fraction for two-phase region, liquid and gas, respectively.

2.3 Heat balance equations for the tube metal

The energy conservation equations for sodium side and water/steam side are coupled via the following relationship between heat sources.

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

, where C_p, V, T_M, Q_s, Q_p are the specific heat, volume, the center temperature of the tube wall, the heat sources to the sodium-side and water/steam-side, respectively.

The axial conduction of heat is neglected, and T_M represents the metal temperature at the mid-point in the tube wall. The left-hand-side of the equation represents the thermal inertia of the tube metal. Integration of the equation yields :

$$\rho C_p V \frac{T_M^n - T_M^{n-1}}{\Delta t} = U_s A_s(\overline{T_s} - T_M) - U_p A_p(T_M - \overline{T_p})$$

Heat sources Q_p, Q_s are expressed in terms of the temperatures T_M, T_s, T_p.

$$Q_s = U_s A_s \frac{\frac{\rho C_p V}{\Delta t}(\overline{T_s} - T_M^{n-1}) + U_p A_p(\overline{T_s} - \overline{T_p})}{\frac{\rho C_p V}{\Delta t} + U_s A_s + U_p A_p}$$

$$Q_p = U_p A_p \frac{\frac{\rho C_p V}{\Delta t}(T_M^{n-1} - \overline{T_p}) + U_s A_s(\overline{T_s} - \overline{T_p})}{\frac{\rho C_p V}{\Delta t} + U_s A_s + U_p A_p}$$

A_s, A_p are the outside surface area of the tubes, U_p and U_s are the heat transfer coefficients between the metal and fluids, and are including the thermal conductance of metal based on half wall thickness

$$\frac{1}{U_s} = \frac{1}{h_{shell}} + \frac{Dia,o}{2*k}\log\frac{Dia,o}{Dia,c}$$

$$\frac{1}{U_p} = \frac{Dia,o}{2*k}\log\frac{Dia,c}{Dia,i} + \left(\frac{Dia,o}{Dia,i}\right)\frac{1}{h_{tube}} + \left(\frac{Dia,o}{Dia,i}\right)\frac{1}{h_{fouling}}$$

,where Dia, o, Dia, i, Dia, c are the outer diameter, inner diameter and gap diameter of the tube, respectively.

Figure 1 shows control volumes with vertical tubes and two fluids.

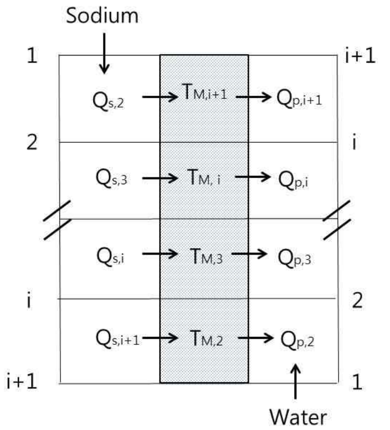

Fig. 1. Illustration of the temperatures and flows

2.4 Empirical correlations

The frictional and heat transfer resistances are calculated with the aid of empirical correlations. The flow regions of the water/steam sides were divided into three regions, which are sub-cooled, saturated and super-heated regions. The fouling factor was applied to the water/steam side only, that are 5678.6, 11357.0 W/m²-ºC.

Table1. Empirical correlations

- Water side - pressure drop correlation
  - single-phase : Blasius, Serghides
  - two-phase friction multiplier : HEM, Jones
- Water side - heat transfer correlation
  - single-phase: Dittus-Boelter
  - nucleate boiling region : Rohsenow
  - water/steam side fouling factor : 5678.6, 11357.0 W/m²-ºC
- Sodium side heat transfer correlation
  - Graber-Rieger
  - Lubarsky-Kaufman

2.5 Numerical approach

The equations are discretized in space by integration from point i to i + 1, and the forward-difference scheme in time is employed to derive the difference equations for the mass, momentum, and energy conservation. The one-dimensional flow channel is divided into axial computational cells or control volumes, with a non-staggered grid, i.e., the grid points are located at the cell edges, as shown in Fig. 2.

