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

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1. Introduction

A computer program developed for predicting two-phase flow instability in a steam generator heated by liquid sodium was presented in a previous work [1]. For steady-state and dynamic analyses, a single-channel, one-dimensional model was developed.

To study the system stability, a novel solution scheme to the finite difference equations developed by Chatoorgoon [2] was used. The method avoids many approximations, the use of property derivatives, and a matrix inversion.

In this paper, the results of parametric studies for different operating conditions and numerical discretization parameters are presented.

2. Methods and Results

2.1 Governing equations for fluids

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:

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

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

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

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

2.2 Auxiliary variables

The dependent variables (u, p, h) are calculated from the solution of the governing equations in section 2.1. 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:

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

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

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

2.3 Heat balance equations for the tube metal

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

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

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

2.4 Empirical correlations

The frictional and heat transfer resistances are calculated with the aid of empirical correlations. The flow regions of the water/steam sides are 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 is, 8,517 W/m²-ºC.

Table 1. 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 : 8,517 W/m²-ºC
- Sodium side heat transfer correlation
  - Graber-Rieger

- Lubarsky-Kaufman
- JAEA experiment

2.5 Numerical approach

The equations are discretized in space by the 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. 1.

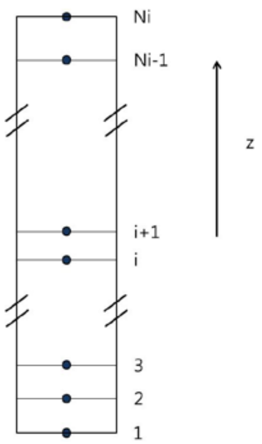

Fig. 1. Spatial grid and control volume in the flow channel.

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. 2 [2]:

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 the last grid Ni. The 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 is slightly perturbed. In the present analysis, velocities in a steady-state are increased by 1% as the initial condition at every grid point [3].

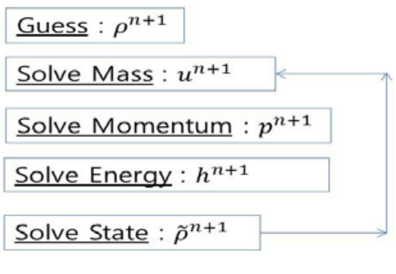

Fig. 2. Sequence of solving.

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 iterates 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” is employed.

2.7 Stability Analysis

To demonstrate the ability of the program, experimental results of the tests, which were performed by JAEA [3], [4], are compared with the calculation results. The specifications of the 1 MW DWT-SG are given in Table 2.

Table 3 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. The number of nodes and time step of 151 and 0.01 seconds are used for the conditions.

Table 2. Specifications of DWT-SG [4], [5]

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	3.5×10^4 W/(m2-K)

Table 3. Unstable condition 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

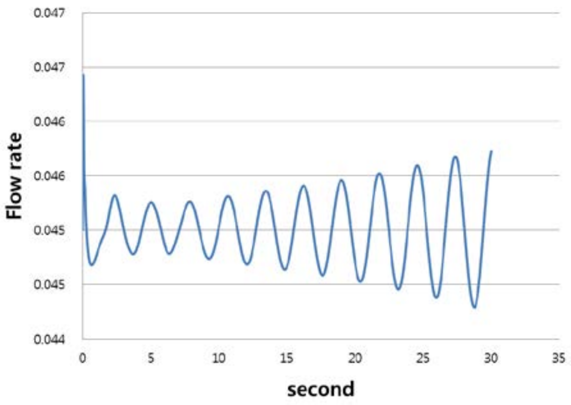

Fig.3. Stability analysis results for the condition of Table 2 at a sodium flow rate of 4.881 kg/s

To ensure the time step and grid size independence of the results, a grid refinement study is performed. For the refinement study, the test conditions at 100% power in Table 2 are used, and Fig. 4 shows the effects of the time step size while keeping the number of nodes of 151. The system is found to be stable for a time step size of 0.05 seconds, and unstable for the time step size of 0.02 seconds, respectively. This suggests that the time step size should be less than 0.02 seconds for an accurate stability analysis. A large time step may induce a numerical diffusion and hence an artificial flow stability into the system.

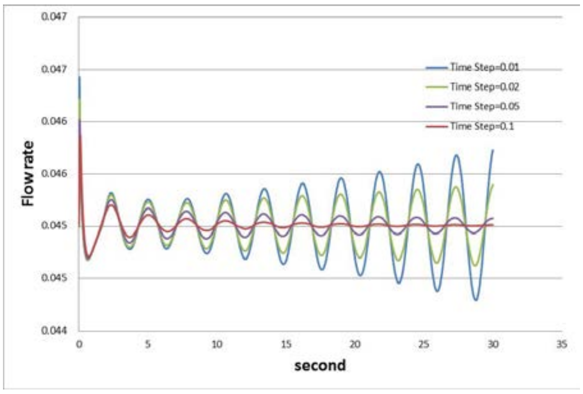

Fig. 4. Effect of time step

Fig. 5 shows the effects of the grid step size while keeping a time step size of 0.01. It was found that when the number of nodes is changed from 150 to 200, the grid size does not have a significant effect on the magnitude and frequency of the oscillations, and it remains nearly the same. This suggests that 150 nodes is an adequate number for an analysis of this system.

