GVTRAN–PC – A STEAM GENERATOR TRANSIENT SIMULATOR

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ABSTRACT

The present report presents the methodology utilized to develop GVTRAN–PC program, the steam generator simulation program for the microcomputer environment, which possess a capability to reproduce the experimental data with accuracies comparable to those of the mainframe simulators. The methodology is based on the mass and energy conservation in the control volumes which represents both the primary and the secondary fluid in the U–tube steam generator. The quasi–static momentum conservation in the secondary fluid control volumes determines in a semi–iterative scheme the liquid level in the feedwater chamber. GVTRAN–PC program has been tested against typical PWR pump trip transient experimental data and the calculation results showed good agreement in most representative parameters, viz. the feedchamber water–level and the steam dome pressure.

1.INTRODUCTION

An accurate and inexpensive analysis capability is the quality which is extensively sought in a plant simulator, for the licensing procedure and operation managements require a great number of detailed plant performance evaluations under hypothetical accident sequences and initiating conditions. Nevertheless, in view of the increasing analytical complexity, the existing codes are not fast enough to permit thoroughly examination of all the most probable sequences in an accident analysis. The present work tries to contribute to the development of a faster and better plant simulator, by developing a fast and accurate microcomputer based steam generator simulator.

The present report presents the methodology developed and implemented in GVTRAN–PC program, the steam generator simulator for the microcomputer environment. The primary circuit of the steam generator is simply treated with the mass and energy conservation equations, by assuming a constant pressure in the primary tube region. In the secondary circuit the mass and energy conservation are imposed with properly chosen two–phase correlations. The feedchamber water level are determined with the momentum conservation equation in a quasi–static approximation.

The simplicity of GVTRAN–PC program is also warranted by a reduced number of control volumes both in the primary and in the secondary region. The most important effect in the secondary region which must be carefully tracked is the level at which the bulk boiling initiates because the void fraction changes quite abruptly at that point and, consequently, strongly influencing the heat transfer rate from the primary to the secondary fluid. The program tracks the boundary of bulk boiling region with the moving boundary approach by defining only two control volumes in the secondary tube zone and, correspondingly, four control volumes in the primary tube zone.

The performance of GVTRAN–PC program has been evaluated by calculating a pump trip transient recorded during a startup testing of Donald C. Cook Nuclear Station Unit One. The calculated results were favorably compared with the experimental data and the quality of the results is satisfactory even in comparison to the four–equation non–equilibrium liquid model implemented in the main frame steam generator TRANSG simulator.

In overall, GVTRAN–PC program possess a set of qualities which highly commends for its implementation in a nuclear plant simulator, viz. coding simplicity, computation velocity and acceptable accuracy.

2.METHODOLOGY

GVTRAN program solves the equations for the mass, energy and momentum conservation in the secondary side of the steam generator, while in the primary side only mass and energy conservations are specified and a constant pressure assumption is considered. The conservation equations are solved numerically with the Classical Runge–Kutta method with the suitable mesh spacings for stability requirements. In the following paragraphs the detailed descriptions of the methodology are presented.

2.1 Conservation Equations in the Control Volume. The conservation equations for the steam generator modelling are listed below. The terms related to the kinetic energy, potential energy and viscous heat dissipation will be neglected. The laws of conservation for an infinitesimal volume element are for the mass conservation equation:

$$\frac{\partial}{\partial t}\rho = -\nabla\cdot(\rho\,\vec{v}) \; ; \qquad (2.1.1)$$

for the momentum conservation equation:

$$\frac{\partial}{\partial t}(\rho\vec{v}) = -\nabla\cdot(\rho\underline{\underline{v}}\,\underline{\underline{v}}) - \nabla\cdot\underline{\underline{\tau}} - \nabla\cdot\underline{\underline{P}} + \rho\vec{g} \; ; \qquad (2.1.2)$$

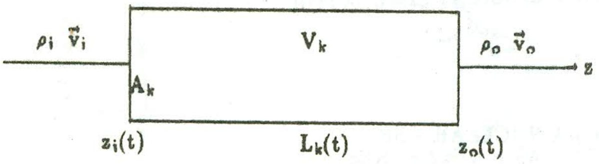
and for the energy conservation equation:

$$\frac{\partial}{\partial t}(\rho h) = -\nabla\cdot(\rho h\vec{v}) - \nabla\cdot\vec{q} + \frac{\partial}{\partial t}P, \qquad (2.1.3)$$

where conventional notations[2] have been used.

