Modeling of pressure transients in steam generators (SGEN)

T. Pättikangas, V. Hovi and J. Niemi
VTT Technical Research Centre of Finland

T. Toppila and T. Rämä
Fortum Power and Heat Oy
Introduction

Two-phase models for the primary and secondary sides of steam generators are developed:

- Horizontal steam generator of VVER-440 plant.
- Vertical EPR-type steam generator of the PWR-PACTEL test facility.

APROS system code model is used for primary side and the calculated enthalpy sources are transferred to the ANSYS Fluent CFD code.

Geometry on the secondary side is not described in detail, but porous media model of is adopted for the region occupied by the primary tubes.

Stosic and Stevanovic (Framatome ANP) have previously used similar approach for horizontal steam generator of VVER-1000.
Conservation laws

- Conservation of mass of phase $q$

$$\frac{\partial}{\partial t}(\gamma \alpha_q \rho_q) + \nabla \cdot (\gamma \alpha_q \rho_q \mathbf{v}_q) = S_{\text{mass},q}$$

- Conservation of momentum

$$\frac{\partial}{\partial t}(\gamma \alpha_q \rho_q \mathbf{v}_q) + \nabla \cdot (\gamma \alpha_q \rho_q \mathbf{v}_q \mathbf{v}_q) = S_{\text{M},q}$$

- Conservation of energy

$$\frac{\partial}{\partial t}(\gamma \alpha_q \rho_q \mathbf{h}_q) + \nabla \cdot (\gamma \alpha_q \rho_q \mathbf{v}_q \mathbf{h}_q) = S_{\text{E},q}$$

- Volume fractions

$$\alpha_1 + \alpha_2 = 1$$

- A detailed description of the model was given by Pättikangas, et al. in CFD4NRS-3, Washington D.C., 14–16 September 2010.
Current Heat Transfer models

Available Interface Heat Transfer Correlations:
Chen and Mayinger, Lee and Ryley or Ranz-Marshall

\[ \Gamma = \frac{Q_E + Q_{li} + Q_{vi}}{h'' - h'} \]

Vapor \( T_v \)

Liquid \( T_l \)

Interface \( T_{\text{sat}} \)

Heat transfer in tubes \( T_w \)

Dittus-Boelter

Thom pool boiling

Dittus-Boelter
Fluent model of the PWR PACTEL steam generator
APROS model of the PWR PACTEL steam generator

Primary side

Secondary side

Gap
Simulation results of steady state experiment NC-10 (1/4)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Test (NC-10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{SG}$</td>
<td>334 kW</td>
</tr>
<tr>
<td>$p_{prim}$</td>
<td>75 bar</td>
</tr>
<tr>
<td>$p_{sec}$</td>
<td>20 bar</td>
</tr>
<tr>
<td>$\dot{q}_{m,prim}$</td>
<td>1.1 kg/s</td>
</tr>
<tr>
<td>$\dot{q}_{m,feed}$</td>
<td>125 g/s</td>
</tr>
<tr>
<td>$\dot{q}_{m,vapor}$</td>
<td>-</td>
</tr>
<tr>
<td>$T_{prim, in}$</td>
<td>279 C</td>
</tr>
<tr>
<td>$T_{prim, out}$</td>
<td>216 C</td>
</tr>
<tr>
<td>Level</td>
<td>3.9 m</td>
</tr>
</tbody>
</table>

The experiment NC-10 was done in project PAOLA by Vesa Riikonen et al. at LUT Energy.
Simulation results of steady state experiment NC-10 (2/4)

Vapor generation rate [kg/m³s]

Condensation rate [kg/m³s]

Over the scale
Simulation results of steady state experiment NC-10 (3/4)

<table>
<thead>
<tr>
<th>Point</th>
<th>Measurement</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>212.6 °C</td>
<td>212.8 °C</td>
</tr>
<tr>
<td>2</td>
<td>213.4 °C</td>
<td>212.5 °C</td>
</tr>
<tr>
<td>3</td>
<td>212.7 °C</td>
<td>212.3 °C</td>
</tr>
<tr>
<td>4</td>
<td>212.6 °C</td>
<td>212.5 °C</td>
</tr>
<tr>
<td>5</td>
<td>210.8 °C</td>
<td>211.6 °C</td>
</tr>
<tr>
<td>6</td>
<td>212.4 °C</td>
<td>212.1 °C</td>
</tr>
<tr>
<td>7</td>
<td>212.3 °C</td>
<td>212.1 °C</td>
</tr>
</tbody>
</table>
Simulation results of steady state experiment NC-10 (4/4)