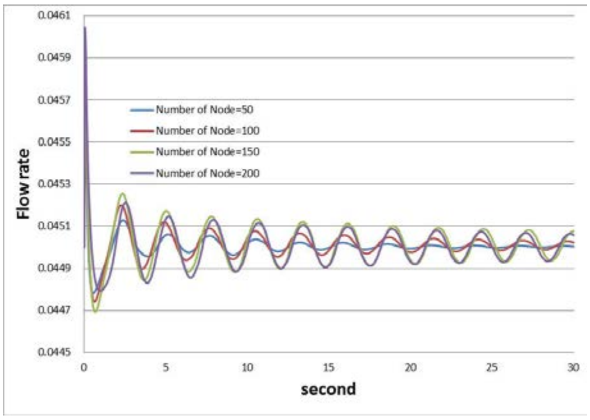

Fig. 5. Effect of the number of nodes

Fig. 6 shows the effects of the pressure tolerance at the tube exit while maintaining a time step size of 0.01 and 151 nodes. The pressure tolerance is reduced from 100 Pa to 0.1 Pa. It was found that when the pressure tolerance is below 10 Pa, the magnitude and frequency of the oscillations remains the same.

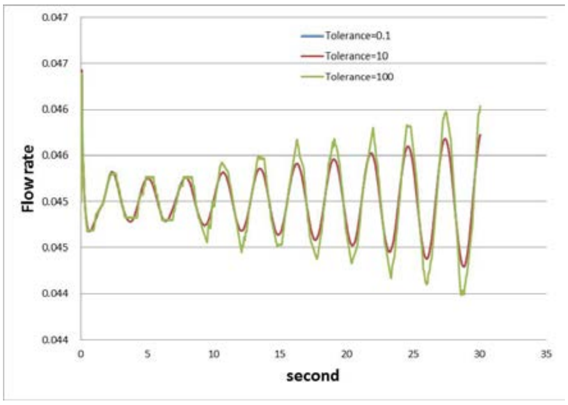

Fig. 6. Effects of Tolerance [pa] in Pressure Boundary Condition at the Tube Exit

The system is analyzed for different system pressures and thermal inertias of the tube wall conditions.

Fig. 7 shows the effects of system pressure at the tube inlet while keeping the flow rate of 4.172 kg/s, as given in Table 2. The pressure is reduced from 100% to 80% of 14.87 MPa. It was found that when the pressure is 20% less than the test condition, the magnitude of the oscillations is growing, and when the pressure is 18% less than the test condition, the magnitude of the oscillations is sustained.

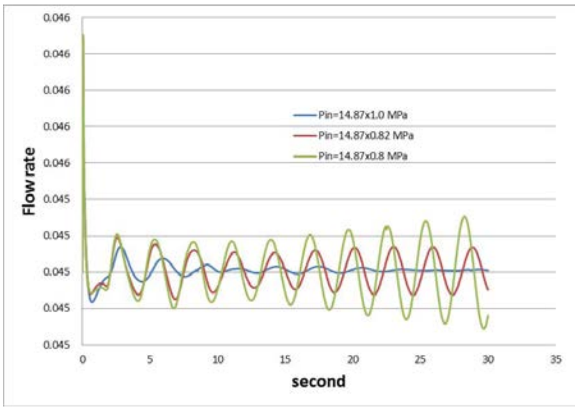

Fig. 7. Effects of tube inlet pressure

Fig. 8 shows the effects of tube wall thermal inertia with a flow rate of 4.881 kg/s, as given in Fig. 3. The tube wall thermal inertia is changed from the reference case to the no tube volume. It was found that when the tube wall thermal inertia is decreasing, the magnitude of oscillations is growing.

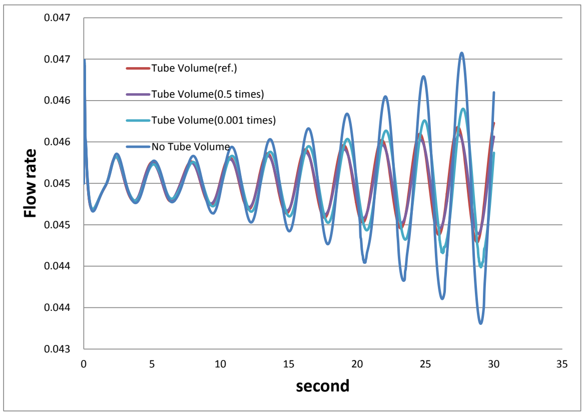

Fig. 8. Effects of thermal inertia of the tube wall

3. Conclusions

A computer code was developed for investigating the two-phase flow stability under sodium-heated conditions in the shell-side of an SG. Parametric studies for different operating conditions and numerical parameters were presented.

ACKNOWLEDGEMENT

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