2.2 Macroscopic Mass Conservation. The figure below illustrates the one–dimensional control volume model implemented in the program.

In general the control volumes outer surfaces are nonstationary, that is, there can be a moving boundary between adjacent control volumes. The Leibnitz's integration rule is therefore used for the macroscopic balances.



A constant flow area, A_k, is assumed, such that the integration of Equation 2.1.1. in the volume V_k, yields

$$\frac{d}{dt}\bar{\rho}_k = \frac{W_i - W_o - \bar{\rho}_k A_k \frac{d}{dt} L_k}{A_k L_k} \tag{2.2.1}$$

where

$$\bar{\rho}_k = \int_{z_i(t)}^{z_o(t)} \rho dz / L_k ,$$

$$W_i = A_k \rho_i (v_i - v_{si}) ,$$

$$W_o = A_k \rho_o (v_o - v_{so}) , \text{ and}$$

v_{si}, v_{so} are the velocities of the left and right boundaries of the control volume V_k, respectively.

2.3 Macroscopic Momentum Conservation. The momentum conservation equation, Equation 2.1.2, is integrated in the control volume V_k, yielding

$$\frac{d}{dt}G_k(t) = W_i v_i - W_o v_o - A_k L_k \frac{2\rho v^2}{D_e} f_F$$

$$A_k P_i - A_k P_o + A_k g(\rho_o z_o - \rho_i z_i). \tag{2.3.1}$$

where

$$G_k(t) = A_k \int_{z_i(t)}^{z_o(t)} (\rho v) dz,$$

D_e is the equivalent hydraulic diameter, and

f_F is the Fanning friction factor.

2.4 Macroscopic Energy Conservation. The energy conservation, Equation 2.1.3, is integrated in the control volume, yielding

$$\frac{d}{dt}(\rho h A_k L_k) = W_i h_i - W_o h_o + \overline{M}_k L_k q'' + A_k L_k \frac{d}{dt}\overline{P}. \tag{2.4.1}$$

where

$\overline{M}_k$ is the effective perimeter of the flow channel, and

$$\bar{P} = \int_V PdV/V_k .$$

3. STEAM GENERATOR MODELLING

The following paragraphs describe the modelling approximations adopted in the GVTRAN–PC program to simulate the most important phenomena that are observed in the U–tube steam generators. The primary and secondary side control volumes and the numerical approximations to the conservation equations will also be described.

3.1 Control Volume Definition. The GVTRAN–PC program is written for the U–type steam generator. The control volumes defined in the steam generator are illustrated in Figure 3.1.1 below, where some significant parameters are shown schematically.

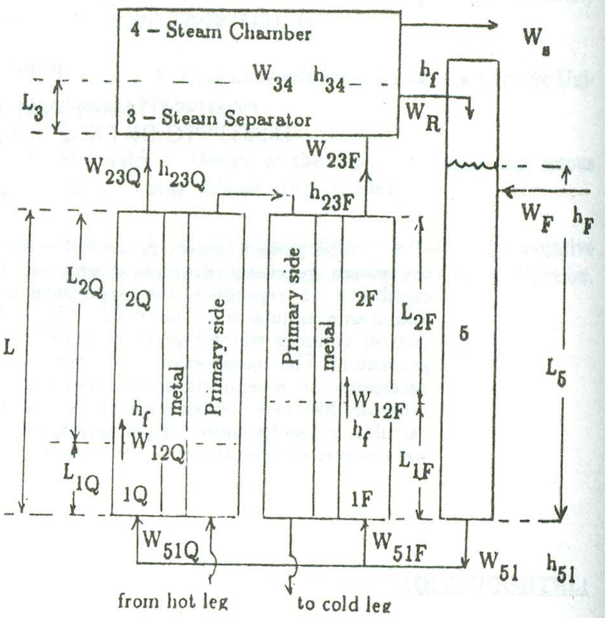


Figure 3.1.1 Control Volumes in the U–tube Steam Generator.