- Positive = flow from cold to hot side
Experiment RF-02: Pressure Rise (1/3)
Experiment RF-02: Pressure Rise (2/3)

Tube Temperature

<table>
<thead>
<tr>
<th>°C</th>
<th>228</th>
<th>227</th>
<th>226</th>
<th>225</th>
<th>224</th>
<th>223</th>
<th>222</th>
<th>221</th>
<th>220</th>
<th>219</th>
<th>218</th>
<th>217</th>
<th>216</th>
<th>215</th>
<th>214</th>
<th>213</th>
<th>212</th>
</tr>
</thead>
<tbody>
<tr>
<td>900 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>950 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1050 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1100 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1150 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1200 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1250 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[Image of temperature distribution over time]
Experiment RF-02: Pressure Rise (3/3)

Vapor fraction

- 1.00
- 0.95
- 0.90
- 0.85
- 0.80
- 0.75
- 0.70
- 0.65
- 0.60
- 0.55
- 0.50
- 0.45
- 0.40
- 0.35
- 0.30
- 0.25
- 0.20
- 0.15
- 0.10
- 0.05
- 0.00

- 900 s
- 950 s
- 1000 s
- 1050 s
- 1100 s
- 1150 s
- 1200 s
- 1250 s
VVER-440 steam generator

- Horizontal steam generator.
- Generates steam 140 kg/s.
- Primary side pressure 123 bar and secondary side pressure 45 bar.
- Primary water inlet temperature 299°C and outlet temperature 265°C.
Simulation procedure for the loss-of-feedwater transient

- All feedwater pumps trip.
- First simulated with Apros plant model of the Loviisa NPP for boundary conditions for the more detailed Apros model of the steam generator.
- From the Apros plant model the pressure and mass flow boundary conditions for the CFD simulation.
- From the more detailed steam generator model heat transfer boundary conditions for the CFD simulation.

one primary side layer of the steam generator Apros model

temperature field [°C] transferred to Fluent model
**Fluent CFD model**

- 230 000 computational cells.
- Feedwater inlet boundary conditions from the Apros plant model.
- Pressure outlet boundary conditions from the Apros plant model.
- Heat transfer through the temperature field of the primary pipes modelled as porous media.
Loss-of-feedwater transient results; Apros

- Water level starts to decrease $\rightarrow$ turbine valves start to close $\rightarrow$ pressure rises in the steam generator.
- As the water level is low enough $\rightarrow$ reactor shut down followed by turbine shut down $\rightarrow$ secondary side pressure peak.
- Due to the reactor shutdown heat transfer from the primary side decreases $\rightarrow$ steam production decreases $\rightarrow$ pressure starts to decrease.
- Water level starts to increase due to the emergency feedwater flow.

![Graph showing pressure and water level over time](image-url)
Loss-of-feedwater transient results; Apros and Fluent comparison

• Results are very similar for the first 200 seconds.
• Differences arise from the outlet pressure boundary condition. Fluent does not simulate the outlet pressure but it is a boundary condition from Apros model → it is not consistent with what is happening inside the steam generator in the Fluent model.
• Because of that the Fluent model steam starts to condensate, whereas in the Apros model steam generation decreases but stays above zero.
Loss-of-feedwater transient results; Fluent

Void fraction at the centerline of the steam generator.
Conclusions on the vertical steam generator model

- Model for the EPR-type steam generator of the PWR Pactel facility has been constructed.

- The steady state experiment NC-10 has been calculated.

- Pressure drop and pressure rise transients on the secondary side have also been calculated.

- The CFD results are in reasonable agreement with the experiments and Apros calculations.

- Construction of a model for an EPR steam generator is started.
Conclusions on the horizontal steam generator model

- Model for the VVER-440 steam generator has been constructed.

- Simulations of stationary situations were first performed and the model was compared against available experimental data
  - void fraction measurements at a few points
  - observations on the mixture level at the Loviisa NPP

- Loss-of-feedwater transient was analyzed. Results were compared against Apros simulations.

- A potential application of the model is the life time management of the steam generators of Loviisa NPP.