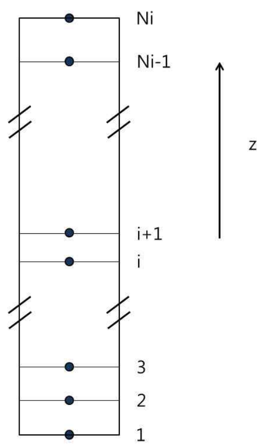

Fig. 2. Spatial grid and control volume in the flow channel.

The kinetic energy terms and pressure term in the energy equation for two-phase systems can be ignored, as they are generally very small.

The algorithm employed to solve the coupled, non-linear, time-dependent discretized equations is given in Fig. 3 [1]:

There are four unknown variables (ρ, u, p and h) to be solved at each time step for each grid point i from 2 to last grid Ni. Inlet conditions (ρ, p and h) of the flow are maintained constant at grid point 1. Before starting the transient simulations, the steady-state solution for the unknown variables was slightly perturbed. In the present analysis, velocities in a steady-state were increased by 1% as an initial condition at every grid point.

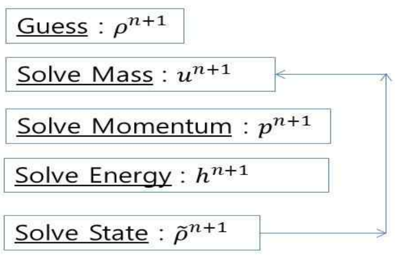

Fig. 3. Sequence of solving.

2.6 Boundary Conditions

For the present investigation, a constant pressure drop boundary condition along with constant inlet conditions are applied to the flow channel, i.e., the inlet temperature, inlet pressure, and outlet pressure are assumed to be prescribed. The program will iterate on the inlet flow velocity to match the outlet pressure boundary condition. To obtain an improved guess for the inlet flow velocity, u, a "Bi-section Method" was employed.

2.7 Stability Analysis

To demonstrate the ability of the program, experimental results of tests, which were performed by JAEA [3], [4] were compared with calculation results. The specification of the 1 MW DWT-SG is given in Table 2. Steady-state analyses were carried out for the 1 MW DWT-SG with test data. Number of node and time step of 151 and 0.01 second were used for stable and unstable conditions calculation. Fouling factors for water and steam are 5678.6, 11357. W/m2-C respectively. Blasius, Dittus-Boelter, Rohsenow, Graber-Rieger correlations are used. Table 3 shows that calculated results in steady-state are good agreement with test results, and it has 0.6% difference in heat transfer rates. Fig 4 shows temperature distributions of sodium, water/steam and tube metal. Fig 5 shows heat flux along the tube length. Fig. 6 shows stability analysis result for the condition of Table 3. Table 4 and Table 5 are test data of unstable condition at 100% and 70 % power. Fig. 7 and Fig. 8 show that instability occur at increased sodium flow by 17% and 16% of test sodium flow data. This means the developed code can predict the threshold sodium flow for the range of error within about 17% with 1 MW DWT-SG experimental data.

Table 2. Specification of DWT-SG[3], [4]

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	3.5×10^4W/(m2-K)

Table 3. Test and calculation data

	test	calculation
Sodium inlet temperature	536.5 °C	
Sodium outlet temperature	337.5 °C	338.3 °C
Sodium flowrate	4.125 kg/s	
Feed water temperature	237.7 °C	
Steam temperature	522.2 °C	527.2 °C
Feed water flowrate	0.45 kg/s	
Feed water pressure	14.87 MPa	
Steam pressure	14.78 MPa	14.77 MPa