3.2 Mass Conservation in the Steam Generator. Subcooled Regions. The subcooled regions, 1Q and 1F, can be modelled with the simplifying assumptions by neglecting the time variation of the average density during the time span considered in the analysis. Equation 2.2.1 yields

$$W_{12Q} = W_{51Q} - \rho_{1Q} A_{tb} \frac{d}{dt} L_{1Q} \tag{3.2.1}$$

$$W_{12F} = W_{51F} - \rho_{1F} A_{tb} \frac{d}{dt} L_{1F} \tag{3.2.2}$$

Bulk Boiling Region. In the bulk boiling region, disregarding the local boiling region, Equation 2.2.1 becomes

$$W_{23Q} = W_{12Q} + \rho_{2Q} A_{tb} \frac{d}{dt} L_{1Q} - A_{2Q} L_{2Q} \frac{d}{dt} \rho_{2Q} \tag{3.2.3}$$

and

$$W_{23F} = W_{12F} + \rho_{2F} A_{tb} \frac{d}{dt} L_{1F} - A_{2F} L_{2F} \frac{d}{dt} \rho_{2F} \tag{3.2.4}$$

Steam Separator. The steam separator mixture inflow, W_{23}, is the sum of W_{23Q} and W_{23F} mass flows, such that the mass conservation can be given as

$$W_{34} = W_{23} - W_R - \rho_3 A_3 \frac{d}{dt} L_3 - A_3 L_3 \frac{d}{dt} \rho_3 \tag{3.2.5}$$

The partial derivatives of L_{1Q}, L_{1F} and L_3 are obtained from the energy balance.

Downcomer Region. In the *downcomer* region the mass conservation equation, Equation 2.2.1, can be written as

$$\frac{d}{dt}L_5 = \frac{W_F + W_R - W_{51}}{A_5\,\rho_5} \qquad (3.2.6)$$

3.3 Energy Conservation inthe Steam Generator.

Subcooled Region. In the subcooled region the terms corresponding to the time derivative of the enthalpy and density will be neglected, justified by a low dependence on pressure, and the pressure time derivative has found to be insignificant. Thus from Equation 2.4.1, one gets

$$\frac{d}{dt}L_{1Q} = \frac{2W_{51Q}}{t\,b\,\rho_{1Q}} + \frac{S_{1Q}q''}{A_{tb}\rho_{1Q}(h_{1Q} - h_f)} \qquad (3.3.1)$$

Similar expression is obtained for the cold leg region.

Bulk Boiling Region. In the bulk boiling region both the enthalpy variation term and the compression term are considered, such that the energy conservation equation, approximating P_{2Q} as the steam pressure P_s, becomes

$$\frac{d}{dt}h_{2Q} = [\,-(h_{2Q} - h_f)(W_{23Q} + W_{12Q}) + \bar{M}_{2Q}L_{2Q}q''_{2Q} + \frac{A_{tb}L_{2Q}}{J}\frac{d}{dt}P_s\,]/M_{2Q} \qquad (3.3.2)$$

Similar expression is obtained for the cold leg region.

Steam Separator. The steam separator, represented by volume 3, presents as an input enthalpy, the weighted average of the exit enthalpies from the region 2Q and 2F,

$$\frac{d}{dt}L_3 = \frac{W_{23}}{A_3\rho_3} - \frac{\left[\frac{R^*}{R^* - 1}\right]}{A_3\rho_3 h_{fg}}\left[W_R h_{fg} + \frac{A_3L_3}{J}\frac{d}{dt}P_s\right] \qquad (3.3.3)$$

where $R^* = R/\chi_s$; R is the recirculation ratio, and χ_s is the steam quality at the steam generator outlet.

Steam Chamber. The conservation equations for the region 4 are derived by balancing the mass and energy in volume 3 and 4 simultaneously, once the variable L_3 is a moving boundary. The expression for the pressure variation is obtained as

$$\frac{d}{dt}P_s = \{[h_{23} - \frac{(\rho_f h_f - \rho_g h_g)}{(\rho_f - \rho_g)}]W_{23} - \frac{\rho_g}{(\rho_f - \rho_g)}h_{fg}W_R^* - \frac{\rho_f}{(\rho_f - \rho_g)}h_{fg}W_s^*\}/\{V_L\rho_f\frac{d}{dP}h_f + V_G\rho_g\frac{d}{dP}h_g + V_L(\frac{d}{dP}\rho_f)\frac{\rho_g}{(\rho_f - \rho_g)}h_{fg} + V_G(\frac{d}{dP}\rho_g)\frac{\rho_f}{(\rho_f - \rho_g)}h_{fg} - \frac{V_T}{J}\} \qquad (3.3.4)$$

where

$$W_R^* = W_R + (1 - \chi_s)W_s\,,$$
$$W_s^* = \chi_s W_s$$

Downcomer Region. The energy conservation equation, Equação 2.4.1, applied to region 5, yields

$$\frac{d}{dt}h_5 = \frac{1}{\rho_f A_5 L_5}\{\,W_F(h_F - h_5) + W_R(h_f - h_5) - W_{51}(h_{51} - h_5)\} \qquad (3.3.5)$$

Primary Side Regions. Density and pressure variations are neglected in the primary side regions, and the straiforward heat conduction equations are solved in the tube regions.

4. MOMENTUM CONSERVATION

4.1 Momentum Conservation. Equation 2.3.1 is applied throughout the recirculation circuit regions observing though that the time derivative term is only retained in the downcomer region. The right hand side collects the pressure loss terms in the control volumes, and the resulting expression is given as

$$\frac{L_5}{A_5}\frac{d}{dt}W_{51} = g\rho_f[L_5 - (L_1 + L_2' + L_3')] - \frac{W_{51}^2}{2\,\rho_f\,A_1^2}\left[\,2\{\frac{(1 - \chi_2)^2}{(1 - \alpha_2)} - 1 + \frac{\chi^2}{\alpha_2}\frac{\rho_f}{\rho_g}\} + \frac{f_{DW1}L_1}{D_{e1}} + \frac{f_{DW2}L_2\Phi_{LO}^2}{D_{e2}} + (\frac{A_1}{A_5})^2(\frac{f_{DW5}L_5}{D_{e5}} + K_5) + (\frac{A_1}{A_3})^2K_3\right] \qquad (4.1.1)$$

In the subcooled region and in two–phase region the acceleration term is negligible, its contribution being a few cents of the total pressure loss, and in the bulk boiling regions the slip–flow model is considered.

Equation 4.1.1 is approximated in GVTRAN–PC by neglecting the left hand side term since its contribution has found to be about four order of magnitude smaller than the rest of the terms in a pump trip transient.

On the other hand its inclusion in the program had only been made possible with the use of very small integration time–steps, order of 0.0001 second in the classical Runge–Kutta scheme, the restriction being the numerical stability criteria.

Without the time derivative term the integration time–step can be as large as 0.05 second, allowing a significant computational load reduction while the degree of accuracy of the complete model is practically retained.

5. GVTRAN–PC TEST CALCULATIONS

GVTRAN program was tested against the actual transient measurements recorded during a startup testing of Donald C. Cook Nuclear Station Unit One ("Supplement to Donald C. Cook Nuclear Plant Unit One Startup Report", Indiana and Michigan Power Company(September 1976)). The transient consisted of a plant turbine trip from 100% of the rated power. The boundary conditions for the initial steady state calculation are given in Reference 1.