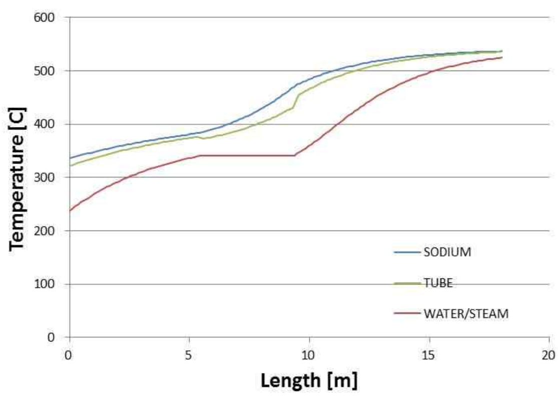

Fig. 4. Temperature distributions of sodium, water/steam and tube metal

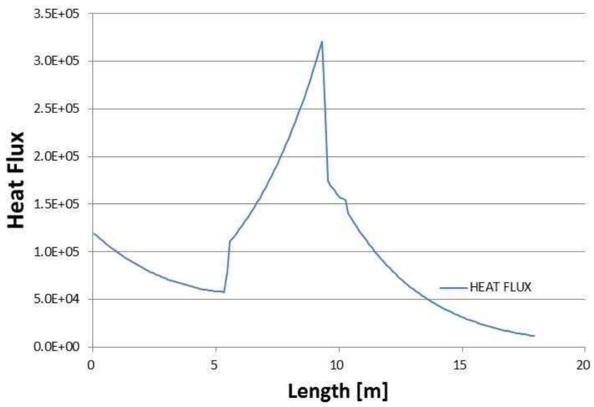

Fig. 5. Heat flux profile

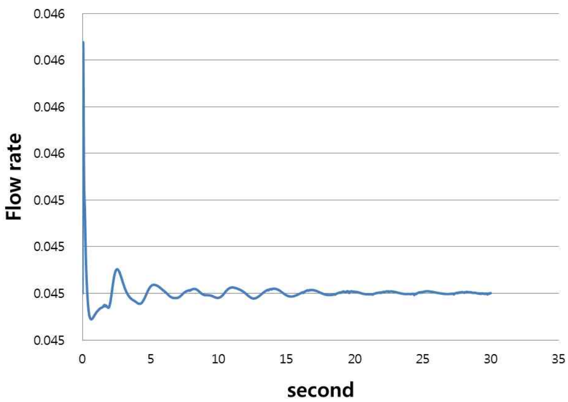

Fig. 6. Stability analysis result for the condition of Table 3

Table 4. Unstable condition test data at 100% power

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

Table 5. Unstable condition test data at 70% power

Sodium inlet temperature	502.1 °C
Sodium outlet temperature	322.4 °C
Sodium flowrate	3.286 kg/s
Feed water temperature	239 °C
Steam temperature	488 °C
Feed water flowrate	0.33 kg/s
Feed water pressure	13.083 MPa
Orifice coefficient	260

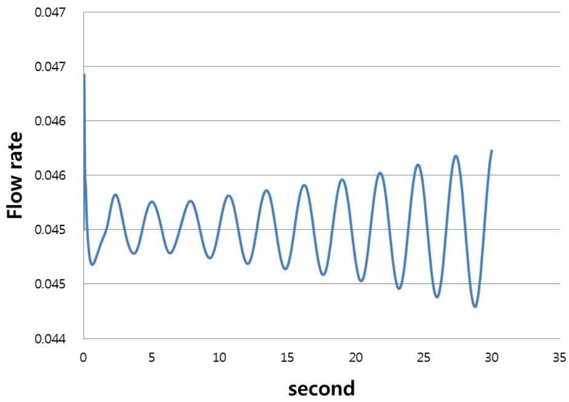

Fig.7. Stability analysis result for the condition of Table 4 at sodium flow rate, 4.881 kg/s .

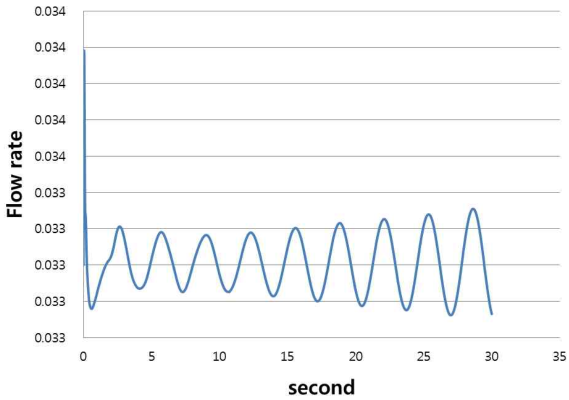

Fig. 8. Stability analysis result for the condition of Table 5 at sodium flow rate, 3.812 kg/s.

3. Conclusions

A computer code was developed for investigating the two-phase flow stability under sodium-heated conditions in the shell-side of a SG. A solution algorithm for the sodium flow field and tube conduction has been developed for application to sodium-heated SG.

ACKNOWLEDGEMENT

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