The turbine trip was manually initiated while the plant was operating at full power. Thereafter the main steam turbine stop valve was automatically closed causing, as a consequence, the trip of the reactor and turbine driven feed pumps. The boundary conditions for GVTRAN–PC input are

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– in the secondary side: the steam outlet mass flow rate and feed inlet mass flow rate and temperature;

– in the primary side: the inlet pressure, temperature and mass flow rate.

The feed chamber water level and the steam dome pressure calculated with GVTRAN–PC program is plotted in Figure 5.1 and 5.2 together with the experimental data and results calculated with the TRANSG program[1]. The comparison of the results is quite satisfactory in spite of the simplified model employed in GVTRAN–PC program in comparison with the TRANSG 4–equation drift–flux model. Both water level and pressure deviations are well within the acceptable range considering the margin of uncertainties in the experimental data.

The computational expenditures was not directly compared, but a partial prognostic can be inferred from the smaller number of conservation equations and control volumes which are required in the GVTRAN–PC program, viz. 4 control volumes in primary side and 4 control volumes in the secondary side, against 18 and 16 control volumes, respectively, in TRANSG program.

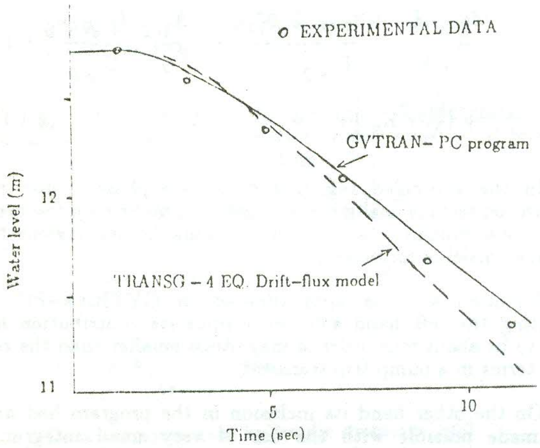

Figure 5.1 – Feed chamber water level in D.C. Cook transient.

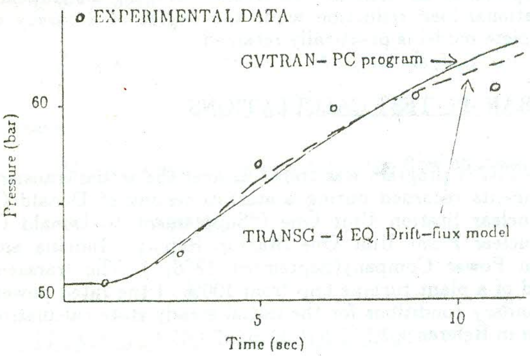

Figure 5.2 – Steam chamber pressure in D.C. Cook transient.

6. CONCLUDING REMARKS

The steam generator model presently developed and implemented in GVTRAN–PC program has been demonstrated to be satisfactorily accurate in reproducing a typical transient in a PWR nuclear station.

The accuracy of the results was not compromised even with the use of the fewer control volumes, only two volumes in the secondary tube region, because the moving boundary approach had been adopted at the boundary of the bulk boiling region, permitting, thus, a fairly good representation of the time variation of the two–phase region height without the recourse to a fine mesh representation.

The momentum conservation equation has only been balanced in the secondary region, and its solution by a quasi–static approach resulted in a significant saving in the computation time, whereas retaining a good accuracy in the water level representation.

In conclusion, GVTRAN–PC possess a combination of few characteristics, all of them highly praised in a nuclear plant simulator: coding simplicity for a quick intermachine transfer, computation velocity compatible with on–line monitoring, and accuracy acceptable for a typical transient analysis.

REFERENCES

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2. BIRD,R.B.; STEWART,W.E. & LIGHTFOOT,E.N. Transport Phenomena. New York, John Wiley, 1960.